MANAGING IRRIGATED AGRICULTURE TO IMPROVE WATER QUALITY

Proceedings of
National Conference on
Managing Irrigated Agriculture to
Improve Water Quality

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MANAGING IRRIGATED AGRICULTURE

The Need for Implementing Irrigation Return Flow Quality Control

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ABSTRACT

The practice of irrigation increases salinity and has other detrimental effects on water quality. Major water pollution problems resulting from irrigation occur in nearly all of the western river basins. Control measures need to be evaluated and implemented that will be effective in alleviating the deleterious effects of irrigation return flows. These will involve physical changes in irrigation systems, improvements in present management and cultural practices, and/or changes in the institutional influences upon the system. Research investigations will be required to further evaluate the effectiveness of new and improved water pollution control programs in river basin areas. Demonstration and educational activities will play a major role in gaining local acceptance and support of recommended control programs. To implement irrigation return flow quality controls, economic incentives to the irrigator must be provided along with changes in the institutional constraints presently imposed on water management reform.

INTRODUCTION

The water quality problems associated with irrigation return flows are of special concern because irrigated agriculture is the largest consumer of our water resources. Additionally, it is of major economic importance to the Nation as the source of a significant part of the food and fiber produced annually. Irrigation return flows constitute a large portion of the flow in many streams of the Western United States. Due to the consumptive nature of irrigation, some degree of salt concentration has been accepted as the price for irrigation development. Nevertheless, there are many areas where water quality degradation has been unduly serious and excessive. As pressures on water resources increase, there is mounting concern for proper and adequate control of such serious water quality deterioration. The need for more precise information as a basis for wise action has been brought sharply into focus. The exact role of irrigation return flows in both surface and groundwater quality problems is now, and must continue to be examined more closely to develop and implement measures to control or alleviate the unnecessary detrimental effects.

Legal authority to implement water pollution control was initiated essentially with the passage of the Water Quality Act of 1965 (P.L. 89-234), and the Clean Water Restoration Act of 1966 (P.L. 89-753) which together greatly expanded earlier basic laws and directed that a "national policy for the prevention, control, and abatement of water pollution" be established. No segment of the national economy was exempted from the implied intent of this National policy. The Water Quality Act of 1965 further provided for all states to establish water quality standards for their interstate and coastal waters. The setting of these standards required crucial decisions by each state regarding the uses of their water resources, quality criteria to support these uses, and specific plans for achieving these levels of quality. The chief purpose of the national program has been to enhance the quality and value of polluted water and to protect the quality of clean water. Although the major efforts to date have been in the treatment and control of municipal and industrial wastes, agriculture is by no means exempted from the fight against water quality degradation.

Irrigation Return Flow System

The relationships of the irrigation return flow system to a river basin are very complex, as shown by the model in Figure 1. The primary sources of irrigation return flow are shown to be bypass water, canal seepage, deep percolation or groundwater flow, and tailwater or surface return flow. Bypass water is required to maintain hydraulic head and adequate flow through the canal system. It is usually returned directly to the river and few pollutants are added to the river by this route. Canal seepage, on the other hand, contributes to high water tables, aggravates subsurface salinity, encourages phreatophyte growth, and generally increases saline drainage from irrigated areas. Canal seepage amounts to a significant fraction of the total diversion in many project areas. Tailwater and deep percolation are the major contributors to irrigation return flow from irrigated cropland. These sources convey dissolved salts, plant nutrients, eroded sediments, pesticides, and other pollutants to the stream drainage system.

The diversion-return flow cycle shown in Figure 1 is typical of many western rivers, and may be repeated many times over in a river basin. The flow at any point along the river may be composed of undiverted river flow, natural inflow, irrigation return flow, municipal and industrial effluents, and return flow of other used water. The proportion of each depends on such factors as the number of diversions, the extent and diversity of uses, the location along the river, and the amount of each of the various inflows to the stream.

Many of the components and processes involved in the irrigation return flow system can be subjected to some degree of manipulation or control for the purpose of improving the quality of irrigation return flows, thereby reducing the pollutant load presently reaching receiving streams. Additional investigations and further research will be required in many areas to define pollutant sources and develop technology needed to implement control measures. The major goal of this conference is to accumulate present knowledge and technology in such a

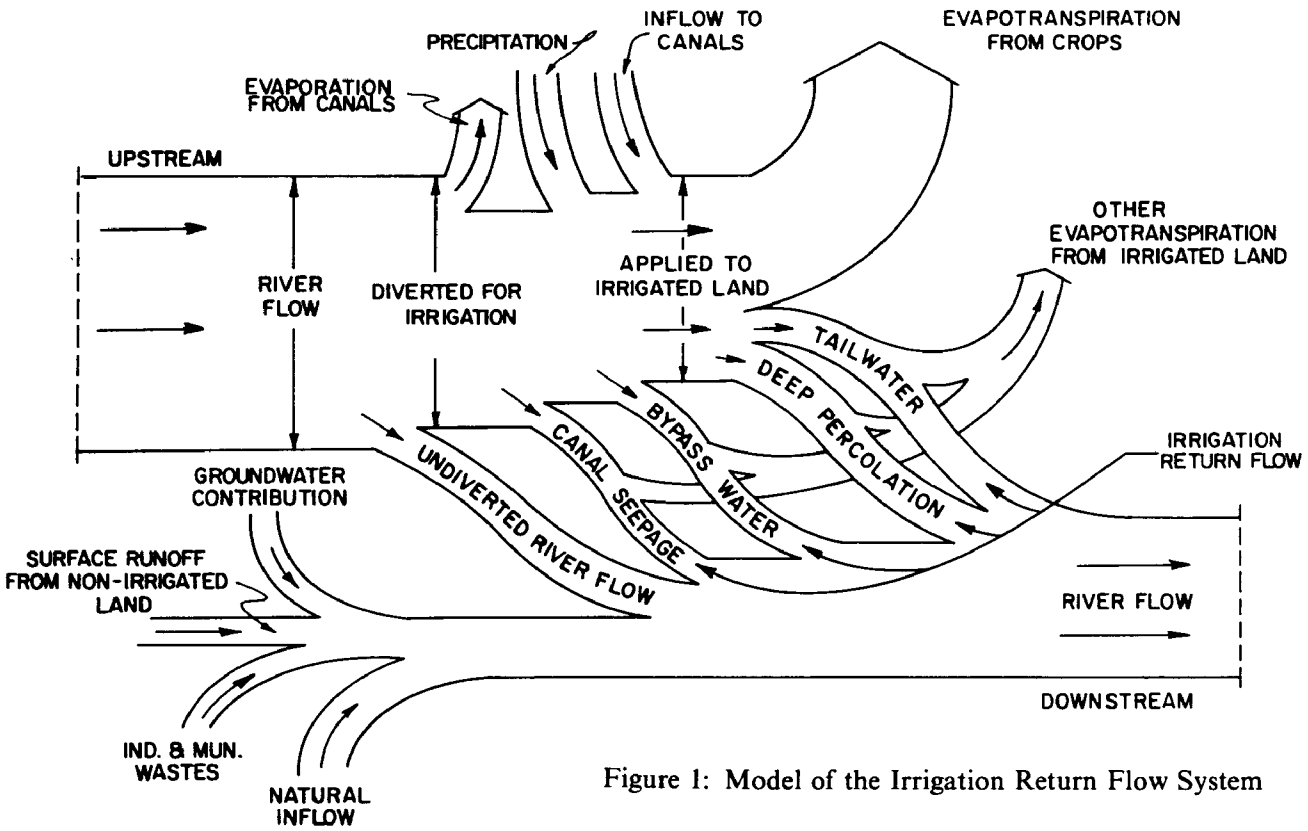

Figure 1: Model of the Irrigation Return Flow System

manner as to make it available for implementation, and at the same time delineate those areas where technology is lacking.

Projected Impact Of Irrigation On Water Resources

Since 1890, the total irrigated land in the United States has increased from about four million acres (1) to an estimated 48 million acres in 1970, or an increase of about 12-fold. More recently, the value of supplemental irrigation in the more humid Eastern United States has been recognized, with an estimated five million acres being irrigated in 1970 (2). There is reason to believe that the acreage of irrigated land will continue to increase.

The Economic Research Service (3) has made projective estimates of irrigated acreage in the United States to the year 2020. A breakdown of these projections by major river basins (Figure 2) is shown in Table 1. The projected increase in irrigated acreage in the United States from 1969 to 2000 is roughly 30 percent, with the projected increase for the same period in the western states being about 25 percent.

Soils in many of the irrigated areas in arid regions contain large quantities of salt and are classed as saline. Some are high in exchangeable sodium and are referred to as sodic soils. It has been estimated (1) that crop production is reduced on one-quarter of the irrigated lands in the Western United States due to saline soils. Salinity presents a potential hazard to about half of the irrigated acreage in the West. California, which has the greatest acreage of irrigated land, also has the largest area of salt-affected soils.

More than one-third of the irrigated lands in the states of Colorado, Hawaii, Nevada, South Dakota, and Utah are affected by highly saline soils. Impaired crop production due to salt-affected soils is not restricted to the arid regions of the United States. It has been estimated that one-third of the world's irrigated land is plagued by salt problems (4).

The National Academy of Sciences (5) has projected water demands in the United States for the year 2000 as compared to the data for 1954. Total diversion, consumptive use, and return flows were projected for irrigation, municipal, manufacturing, mining, and power plant cooling. The figures projected for irrigation are particularly pertinent to this discussion. In 1954, the gross withdrawal for irrigation averaged 176 billion gallons (540,000 acre-ft.) daily, and consumptive use was 104 billion

Figure 2: Major Hydrologic Regions in the United States

gallons (319,000 acre-ft.) daily. It was projected for the year 2000 that gross withdrawal would be 184.5 billion gallons (565,500 acre-ft.) daily and consumptive use 126 billion gallons (387,000 acre-ft.) daily. The projected increase in irrigation withdrawal amounted to about a 5 percent increase, while the increase in irrigated acreage from 1954 to 2000 is expected to double. Thus, the projections for water withdrawals reflect an expected major increase in irrigation efficiency. Further projections (5) were made for estimated annual irrigation water requirements based upon current efficiencies of application and conveyance of irrigation water as compared to future estimated attainable efficiencies. These projected estimates are shown in Table 2 for the years 1980 and 2000 in the western regions along with totals for the United States. When the projected increase in irrigated acreage is considered along with the projected water requirements at future attainable efficiencies of water-use and conveyance, it is shown that a decrease in surface water withdrawals by the year 1980 (negative values in Table 2) is a distinct possibility. To meet the long-term projections for irrigation water demand will require at least a 2-fold increase in water-use and conveyance efficiencies. These projections are based on the fact that present water resources will not be able to meet future irrigation water requirements at current efficiencies. If irrigated agriculture continues to grow along with other economic sectors, then increased efficiencies will be a necessity. Many problems will have to be solved before such widespread increases in irrigation efficiencies are actually attained. Major among these are changes in interpretations of water law and other institutional constraints to water management reform. Improved water quality management is critical to prevent further water pollution effects and will get more critical as expansion occurs.

Irrigation Return Flow Water Quality Problems

Usually, the quality of water coming from the mountainous watersheds in the West is excellent. At the base of the mountain ranges, large quantities of water are diverted to valley crop-

TABLE 1

Projected estimates of agricultural irrigation in the United States, from 1969 to 2020 (All data are in thousands of acres.)

	1969	*1980*	*2000*	*2020*
North Atlantic	519	730	990	1,120
South Atlantic — Gulf	1,747	2,480	3,520	4,150
Great Lakes	143	230	350	470
Ohio Basin	99	150	250	340
Tennessee Basin	18	30	50	70
Upper Mississippi	121	210	310	410
Lower Mississippi	972	1,400	2,070	2,570
TOTAL-EASTERN REGIONS	3,619	5,230	7,540	9,130
Souris — Red — Rainy	20	90	230	250
Missouri Basin	6,985	8,050	8,950	9,600
Arkansas — White — Red	5,357	5,600	6,400	6,690
Texas Gulf	5,890	6,510	7,350	7,770
Rio Grande	2,020	2,050	2,180	2,200
Upper Colorado	1,700	1,900	2,150	2,250
Lower Colorado	1,430	1,820	2,190	2,400
Great Basin	2,240	2,340	2,510	2,570
Columbia — North Pacific	5,815	7,350	7,810	8,490
California	8,050	9,050	9,600	11,540
TOTAL-WESTERN REGIONS	39,507	44,760	49,370	53,760
MAINLAND UNITED STATES	43,126	49,990	56,910	62,890

Source: Economic Research Service, USDA (Ref. 3).

lands. Much of the diverted water is lost to the atmosphere by evapotranspiration (perhaps one-half to two-thirds of the diverted water), with the remaining water supply being irrigation return flow. This return flow will either be surface runoff, shallow horizontal subsurface flow, or will move vertically through the soil profile unitl it reaches a perched water table or the groundwater reservoir, where it will remain in storage or be transported through the groundwater reservoir until it reaches a river channel.

That portion of the water supply which has been diverted for irrigation but lost by evapotranspiration (consumed) is essentially salt-free. Therefore, the irrigation return flow will contain most of the salts originally in the water supply. The surface irrigation return flow will usually contain only slightly higher salt concentrations than the original water supply, but in some cases, the salinity may be increased significantly. Thus, the water percolating through the soil profile contains the majority of salt left behind by the water returned to the atmosphere as vapor through the phenomena of evaporation and transpiration. Consequently, the percolating soil water contains a higher concentration of salts. This is referred to as the "concentrating" effect.

As the water moves through the soil profile, it may pick up additional salts by dissolution. In addition, some salts may be precipitated in the soil, while there will be an exchange between some salt ions in the water and in the soil. The salts picked up by the water in addition to the salts which were in the water applied to the land are termed salt "pickup." The total salt load is the sum of the original salt in the applied water as the result of the concentrating effect plus the salt pickup.

Whether irrigation return flows come from surface runoff or have returned to the system via the soil profile, the water can be expected to undergo a variety of quality changes due to varying exposure conditions. Drainage from surface sources consists mainly (there will be

TABLE 2

Estimated annual irrigation water requirements for years 1980, and 2000
(All units in thousands of acre-feet.) (Excerpted from Ref. 5)

Water Resource Region	Total groundwater and surface-water requirements: At current efficiency[1] 1980[2]	2000	At estimated efficiency 1980	2000	Surface-water requirement at estimated future efficiency 1980	2000	Additional surface-water requirement at estimated future efficiency 1980	2000
Western:								
Upper Missouri	20,747	32,040	16,346	22,331	14,058	19,205	- 1,179[3]	3,968
Upper Arkansas, White, Red	4,876	6,488	4,035	4,922	1,130	1,378	- 199	49
Western Gulf	11,789	15,689	9,226	10,914	4,613	6,003	- 715	675
Upper Rio Grande-Pecos	7,079	8,053	5,522	5,315	2,761	2,923	- 198	- 36[3]
Colorado	20,335	20,708	16,071	14,696	12,214	11,904	- 2,172	-2,482
Great Basin	9,481	9,742	7,449	6,727	6,481	5,852	- 1,735	-2,364
Pacific Northwest	16,837	21,053	13,680	15,132	12,586	13,921	- 2,301	- 966
Central Pacific	35,031	35,623	30,223	27,241	16,623	16,345	- 1,339	-1,617
South Pacific	4,486	4,635	3,671	3,371	2,019	2,023	- 503	- 499
Subtotal (Western Regions)	130,661	154,031	106,223	110,649	72,485	79,554	-10,341[3]	-3,272[3]
United States Totals	139,472	189,457	113,650	137,246	75,819	94,283	- 9,461[3]	9,003

[1]Assuming no increase in efficiency of application and transmission of irrigation water.
[2]Based on adequate irrigation of all land under irrigation.
[3]Negative values indicate a net decrease in water requirements resulting from estimated increased efficiency in use and transmission of irrigation water.

some precipitation runoff) of surface runoff from irrigated land. Because of its limited contact and exposure to the soil surface, the following changes in quality might be expected between application and runoff: (a) dissolved solids concentration only slightly increased; (b) addition of variable and fluctuating amounts of pesticides; (c) addition of variable amounts of fertilizer elements; (d) an increase in sediments and other colloidal material; (e) crop residues and other debris floated from the soil surface; and (f) increased bacterial content.

Drainage water that has moved through the soil profile will experience changes in quality different from surface runoff. Because of its more intimate contact with the soil and the dynamic soil-plant-water regime, the following changes in quality are predictable: (a) considerable increase in dissolved solids concentrations; (b) the distribution of various cations and anions may be quite different; (c) variation in the total salt load depending on whether there has been deposition or leaching; (d) little or no sediment or colloidal material; (e) generally, increased nitrate content; (f) little or no phosphorus content; (g) general reduction of oxidizable organic substances; and (h) reduction of pathogenic organisms and coliform bacteria. Thus each type of return flow will affect the receiving water in proportion to respective discharges and the relative quality of the receiving water.

The quality of irrigation water and return flow is determined largely by the amount and nature of the dissolved and suspended materials they contain. In natural waters, the materials are largely dissolved inorganic salts leached from rocks and minerals of the soils contacted by the water. Irrigation, municipal and industrial use and reuse of water concentrate these salts and add additional kinds and amounts of pollutants. Inorganic salts, pesticides, sediments, detergents, salts of heavy metals, and other organic compounds render water less fit for irrigation and other beneficial uses.

Major Areas Having Water Quality Problems

The more serious water quality problems resulting from irrigation return flow occur in the Western states, where salinity and sediment erosion and transport are the greatest offenders. Plant nutrients and pesticide residues follow closely behind, but are not necessarily confined to the more arid regions of the West. The major areas in the Western United States having serious water quality problems resulting from irrigation return flows are shown in Figure 3. Some of our major river basins are characterized by a high degree of utilization of the water resources and are also experiencing deleterious water quality effects.

Water users in the Lower Colorado River Basin, especially Mexico and the Imperial and Coachella valleys, experience difficulties at the present time due to high salt concentrations in the river. Salt concentrations in the Lower Colorado River are projected to increase by the year 2000 due to anticipated water resource development projects. Projects are presently nearing completion for exporting additional quantities of high quality water from Colorado River watersheds to satisfy water demands in the more populous regions of Utah, Colorado, and New Mexico. The authorized Central Arizona Project will divert large quantities of flow from the Colorado River to Salt River Valley, which is within the basin, but the return flows to the Colorado River will be small. The irrigation return flows will have long-term effects on the salt balance in the Salt River Valley. In addition, large quantities of water will be diverted for use by present and future power plants in the four corners region (Utah, Colorado, New Mexico, and Arizona). A salinity control program, including a combination of controlling mineralized springs and irrigation return flows, would negate a large portion of the damage which will result from anticipated water resource development projects, which will export good quality water to adjacent river basins, thereby leaving less water within the Colorado River Basin for diluting irrigation return flows.

The Rio Grande Basin is another example of an area already experiencing serious water quality problems, with the outlook for even more serious problems. Rapid population growths in Albuquerque, El Paso, and Juarez foretell of immediate difficulties. Whereas studies have been made in the Colorado River Basin which predict future water quality prob-

Figure 3: Major Water Quality Problem Areas in the Western United States

lems due to basin development, such studies have not been undertaken in the Rio Grande River Basin. Future water quality problems in this basin could easily result in international problems somewhat similar to those recently experienced in the Lower Colorado River.

Another major irrigated area presently experiencing water quality problems from irrigation return flows is the San Joaquin Valley. Water deliveries from portions of the recently constructed California State Water Project have begun. New lands are being placed under irrigation and natural salts (including nitrates and boron) in the soil root zone must be leached, with subsequent higher water tables in irrigated lands at lower elevation. A drain is being constructed to carry the return flows to the ocean by way of San Francisco Bay. Because of already serious quality problems in the Bay, it is likely that this drainage water will have to be treated for nitrate removal before being released. The magnitude of the potential problems can only be estimated at the present time.

The Yakima Valley in central Washington is an area which experiences considerable local difficulty due to irrigation return flow. Even though the net quality degradation in the Columbia River is low due to dilution, there is a real need for an irrigation return flow control program to provide for competitive water uses (fishing, recreation, municipal, and industrial) within the Yakima River Basin, as well as to provide economic equity among the agricultural water users.

Numerous other areas in the West experience some degree of water quality problems due to irrigation return flows, including the Pecos River in New Mexico and Texas, the South Platte River in Colorado, the Platte River in Nebraska, the Sevier and Bear Rivers in Utah, the Humboldt River in Nevada, the Santa Ana Basin in California, and other areas. With the

passing of time, the water quality problems in these areas will become more serious because of increasing water demands.

Although salinity problems due to irrigation return flow are not significant in much of the Pacific Northwest, water quality problems re sulting from pesticides, nitrogen, phosphorus, nematodes, and sediments are very important. Also, there is considerable potential for increasing the irrigated acreage in the Columbia River Basin because of abundant water supplies. For example, Idaho could increase its irrigated cropland from 3.66 million acres (1969) to 8 million acres. Such an increase in irrigated acreage could be expected to have a dramatic effect upon the water quantity and quality of the Snake River.

The Navajo Indian Irrigation Project in northwestern New Mexico, presently under construction, will eventually irrigate 110,000 acres of land not previously irrigated. An initial block of 10,000 acres is scheduled for irrigation in the spring of 1975. Of the approximately 500,000 acre-feet of water to be diverted annually, half is expected to be return flow. There are estimates that the quality of these return flows will double in salt concentration due to evapotranspiration, but there are no estimates of salt pickup. Presently, the irrigation system for the initial block is being re-designed to provide more efficient water utilization. If this results in less water being diverted, then the total salt load returning to the San Juan River will not be as great as would have occurred under the original plan of development. In any event, precise predictions of salt load returning to the San Juan River are not available. As a consequence, downstream damages in the Lower Colorado River to Arizona, California, and Mexico are unknown, with only very crude estimates being possible.

The Navajo Indian Irrigation Project is but one example of our present-day problems in predicting the effect of irrigation development upon the quality of downstream receiving waters. As our water resources become more fully utilized, the importance of irrigation return flow quality will be of even greater significance in the overall water management and development in a basin. If large-scale schemes for transporting water to the Intermountain West from the Columbia River Basin or Canada were to become a reality, what would be the effect of irrigating new desert lands in Utah and Nevada, or other adjacent areas? Questions similar to this can be raised regarding the effect of any projected changes to present water resource schemes. Intelligent answers are needed to recommend and initiate water pollution control programs based on wise use of technology.

Irrigation Return Flow Quality Control Measures

Irrigation return flow is an integral part of the hydrologic cycle, therefore, control measures for managing the return flow from irrigated areas must be a coordinate part of the overall water resource development and management. Irrigation return flow quality control is one component in the management of water resources that has been long neglected. In too many instances, economic pursuits have by far superseded considerations for maintaining environmental quality. Those measures which have a potential for controlling the quality of irrigation return flows may involve physical changes in the system, improvements in present management and cultural practices, and/or changes in the institutional influences upon the system.

The irrigation return flow system can be subdivided into three major subsystems: (a) water delivery; (b) the farm; and (c) water removal (Figure 4). The water delivery subsystem includes the transport of water and pollutants from the headwaters of the watershed to the point of diversion, thence to the individual farm. The farm subsystem begins at the point where water is delivered to the farm and continues to the point where drainage water is removed from the farm. Also, the farm subsystem is defined vertically as beginning at the soil surface and terminating at the bottom of the root zone. The water removal subsystem includes both surface runoff from the farm and water moving below the root zone, where quality problems are minimized by having highly efficient water delivery and farm subsystems. Minimizing the quantity of surface runoff will assist in alleviating quality problems due to sediments, phosphates, and pesticides;

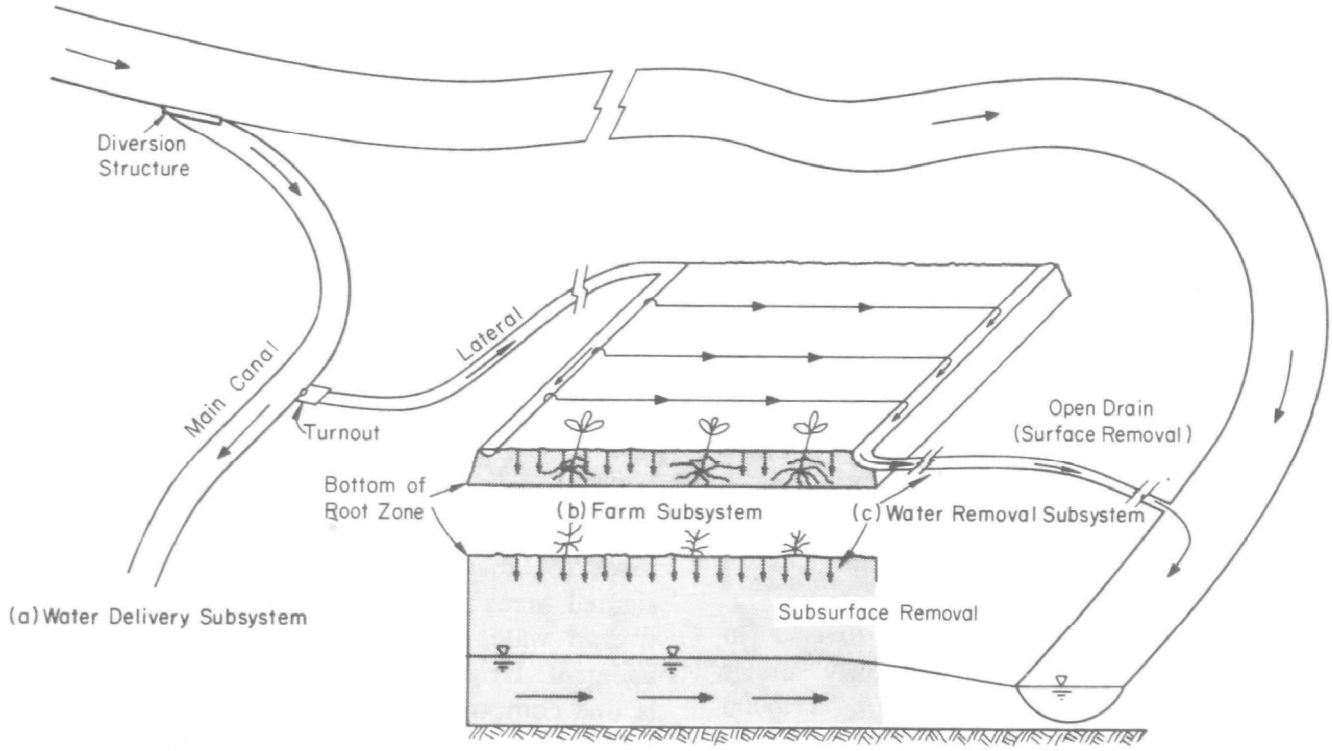

Figure 4: The Water Delivery, Farm, and Water Removal Subsystems

whereas minimizing deep percolation losses will reduce quality problems due to salts, including nitrates, in areas where salt pickup occurs.

Water Delivery

The importation of high quality water from adjacent river basins, weather modification to increase precipitation and runoff from the watersheds, bypassing mineralized springs, evaporation reduction from water and soil surfaces, and phreatophyte eradication are some of the available measures for improving the quality of water within a river basin. Consequently, they play a role in the management of the irrigation return flow system. More feasible approaches may be found in the control of losses from storage and conveyance systems.

Canal and Lateral Lining — Seepage losses from irrigation canals may be considerable and result in low water-conveyance efficiencies. Historically, the economics of canal lining has been justified primarily on the basis of value of the water saved. The possibility that canal seepage may greatly increase the total contribution of dissolved solids to receiving waters has only recently been given serious attention. Average seasonal canal losses have been found to vary from 13 percent of the diversion on the Uncompahgre Project, Colorado, to 48 percent of the diversions on the Carlsbad Project, New Mexico (1). On the basis of a conservative estimate that 20 percent of the total water diverted for irrigation in the United States is lost by canal seepage, the loss to the intended users would be 24 million acre-feet per year. This in itself is significant, but if soils along the canals are high in residual salts, the salt pickup contribution from this source could easily exceed that leached from the irrigated land to maintain a salt balance. Because of enhancement in both quantity and quality, the value of improved water quality is another benefit to be utilized in the economic justification of canal lining.

Evaporation losses from canals commonly amount to a few percent of the diverted water. The installation of a closed conduit conveyance system has the advantage of minimizing both seepage and evaporation losses. Either lined open channels or closed conduits will reduce evapotranspiration losses due to phreatophytes and other vegetation along canals. The closed conduit system uses less land and provides for better water control than a canal system. Water

quality improvements may very well prove to be the greatest economic justification for closed conduit systems because of minimal seepage losses and considerable flexibility in water control.

Project Efficiency — Because the amount of water passing critical points in the irrigation delivery system must be known to provide water control and improve water-use efficiency, provisions for effective flow measurement must be made. Many present day systems employ no flow measuring devices and, in some cases, the individual farmer operates his own turnout facility with no close control of the amount diverted to the farm.

Economics play a major role in existing project irrigation efficiencies, and a close correlation exists between water abundance and/or cost of water and project efficiency. For example, where water is scarce or high in cost, the efficiencies are found to be higher. Project management, as well as farm management, involves balancing the immediate cost of water against the higher labor and investment costs required to use it more efficiently. The costs of inefficient water use may not be recognized immediately, but may be reflected in reduced yields due to nutrient losses or increased salinity, or in extra drainage facilities required later to control rising water tables.

Farm Water Management

The most significant improvements in controlling irrigation return flow quality will potentially come from improved farm water management. Because of the nature of irrigated agriculture, whereby salts must be leached from the root zone, an optimum solution will require improvements in on-the-farm water management. In order to attain high irrigation application efficiencies, the timing and amount of water being delivered to the farm must be controlled. At the same time, the farmer must be capable of controlling the water supply as it moves across the farm by regulating the water delivery rate and measuring the quantity of water applied.

Application Methods — The effect of methods of application on the quality and quantity of return flow has not received detailed study. Conventional surface and sprinkler methods are most commonly used because of their low initial cost and ease of adaptability to a wide range of field and surface conditions. New and unique approaches to application methods need to be found. Two that appear to offer great promise in the control of both quantity and quality of return flows are subsurface application (6) and drip or "trickle" methods (7).

With subsurface irrigation, water can be applied to the crop in small amounts and at frequent intervals so that evaporation and the concomitant increase in salt concentration are reduced. The water content of the soil is maintained below field capacity so that some precipitation can be stored, introducing an additional dilution factor. Comparable crop yields have been produced with 40 to 50 percent less water than is required with furrow irrigation. Thus, limited water supplies can be extended or the acreage which can be irrigated with a given water supply can be increased. Application rates can be closely controlled and the method can be readily automated.

The major advantages of drip irrigation include increased crop yield, reduced salinity damage, and shortened growing season with earlier harvest. The method involves the slow release of water on the surface near the base of the plants. Evaporation losses are greatly reduced and moisture release is confined to the area of the plant root system.

Both of these methods need to be evaluated as to their potential for reducing salinity in return flows, increasing yields with limited water supplies, and reducing fertilizer nutrient losses. Liquid fertilizers can be applied by either of these methods in small controlled doses throughout the growing season. The potential economic advantages of saving both water and fertilizer nutrients and reducing labor costs of operation make these methods attractive. Economic evaluation might show that these benefits would largely offset the initial cost of installation.

Irrigation Scheduling — Historically, irrigation has been practiced more as an art than a science. When left to his own discretion, a farmer may delay irrigation until the crop is stressed and then apply more water than actually needed, resulting in poor water management and reduced yields. This two-fold problem is

presently being overcome by irrigation scheduling based on climatic, soil, and crop data (8). Commercial firms gather the data and notify the irrigator when to irrigate a certain crop and the amount to be applied. The farmer pays a fee for the service and is thus relieved of the responsibility of deciding when is the best time to irrigate.

Experience in southern Idaho and the Salt River Project in Arizona during the past few years clearly indicates increased yields due only to scientific scheduling of irrigation. To date there has been little reduction in water use, although it seems likely that this would occur with time as more experience is gained with the scheduling program. This approach offers great promise as a water management tool and may provide the knowledge and experience needed to overcome present antiquated institutional, political, and legal constraints to water management reform.

Tailwater Recovery — In water-short areas, tailwater recovery is practiced. In addition to increasing water-use efficiencies, the practice serves as a control of sediment with its adsorbed pollutants. Recovered water is readily returned to the irrigation supply after settling of suspended solids rather than released to surface drainage systems (9). Improved irrigation practices would be needed in order to minimize the quantity of tailwater and sediment load from cropland. In extreme cases, enforceable regulations may be required to effectively control tailwater losses and protect downstream water users.

Fertilizer Nutrients — Nitrogen-use efficiency may be improved by the use of slow-release fertilizers or by adding liquid fertilizers frequently at low levels through the irrigation water supply. The present higher cost of these products is the chief deterrent to increased acceptance. If regulations were imposed to require their use in areas where nitrogen problems occur, increased sales volume would act to lower the cost of production and a more favorable pricing schedule would result. An added advantage of slow-release fertilizers is fewer applications per season. Further evaluation of these products with regard to improved quality of irrigation return flow is required.

Cultural Practices — In areas of slowly permeable soils and saline water supply, cultural practices become significant if crops are to be grown successfully. Under these conditions, management alternatives are: (a) use of more salt tolerant crops; (b) special deep tillage may be required; (c) leaching in the off-season or alternate years; (d) careful seed-bed preparation and seed placement; and (e) close control of timing and amount of water applied. Special practices such as mulching and reduced tillage may be effective in reducing soil water evaporation. These special cultural practices have been aimed more at crop production under less-than-ideal conditions than toward improved quality of return flow, although the two could go hand-in-hand. Soil structure, texture and stratification are the principal properties that control water storage in the soil. Deep tillage may be required to disrupt slowly permeable layers, permitting greater water storage capacity and deeper root penetration. Cultural practices which can play a significant role in water quality management need further evaluation.

Control of Leaching — Another possible control measure would be to reduce deep percolation losses, which would minimize salt pickup from underlying geologic formations. The most drastic action would be to eliminate irrigation in areas of high salinity such as those where the soils are formed from, and overlying, salty shales. Preventing or reducing the amount of water penetrating to deeper saline strata would also reduce the salt load in return flows. The use of natural or artificial barriers below the root zone, coupled with drainage systems to intercept drainage water before it reaches the deeper strata, would be effective. Regulating the amount of water applied to the land and thereby regulating the amount of drainage constitutes a combination of controlled leaching and dilution. Further study is needed to evaluate this approach to the control of salinity in return flows.

Water Removal

The water removal subsystem transports surface runoff and subsurface drainage from irrigated lands. The tailwater may be returned to the delivery system, become water supply for an adjacent farm, or be transported back to the

river. Subsurface drainage may seep into open drains or to low lands along the river where salt damage often occurs. There are essentially three management alternatives for preventing or minimizing the quantity of pollutants discharged to the river: (a) divert the drainage to some discharge point or sink area away from the river; (b) treatment for removal of pollutants prior to reuse or discharge; and (c) provide dilution to minimize the detrimental effects. Economic considerations are of prime importance in each of these alternatives.

Diversion — Subsurface return flows are often collected by tile drainage systems underlying irrigated areas. Being thus collected into a common sump or open drain, they may easily be diverted to some point away from the river. The proposed drainage system for the San Joaquin Valley and the present system for the Wellton-Mohawk district in southern Arizona are examples of return flows being removed without returning to the river or supply canal system. Return flows diverted to suitable sink areas may provide wildlife habitat. Either of these alternatives prevents the addition of pollutant loads to the river system. Other considerations, such as water rights of downstream users, may be important in selecting suitable diversion schemes for irrigation return flows.

Treatment — The present high cost of desalination processes is the chief deterrent to their use for reclaiming saline water. Only in extreme cases would they prove economically feasible. Recent cooperative research at Firebaugh, California, conducted by the Envirnomental Protection Agency, Bureau of Reclamation, and California Department of Water Resources has developed methods for removing nitrates from irrigation return flows. In these studies, both algae stripping and bacterial denitrification proved feasible to treat agricultural tile drainage prior to its release into San Francisco Bay via the San Joaquin drainage canal system.

Dilution — Dilution of return flow occurs naturally in nearly all headwater areas. Drainage waters and other return flows are usually diluted in the main stream so that the resultant quality is acceptable downstream for irrigation and other beneficial uses. Multipurpose reservoirs have provided storage capacity for low-flow augmentation which can be beneficial for quality control, although such benefits are usually incidental to other primary requirements for regulated flow.

There are limitations to the effectiveness of dilution as a means of managing return flows. The major physical limitation is the amount of high quality water that can be stored and released at the desired times to achieve maximum benefits from dilution. The legal implications of obtaining water rights for the purpose of dilution could be exceedingly complex. In general, such practices would result in diminished supplies for other purposes and this would occur in areas where water rights already often exceed the supply. Presently, it appears that streamflow regulation for quality control of irrigation return flows cannot be relied upon as a useful management technique. Reservoir storage for quality control has not received favorable support from a national policy standpoint.

Research And Development Needs For Implementation

In the preceding discussion of potential water quality control measures, the need for further study and evaluation of their effects on irrigation return flow quality was indicated. Yet there remain certain areas where advanced technology and knowledge are required for the development and implementation of effective water quality control programs. The needs outlined below are broader in scope and purpose than those relating to the specific control measures. The fact that certain research and development needs are not discussed here only means that the priority is considered less important from the standpoint of immediate needs for getting control programs underway.

Soil-Plant-Salinity Relationships

In assessing the effects of increased salinity of water supplies, it becomes essential that crop damage functions be determined and related to field conditions. At the present time, there exists rather limited knowledge of precise salinity effects upon crop growth. Our knowledge of crop utilization functions as affected by both water quantity and stage of plant growth is also weak. Experimental designs should incorporate both water quantity and quality as variables

in crop production and crop damage functions. The salt tolerance of various crops under a variety of farm water management practices should be investigated. The studies should include short-term effects due to salinity, such as the ability of a plant to withstand high salinity concentrations for short durations. Other cultural practices designed to reduce soil water evaporation should be incorporated in demonstration projects. Evaluation of results should be included in programs to monitor the long-term effects of recommended irrigation and agronomic practices. Rather than using only crop yields as a measure of success, monitoring must include water quantity and quality changes in the root zone, as well as below the root zone.

There remains a need to develop economical slow-release fertilizers which will release nutrients at a rate to match plant needs, thus maximizing plant-use efficiency and minimizing the quantity of fertilizer constituents appearing in irrigation return flows. The use of slow-release fertilizers should be incorporated in experimental designs on irrigation practices. Demonstration projects using such fertilizers could be easily accomplished in most areas where nutrients in irrigation return flow are a problem.

Leaching and Salt Balance

Since crop salt tolerance and soil salt balance are intrinsically interrelated, better techniques for determining optimum leaching requirements are needed. The basic problem is in developing a knowledge of transport phenomena on a field basis, which can then be incorporated into the development of criteria for determining leaching requirements. The transport phenomena will involve a more detailed analysis of leaching based upon an ionic evaluation of salt movement through the soil. For example, certain salts, such as gypsum, are not really deleterious to plant growth and, if these salts are precipitated within the soil, they present no real problem. A more difficult problem results when salts such as sodium are not being leached from the root zone. Criteria for leaching should take into account the type of salts being leached, as well as total dissolved solids, as a means of evaluating leaching requirements and salt balance in field situations.

Much of our present knowledge regarding leaching requirements and the movement of water and salts in the soil has been developed in laboratory-packed columns. The results obtained under these conditions can be unrealistic when compared with undisturbed soil profiles. There is a need to translate this type of information to actual field conditions, and additional studies in this area are needed. The relationships between soil physical characteristics and quality of the water applied must be evaluated to determine actual leaching requirements.

Prediction of Subsurface Return Flow

The greatest single technological need at the present time for the control of irrigation return flow quality is the development of prediction techniques which will describe the quantity and quality of subsurface return flow. The critical problem is in defining the variability in subsurface return flows for large areas, such as an irrigated valley or large basin area.

General models should be developed to describe subsurface return flow which can be adapted to numerous areas. Conceptual models must be developed and the sensitivity of various parameters which will be used in the models must be determined. In studying large areas, a balance must be reached between the sophistication of the model and the cost of collecting field data. These models must be capable of predicting changes in the quantity and quality of subsurface return flows under a variety of water management alternatives. To fully evaluate chemical quality changes, the models should be capable of handling precipitation and exchange reactions which take place as water moves through the soil profile. These transformations alter the ionic balance of the chemical constituents in solution and are very important in describing the quality of irrigation return flow.

Another facet of predictive methods that is not generally available is predicting the long-range quality considerations related to irrigation return flow management and receiving stream quality. Consequently, the problems resulting from the development of new irrigation projects, particularly those involving lands not previously irrigated, are usually confronted after-the-fact.

Economic Evaluation

There is a pressing need to delineate the wide variety of benefits and damages that occur as a result of water quality changes. In assessing costs and benefits associated with irrigation return flow, the development of crop production and crop damage functions due to water quality would provide necessary information for making more accurate economic evaluations and would enhance the decision-making process. Rather than thinking just in terms of crop production, or crop damage, resulting from water quality degradation economic studies should encompass the decreased utility of return flows to downstream water users, due to deteriorating water quality.

Economic studies are needed to define the local, state, regional, and national benefits which would accrue from the implementation, either in an irrigated valley or river basin, of an irrigation return flow control program. For example, a control measure implemented in a particular valley has certain benefits to the local area, including non-agricultural sectors. The degree of quality improvement achieved by this control measure will have a number of benefits to downstream water users. Also, benefits may accrue to upstream users resulting from water exchanges or because of institutional arrangements (e.g., if standards fix the allowable water quality leaving a region, then the improvement of irrigation return flow quality in an existing area may be required before new agricultural lands can be placed under irrigation within the region).

Institutional Changes Needed

Coupled with economic uncertainties, institutional considerations, particularly the interpretation of western water laws, represent the greatest hindrance to promulgating incentives for efficient water use. First, a study should be undertaken to delineate the changes in water law interpretation required to provide efficient water use incentives. Next, the procedures required to have such interpretations included in the water law structure of each state should be determined. Then, as a minimum, such changes in interpretation should be attempted in the states having water quality problems resulting from irrigation return flow. This would be particularly beneficial in a state where a control program would soon be getting underway.

Studies should be undertaken which would evaluate the possibilities of incorporating water quality into a water right (e.g., California Porter-Cologne Act). For the most part, present water rights pertain only to the quantity of water. Since the quality of water can be a limitation upon its use, both quantity and quality should be specified in a water right. A variable water right based on quality may be feasible. For example, a greater quantity of low quality water will be required to produce the same results that can be obtained with a lesser amount of high quality water.

The effects of placing certain regulations upon an area in order to control irrigation return flow quality should be evaluated. For example, regulations regarding the use of fertilizers should be studied. Such studies must consider requirements for administering fertilizer regulations, as well as gaining knowledge on local and downstream benefits, along with local damages. Other regulations that need evaluation are limiting water use (e.g., use of economic charges to control water use), tailwater controls, and effluent standards for drainage systems which incorporate both quantity and quality.

Potential Control Measures

Area-wide investigations will be required in some areas to define the control measures that are needed and feasible to improve downstream water quality. These studies would pinpoint the sources of salinity, nutrients, and other pollutants, and provide background information to support the most feasible approaches to control measures. Once the sources of pollutants are defined, more detailed studies will be required to specify how those sources may best be controlled. Such broad investigations will require the cooperative efforts of several research groups under the guidance of a central advisory committee representing local, state, and federal interests. Local acceptance of proposed control measures will require demonstration projects and extensive educational programs to demonstrate local, regional, and interstate benefits to be gained.

Challenge For The Future

The completion of research studies, reconnaissance investigations, and technological developments will not constitute the final solutions to water quality problems. The knowledge and technology gained from such endeavors must then be applied to specific problems to recommend, initiate and implement the most feasible irrigation return flow water quality control measures. Of the major problem areas in the western river basins, only the Colorado River Basin (10, 11) has been studied on a basin-wide scale for the purpose of developing potential solutions and costs for controlling salinity within the basin. Other similar reconnaissance-type studies may be required in major problem areas, such as the Rio Grande River Basin, San Joaquin Valley, and other smaller areas like Yakima Valley and the Santa Ana Basin.

Once the major problem areas within a river basin have been delineated, more detailed investigations become necessary, particularly for those areas responsible for the greatest water quality degradation. An example of such an area in the Upper Colorado River Basin is Grand Valley where detailed investigations have been accomplished and further studies are scheduled for the immediate future. At this point, it becomes necessary to investigate the water delivery system, farm water management practices, and the water removal system to define the magnitude of control possible for a number of water management alternatives. Knowledge gained and control measures recommended in Grand Valley should prove useful and applicable to other similar irrigated areas in the West. This is where the potential control measures and research needs cited previously play an important role.

The two major problem areas confronting implementation of water quality control programs are considered to be: (a) economic evaluation of the effects of alternative control measures; and (b) changes of the legal, political, and institutional constraints to water management reform. In addition to evaluating the economic benefits accruing to local, regional, and river basin areas, economic incentives must be provided for the individual irrigator. The fact that irrigation farming is an economic endeavor must not be overlooked. In order to maintain the ability to compete in farm production, higher levels of production without undue added costs must be reached. This must be accomplished by improved management practices and maintaining productivity levels of the land. To illustrate, consider the irrigator who may be required to improve his water distribution system, improve water-use efficiency, use an irrigation scheduling service, control tailwater losses, and/or other measures dictated by a basin-wide water quality control program. If it can be shown that such improvements will result in increased crop yields, increased fertilizer-use (decreased nutrient loss) efficiency, lower labor and operating costs, lower system maintenance costs, and maybe other accrued benefits, then the economic incentive will have been provided for the irrigator to cooperate. Demonstration projects and educational programs will provide the key to obtaining support and cooperation at the local level. These activities will also encourage the support of other sectors of the local community.

Constraints imposed by legal, political, and institutional influences may be even more difficult to deal with. In addition to the needed changes in interpretation of water law and the incorporation of water quality in a water right, the operations of many small water districts in a valley area often lead to inefficiencies and inequities among water users. This suggests that one master district managing the water resource for an entire valley might be much more efficient in its operational control of water distribution and drainage facilities. Inequities and competition would be reduced, with the possibility that distribution costs could be lowered. Considerations such as these are essential if the challenge of the future is to be met.

The concept of effluent standards is presently being explored with regard to certain industrial wastes. It is not beyond the realm of possibility that similar approaches may be considered for certain agricultural wastes. Studies and voluntary action programs designed to solve a problem before enforcement actions become necessary would be most desirable. The urgency for immediate action is apparent.

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Salinity Control Needs in The Colorado River Basin

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ABSTRACT

The salinity of the Lower Colorado River is presently high. In the absence of any salinity control measures, it is projected that the average salinity at Imperial Dam, the major Lower Basin diversion point, will increase from 870 ppm to over 1,300 ppm by the turn of the century. Studies have indicated that without salinity control measures damages in the Lower Colorado River Basin due to the above projected salinity will continue to grow, reaching in the order of $45-$60 million per year.

The U.S. Bureau of Reclamation has commenced studies on salinity control projects that could remove about 1.8 million tons of salt annually from the Colorado River. Because of future development, approximately three million tons of salt per year would have to be removed by the end of this century in order to keep the river's salinity at present levels. Thus, the USBR has indicated the need for weather modification, a large scale desalting of concentrated flows, or additional salinity control projects in order to meet the objective of keeping salinity at or below present levels.

Work has commenced on a very promising major salinity control program that is supported by the seven Colorado River Basin States and federal agencies.

INTRODUCTION

The Colorado River Basin comprises 242,000 square miles in the seven states of Colorado, Wyoming, Utah, New Mexico, Arizona, Nevada, and California, and in the Republic of Mexico. The river's salinity is a basinwide problem with the major impact falling on the latter three Lower Basin states and on Mexico. High salinity adversely affects more than eleven million people and over 900,000 acres of highly developed irrigated land in these three states.

The current average annual salinity of the Colorado River ranges from about 50 parts of salt per million parts of water (ppm) at its headwaters in Colorado and Wyoming to 870 ppm at Imperial Dam, the lowest diversion point in the United States. Twenty-seven miles below Imperial Dam the average annual salinity of the river water used by Mexico at the Northerly International Boundary is about 1,160 ppm. Figure 1 shows the Colorado River Basin, key features and the salinity at selected stations for the 1963-67 period.

Sources of Salinity

Salinity concentrations are affected by two basic processes: (1) salt loading, i.e., the pickup of mineral salts from natural and man-made

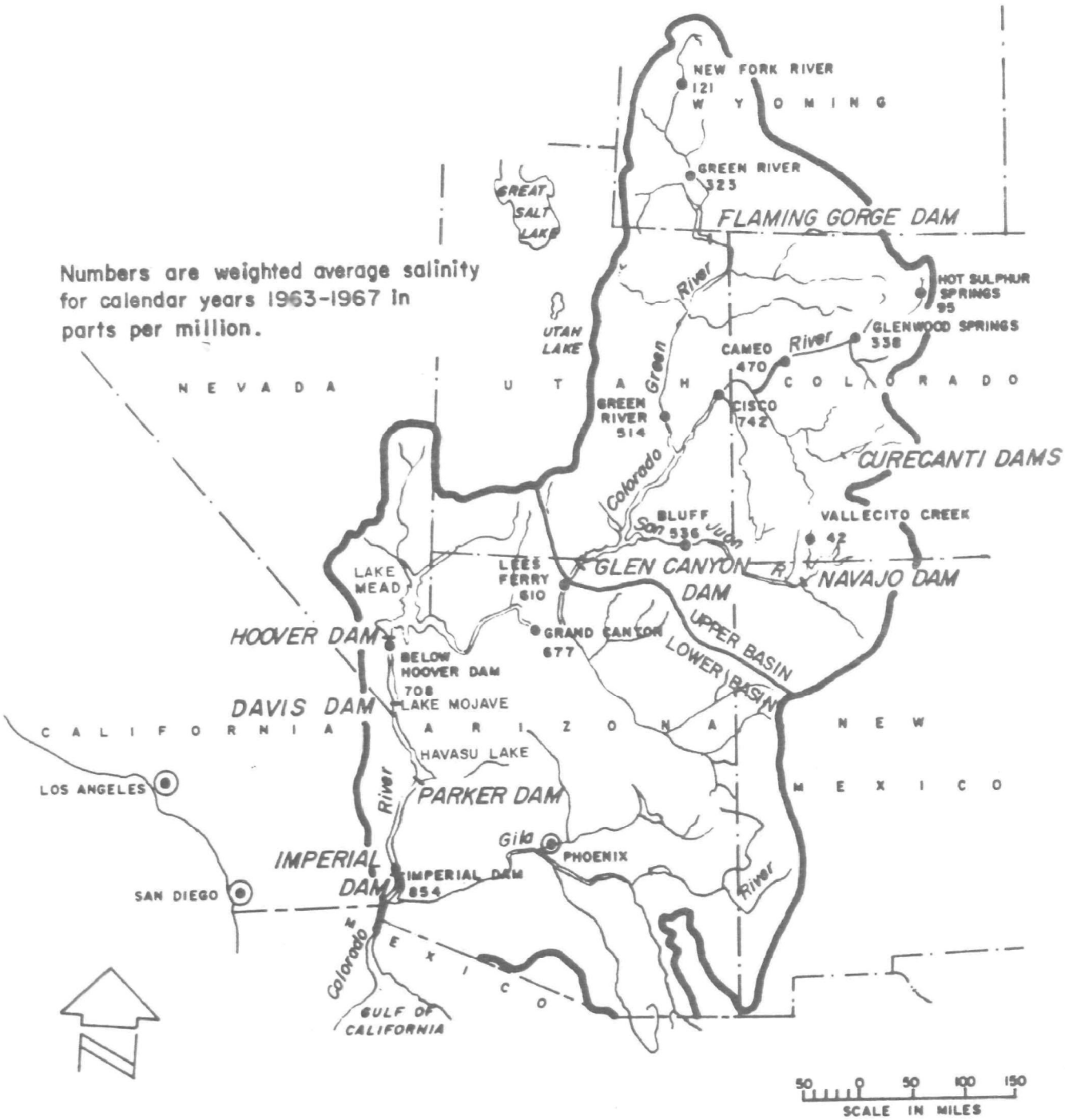

Figure 1: Salinity at Selected Stations within Colorado River Basin

sources, and (2) salt concentrating, the loss of water from the system through evaporation, plant transpiration, and out-of-basin export. Irrigation is a major contributor to salinity through both of the above processes. Water is consumptively used by irrigation, thus reducing the amount of water in the river and concentrating the salinity. In addition, the water that is applied to the farms in excess of consumptive use requirements not only returns to the river the salts contained in all of the diverted water, but it also picks up additional salts from the soils to which it is applied and from the underlying formations.

In its natural state, the Colorado River's dissolved mineral load averaged about 5.1 million tons per year at a concentration of about 250 ppm at Lee Ferry, Arizona, which is located just a few miles downstream of Glen Canyon Dam. About 80 percent of the naturally occurring salts come from diffuse sources and about 20 percent are from natural point sources, such as mineral springs and exposed formations of highly soluble minerals.

When pioneering farmers moved into the Colorado River Basin, their activities increased the salinity of the Colorado River. The main use of the river water was and still is for irrigation. About two million acre-feet of water is consumed by irrigation in the Upper Colorado River Basin, the area upstream of Lee Ferry, Arizona. Studies show that about 3.5 million tons of salts are added annually to the Colorado River by return flows from irrigated areas in the Upper Basin. This amount will increase in the future as additional water is used on projects now being developed. It has been found that irrigated areas in the Upper Basin have salt pickup rates that vary from as little as 0.1 ton per acre per year to as much as 8.5 tons per acre per year. Many projects where irrigation has been practiced continuously for over 80 years still have pickup rates in excess of six tons per acre per year; and it appears that in the absence of any corrective measures, irrigation salt pickup will continue at approximately the same levels.

Municipal and industrial uses in the Upper Basin consumptively use approximately 50,000 acre-feet annually and add approximately 130,000 tons of dissolved salts to the river each year, a minor amount compared with contributions from irrigated agriculture. Other sources of increased salinity in the Upper Basin are: (1) the export of approximately 500,000 acre-feet a year of low salinity water from the headwaters of the Colorado River System to adjoining basins in the states of Utah, Colorado, and New Mexico, further depleting the flow downstream but diminishing only slightly the salt load, and (2) evaporation from storage reservoirs of approximately 300,000 acre-feet per annum. Both of these items are expected to increase in the future.

In recent years, the salinity at Lee Ferry has averaged about 610 ppm, considerably higher than the 250 ppm that prevailed prior to the advent of modern man.

The effect of man's activities in causing increased salinity also takes place in the Lower Basin. Over 900,000 acre-feet of water per year are evaporated from Lakes Mead, Mohave, and Havasu. Water losses between Davis and Imperial Dams from phreatophytes and the river's surface average about 600,000 acre-feet per year. Recent measurements indicate that irrigated agriculture in the Lower Basin, primarily from Parker and Palo Verde Valleys, adds over 200,000 tons of salts per year to the river by the salt pickup process.

Future Increases in Salinity

Several major water projects are now under construction in the Upper Colorado River Basin, and others have been authorized and are awaiting funds for design and construction. In addition to these authorized projects, there are a number of additional projects for which feasibility reports are being made, and others that have been identified as potential projects. The Colorado River Board of California (CRB), the Environmental Protection Agency (EPA), the U.S. Bureau of Reclamation (USBR), and the participants in the recently completed Type I Comprehensive Framework Studies of the Water Resources Council all analyzed the impact of future basin development. Although the projections differed, all investigators agreed that unless salinity control measures are undertaken, the river's salinity will substantially increase in the future.

The CRB has concluded that, without salinity control measures, the average salinity at Parker Dam (the point on the river where The Metropolitan Water District of Southern California now diverts and where the authorized Central Arizona Project will divert) will increase from the present average of 740 ppm to over 1,100 ppm by year 2000. At Imperial Dam, where the bulk of diversions are made for agricultural use in California and Arizona, the comparable values are 870 ppm at present and over 1,300 ppm by the turn of the century. Approximately 75 percent of the increases will be due to Upper Basin developments and 25 percent will be due to Lower Basin developments. It should be noted that the above values are annual averages and that higher seasonal values will occur.

Deleterious Impact of Salinity

The deleterious impact of high salinity water on municipal and industrial water users is felt in a number of ways, including high soap consumption, formation of scale in heating vessels, corrosive attack on distribution pipelines, plumbing systems and appliances, and added water treatment and conditioning costs. A number of estimates have been made as to the cost in dollars to municipal, industrial and agricultural users due to increases in salinity. However, it is difficult to place precise dollar values on the above detriments. Our estimate is that salinity will cause increasing damages and unless action is taken to control salinity, the total economic impact in the Lower Colorado River Basin in the United States due to projected increases in Colorado River salinity would be in the order of $45 to $60 million per year by the turn of the century.

Possible Ways to Reduce Salinity

The importation of large quantities of low salinity water would hlep to reduce the river's salinity. In the past decade considerable publicity has been given to augmenting the Colorado River Basin by importing water to the Basin from the Columbia River Basin or from other northerly river basins. Other proposals have been to desalt seawater or geothermal water and transport the water to the Colorado River. Consideration has also been given to weather modification as a method of increasing the river's runoff.

The 1968 Colorado River Basin Project Act placed a ten-year moratorium on the study of any plan to import water from the Columbia River Basin. To date there has been no development of large-scale desalting plants and, in any event, the cost would be extremely high. Geothermal water development and weather modification are in very preliminary stages of development. There is no indication that large quantities of water will be developed from any of the above sources in the near future.

The most promising approach of reducing salinity is through the construction of projects and implementation of measures which would prevent large quantities of salt from entering the river system.

Salinity Control Projects

Studies recently completed by the EPA and its predecessors, by the USBR and the CRB have pointed the direction for a basinwide salinity control program. The EPA has identified a number of specific projects and, together with the USBR, has conducted limited reconnaissance level studies on them. The most promising of these are now under feasibility investigation by the USBR.

Preliminary information on the USBR's investigations has been released and is referrrd to herein. The USBR, in its appraisal of potential salinity control measures, has set its estimates of salt removal at lower levels than had the EPA in its studies, primarily reflecting therein the presently foreseeable volume of salt removal. The salinity control projects are categorized as point-source control, diffuse-source control, and irrigation-source control projects.

Point-Source Control

These projects are in areas of localized salt contributions such as mineral springs or outcrops of soluble formations adjacent to or underlying surface water sources. They are generally more susceptible of control than other types of salinity control projects. Potential point-source control projects are located at La Verkin Springs, Utah; Glenwood-Dotsero Springs, Crystal Geyser, and Paradox Valley, Colorado;

and Littlefield Springs and Blue Springs, Arizona.

In crossing the Paradox Valley, Colorado, the Dolores River picks up a large mineral load from underlying highly soluble ground formations. The proposed project would include a dam and regulatory reservoir above the valley, and an impervious channel through the valley to minimize the interchange between stream flow and ground water, thereby reducing the salt load by about 200,000 tons annually. A rough estimate of the cost of this project is between $25 to $35 million.

Four projects would control mineral springs: one at Glenwood and Dotsero Springs, Colorado; one at La Verkin Springs, Utah; and one at Littlefield Springs, Arizona; and the fourth at Blue Springs, Arizona. The USBR estimates that about 40 percent of the flow of Glenwood and Dotsero Springs, near the town of Glenwood Springs, could be controlled and about 200,000 tons of salt annually could be removed by means of a desalting plant. Brines could be disposed of by injection into deep wells. This project is estimated to have a construction cost of $40 to $60 million.

The largest natural point source in the Colorado River Basin is Blue Springs on the Little Colorado River. One proposal to eliminate its 500,000-ton annual salt contribution would consist of a low dam downstream of Blue Springs to intercept the springs' flow, pumpint plants and conveyance facilities to transport the water to Flagstaff, and a desalting plant at Flagstaff where the desalted water could be sold. The cost of this project has not been estimated.

The earlier studies by the EPA indicated a potential for removing about 1,200,000 tons of salt annually from the Colorado River Basin by means of all of the above point-source control projects except Littlefield Springs and Crystal Geyser. The USBR's preliminary estimate for salt removal by point-source control is 745,000 tons annually.

Diffuse-Source Control

Diffuse-source control projects are designed to control salt contributions from a larger areal extent than point-source control projects. Therefore, these projects have not been sufficiently studied to formulate even tentative plans or rough cost estimates. The basic concept is to selectively remove the saline (over 1,500 ppm) low flows from a stream and to bypass the high flows. The low flows would be desalted or evaporated. The irrigated areas on these streams would also be investigated to determine if water system improvement and management programs and improved irrigation scheduling might contribute toward reduction of the salt load sufficiently to justify feasibility studies.

The potential diffuse source control projects which appear to provide most favorable prospects for salinity control include the Price, San Rafael, and Dirty Devil Rivers in Utah; McElmo Creek in Colorado; and Big Sandy Creek in Wyoming. Potential tonnages of salt removed by means of diffuse-source control projects have been estimated at 390,000 tons annually by the USBR. Earlier studies by the EPA had identified about 550,000 tons annually to be removed by "Irrigation Improvement" features that could be classified as diffuse-source control projects. These included all of the above-mentioned areas except McElmo Creek. They also included Henry's Fork and Duchesne Rivers in Utah.

Irrigation-Source Control Projects

These projects would consist of (1) improvements of irrigation scheduling and management and (2) construction of improvements to existing water conveyance systems.

The irrigation scheduling and management activities would be aimed at reducing the volume of deep percolation to ground water through saline geologic formations, which would reduce the salt load being introduced into the Colorado River under present conditions. The water saved under this program would become available for other uses. Also, increased net returns would result to the irrigators through greater yields, improved crop quality and lower production costs. The porposed technique is to schedule times and amounts of water to be applied to crops by analyzing the actual soil moisture deficiencies in each area, probably through use of computers. By developing an accurate water budget and giving operational considerations to the root zone reservoir, a basis is provided for attaining high irrigation efficiencies. This might prove to be one of the least expensive of the various methods for reducing salinity levels.

Another method for controlling salts from irrigation sources is construction of improvements to existing water conveyance systems to reduce losses, increase operating efficiency, and further curtail salt loading into the river. Studies will be made of irrigation systems to identify the structural measures needed.

The irrigation areas chosen for this program are the Grand Valley and Lower Gunnison Basins in Colorado, the Uintah Basin in Utah, the Colorado River Indian Reservation in Arizona, and the Palo Verde Irrigation District lands in California. Potential tonnages of salt removal from the Colorado River Basin by means of irrigation-source control projects have been estimated at 680,000 tons annually by the Bureau of Reclamation. The earlier studies by EPA estimated 1,100,000 tons annually of salt could be removed by "Irrigation Improvement" projects, which amount does not include the 550,000 tons previously mentioned under diffuse-source control projects.

Effect of Salinity Control Projects

Preliminary reconnaissance studies by the EPA have indicated projects with a potential to remove approximately 2.9 million tons annually from the river. The USBR has selected projects that it has estimated would remove approximately 1.8 million tons annually for further reconnaissance study and feasibility investigation.

Based upon projected water development in the basin, it is necessary to remove approximately 3 million tons of salt from the river in order to keep salinity at or below present levels. The USBR has proposed large scale desalting and weather modification to supplement salinity control projects. If these do not prove to be successful, it will be necessary to develop additional salinity control projects in order to meet the objective of preventing future increases in salinity.

Recent Significant Actions

In August 1970 the Colorado River Board issued its report entitled "Need for Controlling Salinity of the Colorado River." The report concluded that salinity is a basinwide problem and recommended that the key policy objective should be to maintain salinity of the Lower Colorado River at or near present levels. To accomplish this objective, it was also recommended that construction of salinity control projects should be scheduled for completion coincident with the completion of water projects that would increase salinity in the Colorado River Basin.

The EPA has also given strong support for constructing salinity control projects. Its November 1971 report, "The Mineral Quality Problem in the Colorado River Basin," contained two recommendations that were very similar to the two recommendations, stated above, of the Colorado River Board's August 1970 Salinity Report. However, another EPA recommendation called for the establishment of specific numerical criteria at key points throughout the basin by January 1, 1973.

During February 15-17, 1972, the EPA held the "Seventh Session of the Conference in the Matter of Pollution of the Interstate Waters of the Colorado River and Its Tributaries" in Las Vegas, Nevada. The conferees consist of representatives from the water pollution control agencies in each of the seven Colorado River Basin States, of an EPA representative from each of the two regions of the EPA that encompass the Colorado River Basin, and of an EPA representative from Washington, D.C.

Testimony at the conference was presented by federal, state, and local agencies, as well as by individual citizens. Commissioner Armstrong of the USBR testified as the representative of the Secretary of the Interior and presented a ten-year Colorado River Water Quality Improvement Program. The program includes data collection, feasibility studies, construction, and implementation of projects. The projects include the ones mentioned in the section on Salinity Control Projects. The USBR estimated that the costs would be $300 million or more.

At the conclusion of the conference, the state conferees unanimously agreed upon a resolution containing the following major points:

1. A salinity policy be adopted that would have as its objective the maintenance of salinity concentrations at or below levels presently found in the lower main stem.
2. Salinity is a basinwide problem that needs to be solved while the Upper Basin contin-

ues to develop its compact-apportioned water.

3. To guard against rise in salinity, the salinity control program should be accelerated. The USBR, assisted by the EPA and the Office of Saline Water, should have the primary responsibility for implementing the program.
4. Adoption of numerical salinity criteria be deferred until the potential effectiveness of salinity control measures is better known.

EPA agreed with the resolution in principle, but felt it needed to be strenghened by adding to it a statement that specific tonnages of salts would be removed from the Colorado River at specific times by a salinity control program. EPA requested the USBR to prepare a proposal for an accelerated salinity control program and recessed the conference to await the USBR report. In order to accelerate the salinity control program, it has been proposed that demonstration projects be constructed for the different types of salinity control projects.

CONCLUSIONS

A key policy objective which has been expressed by the seven Colorado River Basin States and by concerned federal agencies is that salinity of the Lower Colorado River should be maintained at or near present levels. Salinity is recognized as a basinwide problem, and a major salinity control program has been initiated to meet the above objective. Mexico is also vitally interested since the Colorado River salinity problem is one of the major controversial issues between the two countries.

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Economic Impact of Salinity Control in The Colorado River Basin

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ABSTRACT

Studies of the economic effects of salinity in Colorado River water by the Colorado River Basin Water Quality Control Project are discussed. The studies describe the effects of salinity on municipal, industrial, and agricultural water users. They also describe the secondary effects of pollution costs on the regional economy. Methods of analysis are described and summary cost data are presented.

INTRODUCTION

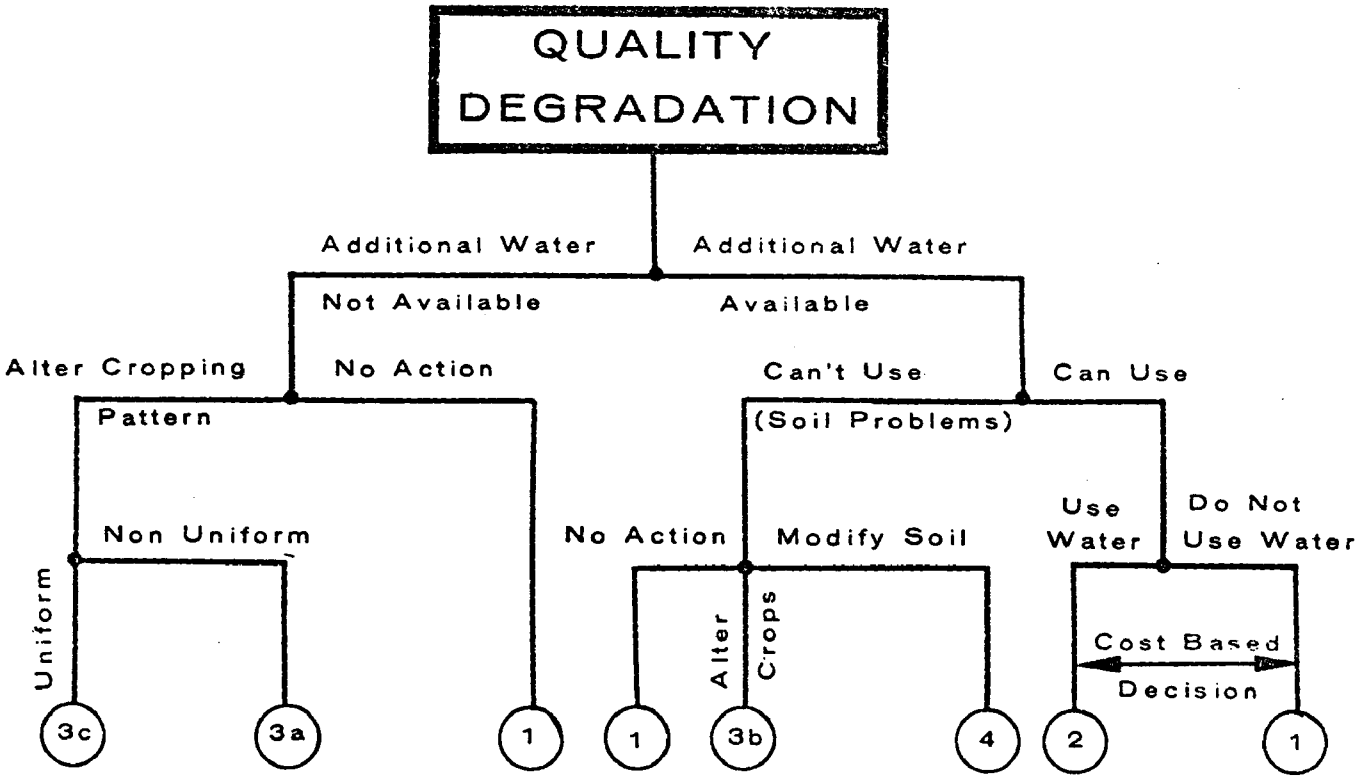
The Colorado River is situated in the southwestern United States and extends 1,400 miles from the Continental Divide in the Rocky Mountains of north central Colorado to the Gulf of California. Its river basin covers an area of 244,000 square miles, approximately one-twelfth of the continental United States. The Colorado River Basin includes parts of seven states; Arizona, California, Colorado, Nevada, New Mexico, Utah and Wyoming. About one percent of the Basin drains lands in Mexico.

The River rises on the east slope of the Continental Divide above 13,000 feet, and flows generally southwestward, leaving the United States at an elevation of about 100 feet above sea level. The Basin is composed of a complex of rugged mountains, high plateaus, deep canyons, deserts and plains.

Climatic extremes in the Basin range from hot and arid in the desert areas to cold and humid in the mountain ranges. Precipitation is largely controlled by elevation and the orographic effects of mountain ranges. At low elevations or in the rain shadow of coastal mountain ranges, one finds desert areas which may receive as little as six inches of precipitation annually, while high mountain areas may receive more than sixty inches.

An average of about 200 million acre-feet of water a year is provided by precipitation in the Colorado River Basin. All but about 18 million acre-feet of this is returned to the atmosphere by evapotranspiration. Most of the stream flows originate in the high forest areas where heavy snowpacks accumulate and where evapotranspiration is low. Thus, approximately two-thirds of the runoff is produced from about six percent of the mountainous area of the Basin.

Stream flows fluctuate widely from year to year and season to season, and many reservoirs have been constructed to make water available for local needs, for exports and for meeting downstream obligations. The usable capacity of the Basin reservoirs is about 62 million acre-feet.



ALTERNATIVE DIAGRAM

1. NO ACTION. LEADS TO YIELD REDUCTION.
2. INCREASE PURCHASE AND USE OF WATER.
3. MAINTAIN SAME TOTAL USE ON FEWER ACRES LEADS TO MORE USE/ACRE.
   a. Remove Least Profitable Crops ($/A-ft.)
   b. Remove Least Tolerant Crops (Yield in $/ppm)
   c. Remove Crops in Proportion to Acreage
4. INCREASED PURCHASE OF SOIL CONDITIONERS.

Figure 1: Irrigation Water User Alternatives for Offsetting the Effects of Mineral Quality Degradation

The Colorado River system carries a large salt burden (dissolved solids) contributed by a variety of natural and man-made sources. Depletion of stream flow by natural evapotranspiration and consumptive use of water for municipal, industrial, and agricultural uses reduces the volume of water available for dilution of this salt burden. As a result, salinity concentrations in the lower river system exceed desirable levels and are approaching critical levels for some water uses. Future water resource and economic developments will increase stream flow depletions and add salt which in turn will result in higher salinity concentrations.

Methods of Analysis

The economic analysis proceeded along the following logic sequence: 1. select a target year

and develop "normative" descriptive data on the economy for that year; 2. select a water use location and evaluate the direct economic effects of increasing salinity on water users at that location; 3. repeat step 2 for all water use locations significantly affected by salinity; 4. select a base "state" of the system and an incremental "change of state" for analysis; 5. using data from steps 2 and 3, determine the cost to each water user associated with the salinity change at his location, and form the total (or aggregate) direct cost to all users. This total represents the direct cost associated with the change of state selected for analysis; 6. using the inter-industry tables, calculate the indirect economic effect of the change in salinity; 7. repeat steps 5 and 6 for other changes in the state of the system over the probable range of future mineral quality conditions; 8. repeat steps 1-7 for other target years.

Each of the foregoing steps will be discussed briefly. The focus will be on critical points of the analysis. For a detailed discussion, one should turn to references listed in the bibliography.

Step 1 - Selection of target years and normative conditions:

The salinity studies described here were begun in the early 1960's. The most recent data available at that time were from 1960 and earlier. A fairly standard 50-year time horizon was chosen for the studies; and intermediate years were selected at 10-year intervals as a matter of convenience in projection. Since several years elapsed during the course of salinity studies, the base year was updated to 1965 prior to release of the final project report.

Step 2 - Selection of water use locations and determination of direct user costs:

One should distinguish between cause and effect in discussing salinity. Causes of increasing salinity are found throughout the Colorado River. However, dramatic increases in salinity levels are not expected in mountainous areas where most of the upper basin diversions occur. Therefore, analysis of the economic impact of mineral pollution was focused on the water service area of the lower Colorado River.

The Project attempted to identify practical alternatives available to each major type of water use in the Basin. The cost of these alternatives was compared and one was selected for the purpose of analyzing basinwide effects. It should be emphasized that, even though one alternative was selected for use in the analysis, the Project did not determine whether such an alternative would likely be implemented in practice. This analysis was carried out for the purpose of measuring the economic effect of anticipated changes in a physical system.

Initial evaluations of possible salinity effects on Basin water uses indicated that adverse physical effects would essentially be limited to municipal, industrial, and agricultural uses. Agricultural use is selected here to demonstrate the analytical technique. An alternative diagram is shown in Figure 1. This diagram indicates that there are four major alternatives to be analyzed, and that there are three variations to one of the alternatives.

One alternative available to an irrigator when the quality of his water supply degrades is to take no remedial action. The direct economic loss in this case is a loss in crop yield. The percent of optimum yield is calculated, for base water quality, and for the incremental change in quality. The economic value of the difference in crop yield associated with the two water quality levels represents the direct cost of pollution for this method of analysis. This calculation is based on experimental crop salt tolerance data from the U.S. salinity Laboratory at Riverside, California. These data are shown in summary form in Figure 2.

A value for soil saturation extract is calculated from data on irrigation water quality, consumptive water use and irrigation practices in the water use area. Where consumptive water use, amount of applied water, and irrigation water quality are known, the amount and quality of drainage water may be calculated from the U.S. Salinity Laboratory "Handbook 60" formulas[10].

The mean conductivity of the soil column is taken as the irrigation and drainage water quality values. This value is divided by two to convert it to the equivalent "soil saturation extract" value, in accordance with the recommendation of the Salinity Laboratory.

Gross crop values are used in this calculation since it is assumed that there are no changes in farm management practices, so that pre-harvest costs remain unchanged.

As an alternative to the no-action condition, the irrigator could choose to maintain existing

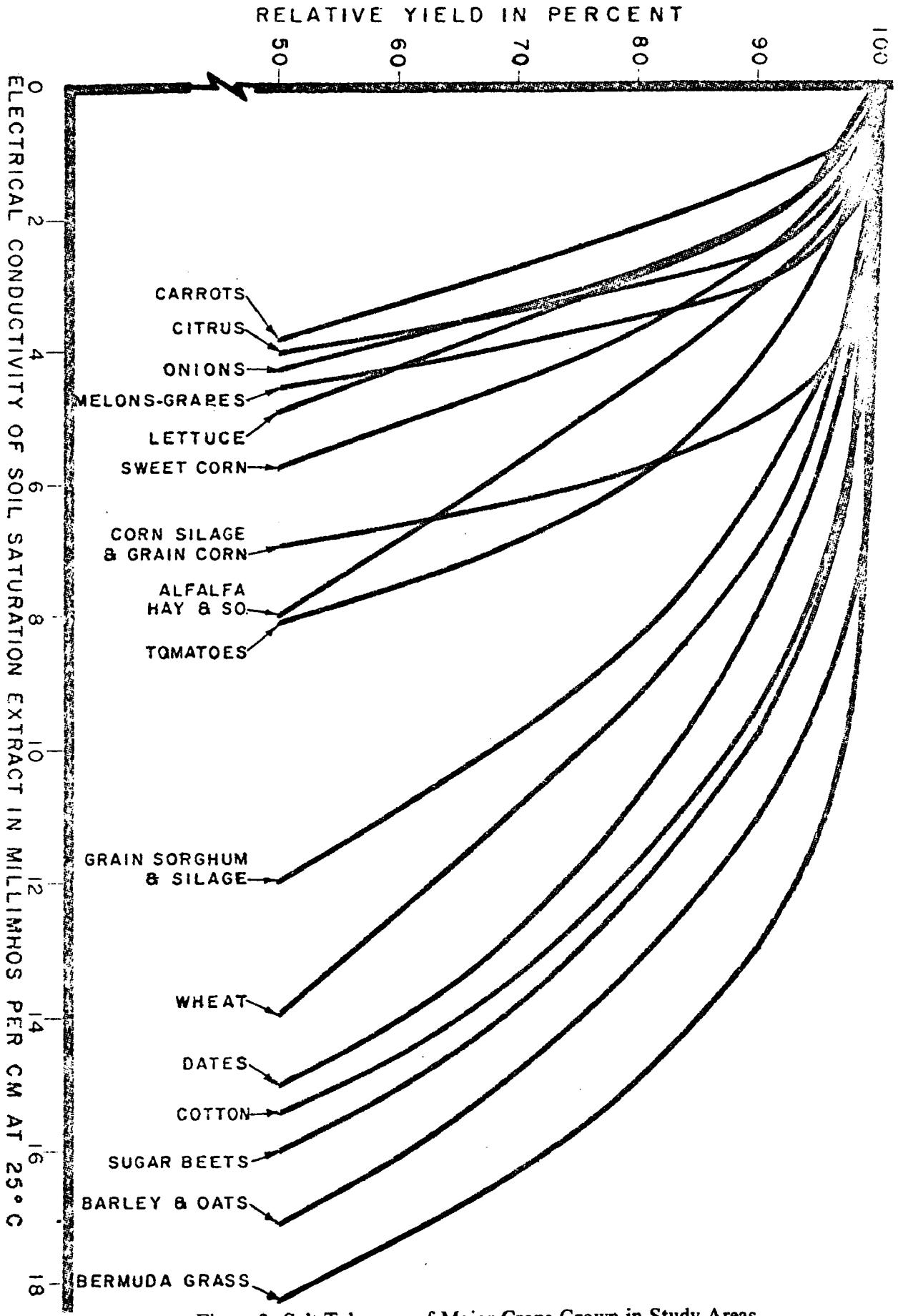


Figure 2: Salt Tolerance of Major Crops Grown in Study Areas

yields as the quality of his water supply degrades. This is shown as alternative No. 2 in figure 1. This could be accomplished by applying more water in order to increase the leaching fraction. In this case the major problem lies in determining how much additional water would be required. Hill and Scofield considered this problem and set forth the concept of "equivalent service"[30] as one method of calculating the amount of water required. Equivalent service requires reduction in the concentration of the drainage water in order to offset the increase in concentration of dissolved solids in the applied water. This concept calls for a substantial increase in the leaching fraction in order to improve the drainage water quality. However, Agriculture Department personnel who collaborated in the study suggested[1] using a more conservative assumption (e.g., one which showed less cost associated with increasing pollution levels). This assumption was that maintaining the quality of the water percolating from the field would result in maintaining constant crop yields.

To determine the penalty costs associated with quality degradation, it is necessary to account for the increase in conveyance losses and to determine the dollar value of this quantity of water. The costs added by the need for extra labor, more fertilizer, and additional drainage associated with the application of more irrigation water were also included. The latter costs were quite substantial, sometimes equal to the value of the water itself.

Costs were determined from studies of forms in the water use area conducted for EPA by the Economic Research Service. Some data were collected directly by project economists. Two values were compared to arrive at a cost for additional water. One was the "residual value". This is a measure of the average amount an irrigator could afford to pay for water based on its utility. This value is computed by developing a farm budget; accounting for all income and for all expenses except water cost; and then by dividing the excess income by the total water use to arrive at a maximum average-water-cost. Theoretically, an irrigator would pay more than this amount for small incremental amounts of water, since he is paying less for the majority of his supply.

Another method of estimating water value was to estimate the cost of developing a supplemental supply. Developmental costs normally exceeded the residual values, so that the latter were used for the purposes of analysis.

Note that detailed cost data are not given here since they varied from area to area. Cost data developed for this project are available from the files of EPA. When more irrigation water is applied, additional labor costs are incurred; additional amounts of fertilizer are lost; and additional drainage facilities may be needed. In the case of additional labor costs it was assumed that irrigators would tend to decrease the interval between irrigations. In order to maximize the interval, an irrigator would apply the maximum amount of water which could be benefically used during each irrigation. It follows that any substantial increased water requirement would necessitate more irrigations per year. The cost of additional irrigations was assessed at $2 per foot of required additional irrigation water in excess of three inches. The initial three inches of additional water was assessed no labor cost. The foregoing values are based on an application of six inches per irrigation at a cost of approximately $1 per irrigation.

Fertilizer losses were calculated according to a first-order chemical solution reaction equation. For convenience, this equation was expressed in the form:

$$L = L_o P^n ;$$

where:

L_o = Quantity of fertilizer presently applied,

L = Quantity of fertilizer remaining,

P = Percent of fertilizer remaining under present conditions, and

n = Ratio of the volume of drainage with degraded water supply to present volume of drainage.

[1]The staff of the Economic Research Service, USDA, collaborated in the investigations; results were also reviewed with Dr. Bernstein and the staff of the Salinity Laboratory, as well as Dr. Vaughn Hansen and Mr. Raymond Hill who served as consultants to the Project.

From this equation, the loss in nitrogen fertilizer associated with increases in drainage water may be calculated. This amount is multiplied 12 cents per pound to establish the direct cost of fertilizer loss.

The third alternative shown on Figure 1 involves taking a portion of the irrigator's crop land out of production, using water thereby saved to increase the amount of leaching water applied to the remaining crop acreage. For this alternative, the profit that would have been made on the crops taken out of production is the measure of direct cost. Three methods of reducing acreage were investigated: (1) removal of a portion of all crops in proportion to total acreage (uniform reduction), (2) removal of the least profitable crops, and (3) removal of the least salt-tolerant crops. These alternatives are shown as "3c", "3a", and "3b", respectively, in figure 1.

The first step in determining detriments by the uniform acreage reduction technique is to calculate the leaching water requirements associated with a base quality and an adjusted quality for the target year. The "constant quality of percolate" method is used to obtain these leaching water quantities. The next step is to calculate the number of acres of land which must be removed from production to obtain this volume of water. It should be noted that acreage removal is reduced to account for the fact that no added water is needed on those acres retired from service.

The fourth alternative shown on figure 1 involves costs for soil conditioners in addition to those for one of the previous alternatives involving increased use of water. Thus, it is clearly more costly.

Costs associated with the alternatives just described were calculated for each major irrigation water use area below Hoover Dam, and the results were compared. Figure 3 shows such a comparison for a typical water use area. The selective acreage reduction technique was rejected since agricultural economists argued that fixed investments, farm practices, and other factors not included in the analysis would preclude practical adoption of this alternative.

Thus, yield decrement was selected as the method of analysis giving the best estimate of the cost to irrigators of increasing levels of salinity in irrigation water supplies.

Similar analyses were made for municipal and industrial water uses. Although irrigation is the major water use in the basin, municipal use is also significant. Hardness, which is closely correlated with dissolved solids content, creates undesirable effects in domestic uses. Three alternative methods of evaluating the economic impact upon municipal uses were examined: (1) the acceptance of undesirable effects, (2) home water softening, and (3) central softening. The costs associated with each of these alternatives were calculated for each major municipality in the geographic region studied. Except for the Colorado River Aqueduct service area, the alternative resulting in highest penalty cost was home softening followed by central softening and acceptance of increased pollution in that order. This ranking undoubtedly reflects the fact that the latter method, based upon soap-wastage, does not account for all the costs incurred. Nevertheless, the soap-wastage method was selected as the measure of municipal water use penalty costs for all municipal entities except those that actually have central softening plants. These are the Metropolitan Water District of Southern California and the city of Calexico, California, in the Southern California water service area. For these municipalities the central softening method was used to calculate pollution costs.

Steps 4 and 5 of the logic sequence involved aggregating salinity costs over Colorado River Basin. The large number and variety of manufacturing industries in the major centers of water use, especially in Southern California[2], made it impracticable to attempt an evaluation of salinity effects on process waters within the scope of this study. In addition, process water use generally falls into one of two categories: (1) use that is insensitive to small incremental changes in mineral concentraction, or (2) use that requires a completely demineralized supply. In either case the effect of changes in mineral quality over the range of concentrations expected to prevail is considered to be unmeasurable.

[2]Bureau of the Census, "Statistical Abstract of the United States," 1964, lists 17, 665 manufacturing plants in the Los Angeles-San Diego metropolitan areas. (Reference No. 32).

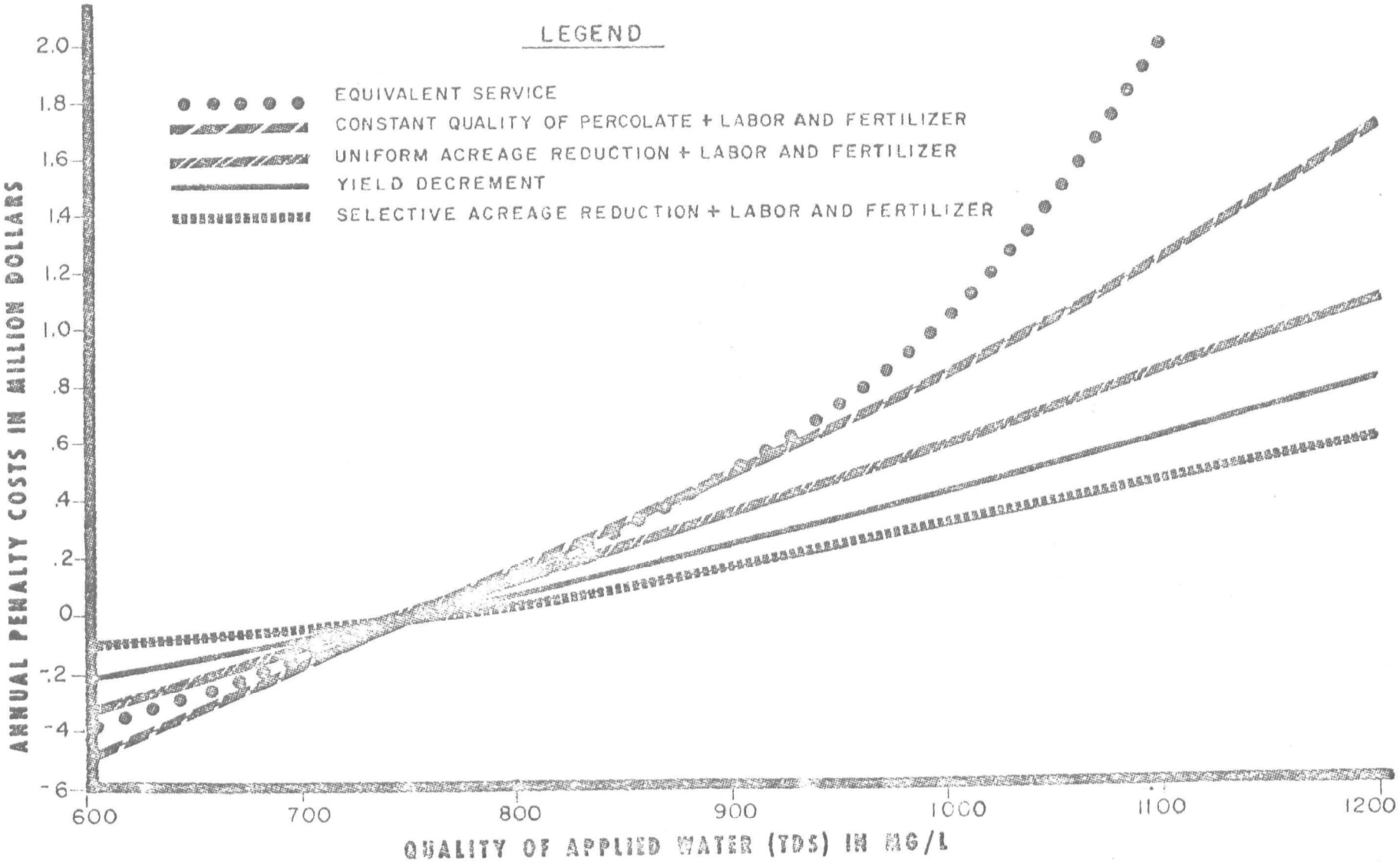


Figure 3: Comparative Results of Irrigated Agriculture Penalty Cost for a Portion of Yuma County-1960

In view of these considerations the Project focused upon cooling and boiler feed waters. Thus, the industrial penalty costs derived by the Project's study are somewhat understated. There is no doubt, however, that the included costs cover a major portion of the fresh water used in manufacturing. In the United States as a whole over 74 percent of all industrial fresh water is used in cooling and boiler feed,[33] and in the State of California 67 percent is so employed.[34] A survey of water use in the chemical and metallurgical complex at Henderson, Nevada, made in August 1964, by the Nevada Department of Public Health[35] showed 80 percent of the water to be employed for cooling, four percent for boiler feed, and the remaining 16 percent for processing, sanitary, and miscellaneous purposes.

There are two pertinent types of cooling and boiler systems. High-pressure boilers require a demineralized supply; thus, they are not sensitive to minor changes in plant intake water quality. Similarly, specially designed cooling towers can accept brackish or highly saline waters; thus, they are insensitive to water quality. Low-pressure boilers and cooling towers on fresh water systems, however, can tolerate only a limited concentration of dissolved mineral constituents. These systems, therefore, are directly affected by changes in mineral quality. This analysis is based entirely on an evaluation of penalty costs associated with Colorado River water used in sensitive systems.

Material balance in these systems establishes the quantity of discharge water required for any level of water use, intake quality, and system tolerance. Increasing concentrations of dissolved mineral constituents in the feed water necessitates an increase in the discharge requirement and thus an increase in the water intake requirement, in order to prevent salt accumulation within the system. The increase in water use, the 1960 cost of water, and feed-water treatment costs were used in the assessment of industrial penalty costs.

The direct economic costs of mineral quality degradation may be summarized in two basic forms, total direct costs and penalty costs. Total direct costs incurred for a given salinity level result from increases in salinity concentrations above the threshold levels of water uses. Penalty costs are the differences between total direct costs for a given salinity level and for a specified base level. They represent the marginal costs of increases in salinity concentrations above base conditions.

Detailed economic studies were aimed at evaluating penalty costs in order to provide a basis for assessing the economic impact of predicted future increases in salinity. Water quality, water use patterns, and economic conditions existing in 1960 were selected as base conditions. Water use and economic conditions projected for the target years 1980 and 2010 and predictions of future salinity concentrations were utilized to estimate total direct costs in the future. Direct panelty costs were then computed from differences in total direct costs. These direct penalty costs are summarized by type of water use and by study area in Table 1. The indirect and total penalty costs, also presented in the table, are discussed below.

Indirect Economic Effects

Because of the interdependence of numerous economic activities, there are indirect effects on the regional economy stemming from the direct economic impact of salinity upon water users. These effects, termed indirect penalty costs, can be determined if the interdependency of economic activities are known.

The Project's economic base study investigated the interdependence of various categories of economic activity or sectors. These interdependent relationships, in the form of transactions tables, were quantified for 1960 conditions, and were projected for the target years 1980 and 2010. A digital computer program known as an "input-output model" was developed to follow changes affecting any given industry through a chain of transactions in order to identify secondary or indirect effects on the economy stemming from the direct economic costs of salinity. Application of the model to evaluate indirect penalty costs is discussed in Appendix B, Chapter V of the Project report. The indirect penalty costs predicted by the model are summarized in Table 1.

Total Penalty Costs

Total penalty costs represent the total marginal costs of increases in salinity concentrations above base conditions. They are the sum of

TABLE 1

Summary of Penalty Costs

Location and Water Use	1980 Direct Penalty Cost	1980 Indirect Penalty Cost	1980 Total Penalty Cost	2010 Direct Penalty Cost	2010 Indirect Penalty Cost	2010 Total Penalty Cost
		($1,000 Annually)*			($1,000 Annually)*	
Lower Main Stem Study Area						
Irrigation Agriculture	1,096	765	1,861	2,424	2,237	4,661
Industrial	107	4	111	410	15	425
Municipal	275	14	289	779	39	818
Sub-Total	1,478	783	2,261	3,613	2,291	5,904
Southern California Study Area						
Irrigated Agriculture	4,617	2,447	7,064	10,072	6,195	16,267
Industrial	56	3	59	103	5	108
Municipal	1,347	305	1,652	2,239	507	2,746
Sub-Total	6,020	2,755	8,775	12,414	6,707	19,121
Gila Study Area						
Irrigated Agriculture	—	—	—	246	125	371
Industrial	—	—	—	—	—	—
Municipal	—	—	—	—	—	—
Sub-Total	—	—	—	246	125	371
Total	7,498	3,538	11,036	16,273	9,123	25,396

* - 1960 Dollars

direct penalty costs incurred by water users and indirect penalty costs suffered by the regional economy. Total penalty costs are also summarized in Table 1.

Several conclusions can be drawn from Table 1.

1. The majority of the penalty costs (an average of 82 percent) will result from water use for irrigated agriculture. This fact may be attributed to the heavy utilization of Colorado River water for irrigation along the Lower Colorado River and in the Southern California area.
2. Over three-fourths of the penalty costs will be incurred in the Southern California water service area. These costs will result primarily from agricultural use in the Imperial and Coachella Valleys, and municipal and industrial uses in the coastal metropolitan areas.
3. Penalty costs in the Gila study area will be minor and will not occur until after 1980 when water deliveries to the Central Arizona Project begin. (It was assumed that all Central Arizona Project water would be utilized for agricultural purposes).

It should be noted that the penalty costs do not represent the total economic impact of salinity; only the incremental increases in costs resulting from rising salinity levels. There were costs being incurred by water users in 1960 as a result of salinity levels existing in 1960. These costs would continue in the future if salinity levels remained at the 1960 base conditions.

Penalty costs cannot be used for evaluation of the economic impact of basinwide salinity controls, especially when reductions in salinity concentrations below 1960 base levels are considered. For this reason, estimates of total salinity detriments have been prepared utilizing the ba-

sic information developed for penalty cost evaluations. These estimates, in the form of empirical relationships between salinity levels at Hoover Dam and salinity detriments, are shown graphically for various target years in Figure 4.

Hoover Dam is a key point on the Colorado River system. Water quality at most points of use in the Lower Basin and Southern California water service area may be directly related to salinity levels at Hoover Dam. Modifications of salt loads contributed by sources located upstream from Hoover Dam also directly affect salinity levels at this location. Salinity concentrations at Hoover Dam were, therefore, utilized as a water quality index to which all economic evaluations were keyed.

Total salinity detriments are the sum of direct costs to water users (including direct penalty costs) and indirect penalty costs. It should be noted that the salinity detriments are expressed in terms of 1970 dollars. It was necessary to modify the basic data utilized in evaluating penalty costs (expressed in terms of 1960 dollars) in order to make the salinity detriments compatible with current estimates of salinity management costs discussed in the next section.

Using the projected salinity levels for Hoover Dam shown in Table 1 and the salinity detriment functions of Figure 4, it is possible to compare the total econonic detriments of salinity under various conditions of water use and resource development. Under 1960 conditions, the annual economic impact of salinity was estimated to total $9.5 million. It is estimated that present salinity detriments have increased to an annual total of $15.5 million. If water resources development proceeds as proposed and no salinity controls are implemented, it is estimated that average annual economic detriments (1970 dollars) would increase to $27.7 million in 1980 and $50.5 million in 2010. If future water resources development is limited to those projects now under construction, estimated annual economic detriments would increase to $21 million in 1980 and $29 million in 2010. It should be noted that all data in this analysis are based on the period of record 1942-61 adjusted to 1960 conditions of water use.

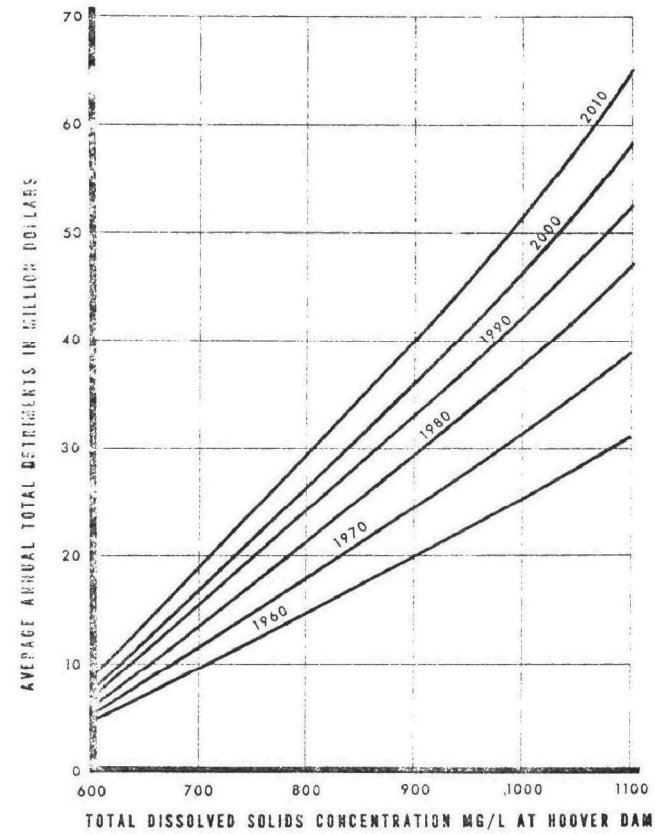


Figure 4: Salinity Detriments

CONCLUSION

The purpose of project activities was to evaluate the magnitude of the pollution problem in the Colorado River; and to stimulate positive pollution abatement action. From what has been reported here, one might get the conclusion that the project was mostly an academic exercise. To avoid leaving that impression, let me emphasize that concurrently project staff was working with other State and Federal agencies to identify the sources and/or causes of pollution and the costs of pollution control. An extensive demonstration effort has been underway here in Grand Valley aimed at determining the feasibility of controlling salinity from irrigated areas. Much research on control techniques has been sponsored at universities throughout the Western states. The Bureau of Reclamation has done reconnaissance level studies of the feasibility of controlling natural salinity sources. These efforts culminated in the most recent session of the Colorado River Conference held a few weeks ago in Las Vegas, Nevada. At this conference, an objective of maintaining salinity at or below existing levels in the critical lower reaches of the River was adopted, and a program was announced by the Bureau of Reclamation which would achieve this objective. The cooperative effort to document the costs of increasing pollution was a prime factor in mobilizing support for this pollution abatement effort.

The Project's activities included sampling programs and field investigations to determine the location and magnitude of agricultural, municipal, industrial and natural sources of mineral pollution throughout the Basin. Engineering studies involved the assessment of adverse effects on water users caused by saline pollution and evaluation of technical possibilities for controlling or minimizing mineral pollution from agricultural, municipal, industrial and natural sources.

In the economic studies, the level and pattern of economic activity in the Basin were developed for 1965 and projected for 1980 and 2010. These data were used to construct inter-industry input-output tables for each major subbasin of the Colorado for each of these three target years. The input-output tables were then used to determine secondary effects of water pollution costs on the regional economy. In all economic and engineering projections for the years 1980 and 2010, full cognizance was taken of legal allocation of Colorado River water and of proposed development of water resource projects by various construction agencies.

This paper focuses upon presentation of some of the unconventional phases of the economic and technical analyses; upon presentation and interpretation of the results; and upon the current status of recommendations for salinity control in direct economic losses to water users and indirect economic losses to the regional economy. Unless salinity controls are implemented, future increases in salinity concentrations will seriously affect water use patterns and may result in large economic losses.

In 1963, based upon recommendations of conferees from the seven basin states and the Federal government, the Colorado River Basin Water Quality Control Project began detailed studies of the mineral quality problem in the Colorado River Basin. Mineral quality, commonly known as salinity, is a complex Basin-wide problem that is becoming increasingly important to users of Colorado River water. Due to the nature, extent, and impact of the salinity problem, the Project extended certain of its activities over the entire Colorado River Basin and the Southern California water service area.

The more significant findings and data from the Project's salinity studies and related pertinent information are summarized in the report entitled, "The Mineral Quality Problem in the Colorado River Basin." Detailed information pertaining to the methodology and findings of the Project's salinity studies are presented in three appendices to that report—Appendix A, "Natural and Man-Made conditions Affecting Mineral Quality," Appendix B. "Physical and Economic Impacts," and Appendix C, "Salinity Control and Management Aspects."

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Soil, Water and Cropping Management for Successful Agriculture in Imperial Valley

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ABSTRACT

Colorado River water, containing about 900 ppm dissolved salts, is the only source of water for Imperial Valley agriculture and is creating salinity problems in that area. Imperial Valley farmers are successfully overcoming these salinity problems, however, by using soil, water and cropping practices that minimize or eliminate the detrimental effects of salt on crop production. Underground tile drains installed in the area have enabled a favorable salt balance to be attained for the Valley since 1949. Profile modification to improve water movement through the stratified soils is practiced to increase leaching of salts. Salt tolerant crops are grown to minimize the detrimental effects of salinity on crop growth and yields.

Successful agriculture in the Imperial Valley is shown by the continued yield increases in the major crops grown. Farmable acreage also has not changed, indicating no loss of farmland because of increasing river water salinity.

The existence of agriculture in the Imperial Valley of California is dependent entirely upon Colorado River irrigation water. The annual rainfall in the Valley is only 2½ inches and agriculture would not be possible were it not for the irrigation water delivered by the All American Canal from the Colorado River. Because of this source of irrigation water, the desert has been transformed into one of the most productive intensively irrigated areas of the world. In 1971, the gross agricultural production of the one-half million acre area was valued at over 300 million dollars—an all time high for the area's 70-year agricultural history.

While Colorado River water is the lifeblood of Imperial Valley agriculture, it is also a potential nemesis because of its salinity. Presently, Colorado River water delivered to Imperial valley contains more than 900 ppm of dissolved salts and the salt content is gradually increasing. River salinity is projected (2) to reach 1000 ppm by the year 1980 and 1340 ppm by the year 2000 if no upriver salinity control measures are taken.

The water presently delivered to Imperial Valley brings with it annually approximately 3½ million tons of salts. To prevent an accumulation of these salts in Imperial Valley soils, it is necessary to continually leach them from the soils so that the salts will not have a harmful effect upon crop production. Controlling or reducing salinity levels in the soil depends upon management practices that involve amount, frequency, and methods of applying water. Leveling, plow-

ing, cultivation, drainage, and other farm operations that affect soil structure affect water management and salt balance. Imperial Valley farmers are utilizing many practices to minimize the salt problem in that area. This discussion will review the various soil management, water management and cropping practices utilized by them to assure permanent and successful farming despite an ever present and increasing irrigation water salinity problem.

Irrigation Water Quality

The chemical composition of the Colorado River water delivered currently to Imperial Valley is shown in Table 1. The water may be evaluated according to salinity, sodium, boron and bicarbonate hazards using the classifications of irrigation waters recommended by the U.S. Salinity Laboratory Staff (4) and Wilcox (5). At the present time the Colorado River water has an electrical conductivity (EC) of 1400 micromho/cm and is classified as high salinity water. Water in this classification should not be used on soil with restricted drainage, and even with adequate drainage, special management for salinity control may be required. Plants with good salt tolerance should be selected if grown with this water.

TABLE 1

Chemical analysis of Colorado River water delivered to Imperial Valley

Electrical Conductivity, EC × 10^3@ 25°C		1.4
Boron, ppm		0.2
Sodium, % of Total Cations		43
pH		8.1
	Equivalents Per Million	*Parts Per Million*
Dissolved solids (1.25 tons/ac. ft.)	—	915
Calcium	5.19	104
Magnesium	2.88	35
Sodium	6.22	143
Potassium	0.14	5
Carbonate	0	0
Bicarbonate	3.06	187
Sulfate	7.41	356
Chloride	4.03	143
Nitrate	0.02	1

Samples taken at All American Canal, Drop 1-Average of biweekly samples taken during 1971.

In the Salinity Laboratory water classification, waters are divided into four classes with respect to the sodium hazard: low, medium, high and very high, depending upon the values for sodium adsorption ratio (SAR) and EC. Colorado River water with a SAR value of 3.2 falls into the low sodium water class. This water can be used for irrigation on almost all soils with little danger of the development of a sodium-soil problem. However, sodium-sensitive crops may accumulate injurious amounts of sodium in the leaves.

The occurrence of boron in toxic concentrations in certain irrigation waters makes it necessary to consider this constituent when assessing the quality of water. The boron concentration in Colorado River water is low (0.2 ppm) and offers no problem for Imperial Valley agriculture.

Bicarbonate in irrigation water is important because of its tendency to precipitate calcium, and to some extent magnesium, in the soil solution as normal carbonates. As calcium and magnesium are lost from a water, the relative proportion of sodium is increased with an attendant increase in the sodium hazard. This hazard is evaluated in terms of the residual sodium carbonate as proposed by Eaton (3). Colorado River water contains an excess of calcium and magnesium ions in relation to carbonate and bicarbonate ions and therefore does not have a residual sodium carbonate problem.

Imperial Valley Soils

The water quality characteristics of Colorado River water establishes that the major problem related to its use is its high and increasing salinity content. Use of such water requires soil management practices designed for salinity control. The control practices required depend upon the soils to which the water is applied. Imperial Valley soils need salinity control practices because of their unique chemical and physical properties.

Imperial Valley soils are alluvial and are composed of highly stratified Colorado River de-

posits, largely from mixed sedimentary rock parent material. The variations in the soils are mostly due to textural differences caused by the manner and sequence in which the alluvial material was deposited. In general, there are no gravel and sand waterbearing strata and the diffuse groundwater is highly saline. Stratum of any one type of soil does not extend over large areas, but occurs as small lenses or pockets. These stratified soils are more than a mile in depth in some areas.

The Imperial and Holtville series are by far the most widespread cultivated soils covering a little more than 75% of the area. Other series include the Meloland and Indio series. The soils are calcareous (pH of 8.0) and are inherently low in organic matter and nitrogen. Nitrogen fertilizer is needed for maximum production of non-leguminous crops. Phosphorus is needed for legumes and winter vegetable crops. Other nutrients (K, Ca, Mg, S and the various trace elements) are available in sufficient quantities in the soil or irrigation water and are no problem at the present time.

The soils have little structure except for the alternating horizontal textural layers in the profiles. The clay fraction is predominately montmorillonitic and the soils generally have low water intake and low hydraulic conductivity characteristics. Impervious clay layers in the profiles further inhibit water movement through the profiles for salt control.

Imperial Valley soils have the characteristics as defined for saline soils and are managed accordingly to prevent salt accumulation and to minimize plant growth inhibition by salt. By definition (4) the electrical conductivity of a saturation extract (ECe) of a saline soil is greater than 4 mmho/cm and the exchangeable sodium percentage (ESP) is less than 15. The salts in the saline Valley soils are mainly neutral salts, such as the chlorides and sulfates of sodium, calcium and magnesium. Sodium seldom comprises more than one-half of the soluble cations. Restricted plant growth is almost directly related to the total salt concentration of the soil solution and is largely independent of the kind of salts present. If drainage is adequate and the excess salts are removed by leaching, saline soils can approach the classification of normal soils. Combinations of soil, water and cropping practices have been established in Imperial Valley for this purpose.

Soil and Water Practices

During the early years of Imperial Valley development, it became very apparent that natural drainage was not adequate for salt control after the productivity of many thousands of acres was seriously affected by rising water tables and increased salinity. In 1922, the Imperial Irrigation District started a system of open drainage ditches that emptied drainage waters into the New and Alamo Rivers which in turn flowed into the Salton Sea. Over 1400 miles of these drains are in use today.

Installation of underground farm tile drain systems began in 1929 to augment drainage by open ditches. Underground tile drains were needed to remove water and salt during leaching operations, to maintain ground water at a safe level during normal irrigation, and to prevent water and salt from returning to the surface from below. There are now about 16,800 miles of drain tile installed in the Valley, serving 370,000 acres. Underground drain systems have been successful in helping to maintain the favorable salt balance attained in 1949.

Correct water management practices in combination with drain tile are necessary for salt control. Sufficient water must be applied for the water requirements of each crop as well as enough extra water for leaching salts down through the soil and out of the root area. The fraction of the irrigation water that must be leached through the root zone to control salinity has been defined as the leaching requirement (LR) and is expressed as the ratio of the EC of the applied irrigation water to the EC of the drainage water required to maintain the soil salinity at a specified level (4). To maintain an average root zone EC of 8 in Imperial Valley soils to which Colorado River water is applied requires about 17 percent excess water for leaching. At the present time this amount of leaching on the average is being accomplished as indicated by the Imperial Irrigation District positive salt balance data.

Equally important to the quantity of water necessary for crop production and salinity control is the uniformity of water application. Good land leveling assures uniform surface flooding

and the equal water distribution needed to prevent salt accumulation on high spots. Land leveling practices vary depending upon soil type, but generally, land in Imperial Valley is graded to between a 1- to 2-foot slope per thousand feet of distance. Fields are landplaned frequently to assure good grade control and surface condition for uniform water application.

Where water movement through the soil is restricted by soil strata that prevent leaching of salts, deep tillage operations are performed to modify profiles. Chiseling, slip plowing or deep moldboard plowing operations to depths of 4 to 5 feet are performed to break up impervious soil layers and improve water penetration in the profile.

Water losses by seepage from canals and farm ditches cause some salinity problems in Imperial Valley. To minimize this problem and to improve water conveyance, canals and farm ditches are being lined with concrete and seepage from the main canals is being recovered for re-use (6). A program of concrete lining of laterals initiated in 1954 by the Imperial Irrigation District in cooperation with landowners has resulted in the concrete lining of over 500 miles of laterals. Almost all farm lateral ditches are concrete lined at the present time.

Furrow-irrigated crops are cultivated using various planting and bed shaping techniques because of high soil salinity. Usually as water moves by capillarity up into a bed during the first irrigation, salts are dissolved from the soil and carried along with the water so that the top of the bed becomes very salty. With single-row flat-beds, soil salinity as low as 4 mmho/cm in the top soil at the time of bedding may result in excessive salinity in the seedbed without special control. Double row beds and sloping beds (1) are used to prevent the accumulation of salt around the seed. Good stands are obtained with these types of beds even where the salinity in the topsoil exceeds 8 mmho/cm. Alternate row irrigation with single-row flat-beds is also helpful in getting good stands where soil salinity problems exist.

Sprinkler application of water has proven to be very helpful for improving crop germination and reducing problems related to salinity in planting beds. Many acres of winter vegetable stands are being established now by a single initial sprinkler irrigation which leaches salt from the surface soil where the seeds germinate. After emergence and for succeeding irrigations the crops are irrigated by conventional furrow methods.

More frequent irrigations than normally necessary for evapotranspiration requirements are applied to Imperial Valley crops to lessen the effects of soil salinity on crop growth. As water is removed from the soil by plant use and evaporation, most of the salt is left behind. The longer the time between irrigations, the saltier the remaining soil moisture becomes, and the more plants suffer because of salinity and water shortage. By irrigating more often, the soil water is kept from becoming too salty and the harmful effects of the salt on plant growth can be minimized.

Cropping Practices

Crops vary in salt tolerance. For some varities both crop growth and yields are reduced considerably by the presence of salts in the soil. The salt tolerance of many crops has been appraised (4) and they have been grouped according to their relative salt tolerance under management practices that are customarily employed when they are grown under irrigation agriculture. Because of the relatively high level of soluble salts in the soils and irrigation water, only moderately tolerant and tolerant crops are grown by Imperial Valley farmers. Salt tolerant and moderately salt tolerant crops such as cotton, sugar beets, barley, wheat, alfalfa, lettuce, cantalopes, and sorghum accounted for almost all of the farmable acreage in Imperial Valley for the year 1971.

Cultivation of some crops such as alfalfa may result in soil salinity increases after several years because of the water management practices required for the crop do not allow sufficient excess water to be applied for adequate leaching. In such cases as these the areas are rotated with other crops such as sugar beets or lettuce to which excess water may be applied for leaching without causing harm to the crop.

The success of Imperial Valley agriculture in overcoming the hazards of saline irrigation water is shown by the continued yield increases for the area's major crops (Figure 1). The yield of barley grain for Imperial Valley, for example,

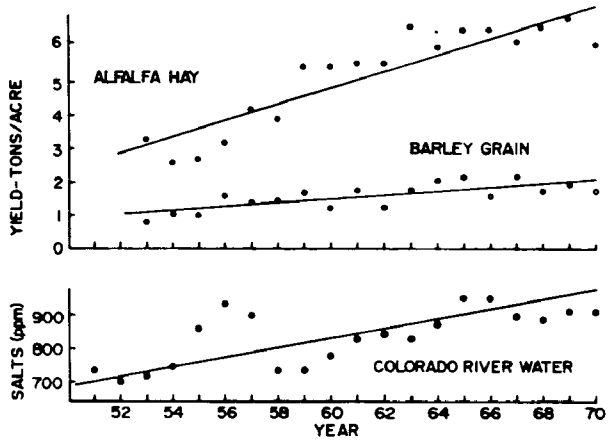

Figure 1: Trends in Alfalfa and Barley Yields, and Colorado River Water Salinity for Imperial Valley During the Period 1951-1970.

has increased at the average rate of 0.06 tons/acre/year during the last 18 years. For the same period, alfalfa hay yields have increased at the average rate of 0.24 tons/acre/year. This achievement has been accomplished despite an increase of 200 ppm in the salinity of the Colorado River irrigation water during the same period.

Acreage of farmable land in the Valley also is remaining constant showing that no areas are being lost because of salinity problems. Total area farmable in the Imperial Valley for the last ten years has been approximately 473,000 acres. If drainage continues to be adequate there should be no problem in keeping Imperial Valley agriculture successful.

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Irrigation Return Flows in Southern Idaho

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ABSTRACT

The quantity and quality of irrigation return flows from a 203,000-acre irrigation tract in southern Idaho were measured and compared to the quantity and quality of the irrigation water. Return flows for a typical water year amounted to 929,350 acre feet representing 64% of the total water input to the tract. The total salt concentration in the subsurface drainage water was more than twice that found in the irrigation water. The mean electrical conductivity of the subsurface drainage water was 1040μ mhos/cm which is as low as in some irrigation waters. The Na^+ concentration increased more than four times as water passed through the soil and became subsurface drainage water. Similar comparisons were made for other cations and anions. Surface runoff water did not differ from irrigation water in chemical quality. Surface drainage water from a 3,000-acre subregion contained up to 3.06 tons of sediment per acre foot during the midpart of the irrigation season.

INTRODUCTION

The quantity and quality of irrigation return flows depend upon the quantity and quality of water diverted for irrigation, the proportions of the return flow from surface runoff and subsurface drainage and other factors. Generally, water passing across the land surface picks up little salt or fertilizer elements except those associated with sediment picked up by erosion. Water passing through the soil reacts chemically with soil materials and dissolves soluble salts where contact is made. As soil water is used in evapotranspiration, salts are concentrated in the water that remains in the soil or drains from it. Thus subsurface drainage water usually differs markedly in quality from the irrigation water passing through the soil influences the quality of the subsurface drainage water and the outputs of total salts, specific ions and fertilizer elements.

Information is needed on the quality of irrigation return flows under various management systems as a basis for improving the quality of irrigation return flows. This paper presents information on the quality and quantity of irrigation return flows from a large irrigation tract in southern Idaho.

Methods and Materials

The study area (Figure 1) was a 203,000-acre tract developed by the Twin Falls Canal Company about 1905. Water is diverted from the Snake River and delivered to farmers at a con-

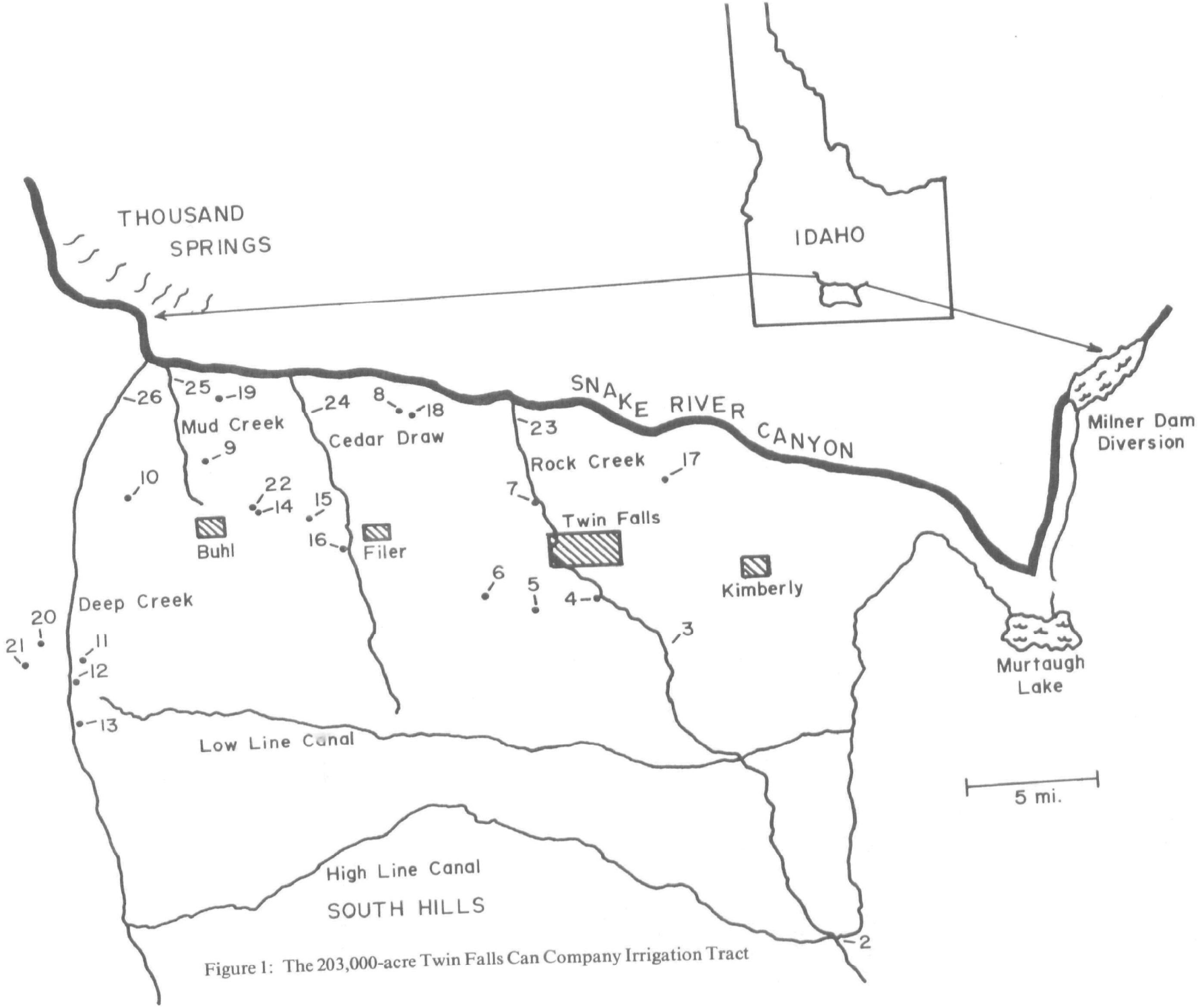

Figure 1: The 203,000-acre Twin Falls Can Company Irrigation Tract

stant rate of 0.5 cubic feet per second (cfs) for each 40 acres during the irrigation season when requested. Water is in the canal system from about April 1 to November 15 each year. Canal flows in the early spring and late fall are considerably lower than during the peak irrigation season of June, July, and August because many farmers have crops that do not require early spring or late fall irrigation.

Soils over most of the study area are moderately deep, uniformly textured silt loams derived from calcareous, wind deposited material, varying from a few inches to 50 feet in depth. These soils are generally well drained. They are underlain by fractured basalt to depths of several hundred feet. Most crops are irrigated by small furrows, and infiltration rates are fairly high. The mean, annual precipitation for the area is 8.5 inches.

The most important crops grown on the tract are alfalfa, dry beans, sugarbeets, small grain, corn and pasture.[1] Row crops are normally seeded in April and May, and harvest is usually completed by late October.

Soon after irrigation was initiated, high water tables appeared in localized areas throughout the tract. To alleviate this problem, the Canal Company used two drainage methods. For the larger areas, horizontal tunnels 4 feet wide by 7 feet high were excavated where test wells indicated significant amounts of water in basalt fractures. These tunnels effectively convey excess water to natural surface drains. The 49th and final tunnel was completed in 1948. The other method combined shallow drainage wells and tile lines in networks to drain smaller areas. The wells are connected by tile lines 3½ to 10 feet below the soil surface. The wells flow from hydrostatic pressure, and the water is conveyed to natural surface drains by tile lines. The practice has proved effective and is still used today. All surface and subsurface drainage returns to the Snake River which flows in a canyon about 500 feet deep, forming the northern boundary of the irrigation project.

Sampling sites were selected throughout the area (numbered on Figure 1) including the project diversion at Milner Dam on the Snake River, four main surface drains, 15 drainage tunnel outlets, five tile-relief well network outlets, and one small stream draining the South Hills watershed. Initially, water samples were collected from each site at two-week intervals and analyzed for total soluble salts, Na^+, K^+, Ca^{++}, Mg^{++}, Cl^-, HCO_3^-, SO_4-S, PO_4-P and NO_3-N concentrations.[3,4,5] Water temperature and pH were also measured at each site. Analysis over a few months showed that the concentrations of some components were nearly constant. Therefore, only PO_4-P, NO_3-N and total salt concentrations and water temperature determinations were continued at two-week intervals. Analyses for other components were made at four-week intervals.

The flow rate from each tunnel and tile-relief well network was measured. Weirs were used where possible. Parshall flumes existed at two sites, and the remainder were gaged periodically by current metering. Water stage recording stations were maintained on the main surface drains. Existing USGS gaging stations were utilized on Cedar Draw and Deep Creek. Flow hydrographs were developed from the data and the monthly flow volume computed for each site. Hydrograph separation techniques[2] were applied to the streamflow data to establish the amounts of surface runoff and subsurface drainage from the area for a typical water year, October 1, 1968 through September 30, 1969.[1]

A water balance for a typical water year of the Canal Company, October 1, 1968 through September 30, 1969, was computed.[1] Using this water balance along with the concentrations of total salts, PO_4-P and NO_3-N, input-output balances for these components were calculated and previously reported.[1] Input-output balances for specific ions and related information have also been calculated (submitted for publication).

The sediment concentration in the major surface drain waters was determined by removing the sediment from samples of known volume collected at two-week intervals during the 1971 irrigation season. The sediment was removed by allowing it to settle and by centrifuging. The sediment was then dried and weighed.

Results and Discussion

The mean concentrations of all ionic components except PO_4-P were higher in subsurface drainage water than in the irrigation water (Table 1). The concentration of each component was nearly constant at each sampling site even though the flow fluctuated with seasons at most

TABLE 1

Mean ionic concentrations at input and subsurface drainage sampling sites for the water year October 1, 1968 to September 30, 1969

No.	Name	Na^+ me/l	K^+ me/l	Ca^{++} me/l	Mg^{++} me/l	Cl^- me/l	HCO_3^- me/l	NO_3-N ppm	SO_4-S ppm	PO_4-P ppm
	Input Streams									
1	Milner	0.90	0.12	2.54	1.23	0.66	3.38	0.12	14	0.066
2	Rock Creek (HL)	0.22	0.12	1.09	0.34	0.17	1.79	0.11	4	0.015
	Drainage Tunnels									
3	Claar	3.65	0.10	5.22	3.62	1.33	6.66	4.02	69	0.013
4	Fish Hatchery	2.92	0.13	3.55	2.85	1.30	5.57	2.24	36	0.013
5	Grossman	3.01	0.10	3.99	2.81	1.18	5.97	2.25	45	0.014
6	Nye	3.64	0.11	3.81	3.02	1.54	5.91	2.44	55	0.009
7	Tolbert	4.06	0.12	4.95	3.23	1.65	6.45	3.30	68	0.012
8	Walters	3.86	0.14	4.47	3.98	1.52	6.67	3.47	56	0.008
9	Mendini	4.73	0.21	3.60	2.88	1.72	7.22	3.97	47	0.009
10	Neyman	4.06	0.23	5.42	2.71	1.55	7.52	3.40	50	0.011
11	Galloway	3.82	0.12	3.88	2.94	1.19	7.12	3.58	35	0.014
12	Cox	3.38	0.12	3.81	2.96	1.24	6.74	3.44	35	0.015
13	Herman	3.00	0.12	5.71	3.01	1.42	7.08	3.00	47	0.017
14	Harvey	3.70	0.13	3.64	2.84	1.37	6.93	3.39	31	0.008
15	Peavy	3.93	0.13	3.57	3.12	1.57	6.47	3.02	36	0.007
16	Padget	3.92	0.13	3.46	3.34	1.62	6.24	3.01	42	0.008
17	Hankins	4.49	0.18	4.27	3.11	1.63	6.62	3.55	53	0.012
	Tile-Relief Well Networks									
18	Brown	4.06	0.16	4.36	3.50	1.67	6.78	3.01	55	0.009
19	Hutchinson	4.38	0.21	4.15	3.06	1.61	7.65	3.20	44	0.012
20	Kaes	2.73	0.19	5.07	3.20	1.83	6.25	3.40	54	0.023
21	Molander	2.80	0.21	4.82	3.59	1.94	6.12	3.79	57	0.009
22	Harvey	3.67	0.14	3.59	3.10	1.42	6.27	3.30	36	0.023
Mean, Subsurface Drainage		3.69	0.15	4.27	3.14	1.52	6.61	3.24	48	0.012

sites. The concentration variation among sampling sites for subsurface drainage water was generally within 25% for any specific chemical component and for total salts.

The relative difference in individual cation concentrations between the irrigation water and the subsurface drainage water was greatest for Na^+ and least for K^+ (Table 2). For anions, the relative increase was greatest for NO_3-N and least for Cl^-. The PO_4-P concentration decreased so that the concentration in the drainage water was less than 1/5 of that in the irrigation water.

The water balance[1] showed that 50% of the total input water (diverted water plus precipitation) became subsurface drainage water, 14% returned to the Snake River as surface runoff and evapotranspiration accounted for the remaining 36% (Table 3). The net output of total salts amounted to approximately one ton per acre per year (Table 4). The portion of the water passing through the soil and the net salt output indicates that more leaching is taking place than is necessary to maintain a salt balance.[6]

During a typical water year, about 1 acre-foot of surface runoff per acre returned to the River,

TABLE 2

Specific ion concentrations in irrigation and subsurface drainage waters and the relative concentration change that occurred as water passed through the soil

Component	C units	Ci^a	Csd^b	$\frac{Csd}{Ci}$
Na^+	me/l	0.90	3.67	4.08
K^+	me/l	0.12	0.15	1.25
Ca^{++}	me/l	2.54	4.27	1.68
Mg^{++}	me/l	1.23	3.14	2.55
Cl^-	me/l	0.66	1.52	2.30
HCO_3^-	me/l	3.38	6.61	1.96
NO_3-N	ppm	0.12	3.24	27.00
SO_4-S	ppm	14.0	48.0	3.43
PO_4-P	ppm	0.066	0.012	0.18
Total Salt	μ mhos/cm	460	1,040	2.26

[a]Ci is the concentration in the irrigation water.

[b]Csd is the concentration in the subsurface drainage water.

TABLE 3

The water balance for the 203,000-acre Twin Falls Tract for a typical water year[1]

	Acre-feet	%
Input		
Diverted from Snake River	1,290,100	89
Runoff from South Hills	32,000	2
Precipitation	130,000	9
City of Twin Falls	900	—
TOTAL	1,453,000	100
Output		
Evapotranspiration	523,650	36
Surface runoff	203,880	14
Subsurface drainage	725,470	50
TOTAL	1,453,000	100

and subsurface drainage amounted to more than 3.5 acre-feet per acre. Thus, the total quantity of return flow from the 203,000-acre tract amounted to 929,350 acre-feet, or 64% of the total input.

There was a net output of all chemical components measured excepting PO_4-P and K^+ (Table 4). The net K^+ input amounted to approximately 13 pounds per acre per year which is significant from the standpoint of fertilizer needs. More than 70% of the PO_4-P entering the tract in the irrigation water reacted with and remained in the soil. The total output of PO_4-P in the drainage water was only 28 tons compared to a total input of 116 tons in the irrigation water and 2,580 tons applied to the land as fertilizer. Results from this study show that applied phosphorus fertilizers remain associated with the soil. They are not dissolved into PO_4-P and leached away by drainage water.

The chemical quality of the subsurface drainage water from the Twin Falls tract is better than that of irrigation water diverted at some points from the lower reaches of the Colorado and Rio Grande Rivers and that from some

TABLE 4

Input-output balances for measured chemical components and total salts for a typical water year on 203,000 acres

Component	*Total Input*	*Total Output*	*Net Input*	*Net Output*
	Tons	Tons	Tons	Tons
Na^+	36,511	88,946	—	52,435
K^+	8,444	7,070	1,374	—
Ca^{++}	90,006	98,272	—	8,266
Mg^{++}	26,475	41,818	—	15,343
Cl^-	41,284	59,723	—	18,439
HCO_3^-	365,880	454,400	—	88,520
NO_3-N	210	3,226	—	3,016
SO_4-S	25,598	51,342	—	25,744
PO_4-P	116	28	88	—
Total salts	520,977	738,077	—	217,100

other sources. However, the total salt concentration in this subsurface drainage water was more than double that in the irrigation water. The quality of the irrigation water was high, and even though the salt concentration is increased by irrigation, the quality of the drainage water is still fairly high.

In some respects, the quality of the drainage water was superior to that of the irrigation water. For example, the PO_4-P load in the drainage water was less than in the irrigation water, and the temperature of the drainage water was lower than that of the irrigation water during midsummer when irrigation water temperatures exceeded 20°C.

The NO_3-N concentration was 27 times higher in the subsurface drainage water than in the irrigation water. This concentration increase coupled with the water balance represents a net NO_3-N output of 30 pounds per acre per year. However, the mean NO_3-N concentration was 3.24 ppm which is well below the 10 ppm set by the Public Health Service as a maximum for drinking water.

Surface runoff water quality did not differ from that of the irrigation water except that the runoff water had a much higher sediment concentration during part of the irrigation season. The four main surface drains from the area contained both surface runoff and subsurface drainage water. Therefore the quality of water in these drains was between the irrigation water and subsurface drainage water qualities. For example, the electrical conductivity of waters in Rock Creek, Cedar Draw, Mud Creek and Deep Creek (sites 23, 24, 25 and 26 respectively) ranged from about 600 to 800μ mhos/cm during the time that water was being diverted into the canal system and from 1,000 to 1,100μ mhos/cm during the winter months when essentially all water in these drains was from subsurface drainage. Concentrations of specific chemical components fluctuated similarly.

The sediment load in surface runoff water varied through the irrigation season. Our sediment data have not been summarized for all streams at this date, but preliminary results indicated that the surface runoff from a 3,000-acre subregion contained from about 0.25 to 3.00 tons of sediment per acre-foot during an irrigation season (Table 5). The amount of sediment removed from the 3,000 acres by erosion

TABLE 5

Sediment load in surface runoff water from 3,000 acres

Sampling Date	*Sediment load*	*Accumulative Sediment output*	*Accumulative runoff*
	Tons/acre-ft.	Tons	acre-ft.
May 25	0.97	—	—
June 2	.54	—	—
June 15	.28	620	1,000
June 29	.97	2,760	2,065
July 13	3.06	6,070	3,179
July 26	2.88	9,025	4,411
August 10	1.92	10,750	5,541
August 24	1.11	11,700	6,805
September 8	.37	12,500	8,791

during irrigation was over 12,000 tons or over 4 tons per acre per season.

In conclusion, irrigation return flows from a 203,000-acre irrigation tract in southern Idaho represented nearly 2/3 of the input water. Most of the return flow was subsurface drainage. The total salt concentration in subsurface drainage water was more than twice that in the irrigation water, but the concentration was lower than occurs in irrigation waters used in some areas of the U.S. The PO_4-P load in the drainage water was less than 30% of that in the irrigation water. Surface runoff water did not differ from irrigation water in chemical quality, but high sediment concentrations were measured during part of the irrigation season.

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Salinity Problems in the Rio Grande Basin

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ABSTRACT

The Rio Grande system carries a large salt burden contributed by a variety of natural and man-made sources. Increased efficiency in water management for agriculture and continued economic development will result in higher salinity concentrations. Additional research is necessary before adequate salinity control and management programs can be considered.

INTRODUCTION

The Rio Grande system carries a large salt burden (dissolved solids) contributed by a variety of natural and man-made sources. Depletion of stream flow by consumptive use of water for irrigation, municipal, and industrial use and by natural evapotranspiration reduces the volume of water available for dilution of this salt burden. As a result, salinity concentrations in portions of the system exceed critical levels for certain water uses. Increased efficiency in water management for agriculture and continued economic development in the basin will increase stream flow depletions and add salt which, in turn, will result in higher salinity concentrations.

As salinity concentrations increase, additional adverse physical effects are produced on some water uses. Unless adequate research information is obtained to support appropriate salinity management programs in the basin, future increases in salinity concentrations will seriously affect water use patterns and will result in large economic losses to water users and to the regional economy.

Because the Rio Grande Basin is primarily an arid region, those few perennial streams within the basin have considerably more influence upon the lives and livelihood of the region's inhabitants than any other element of the physical environment. Any alteration, modification, or subtle change of this resource must, therefore, be carefully evaluated.

The Rio Grande has its headwaters in south-central Colorado and flows 1900 miles to the Gulf of Mexico, see Figure 1. From Colorado it flows south through New Mexico, and then turns southeast at El Paso, Texas, on its way to the Gulf. For the 81 miles from El Paso to Fort Quitman, the river is the international boundary between the Republic of Mexico and the United States.[1]

The river is generally considered to have three regimens as far as water use is considered in the United States: these are the river from its head in Colorado to Fort Quitman, Texas, the Pecos River, and the main stem from Fort Quitman to the Gulf. The reach of the river above Fort Quitman is known as the Upper Basin and below Fort Quitman as the Lower Basin.

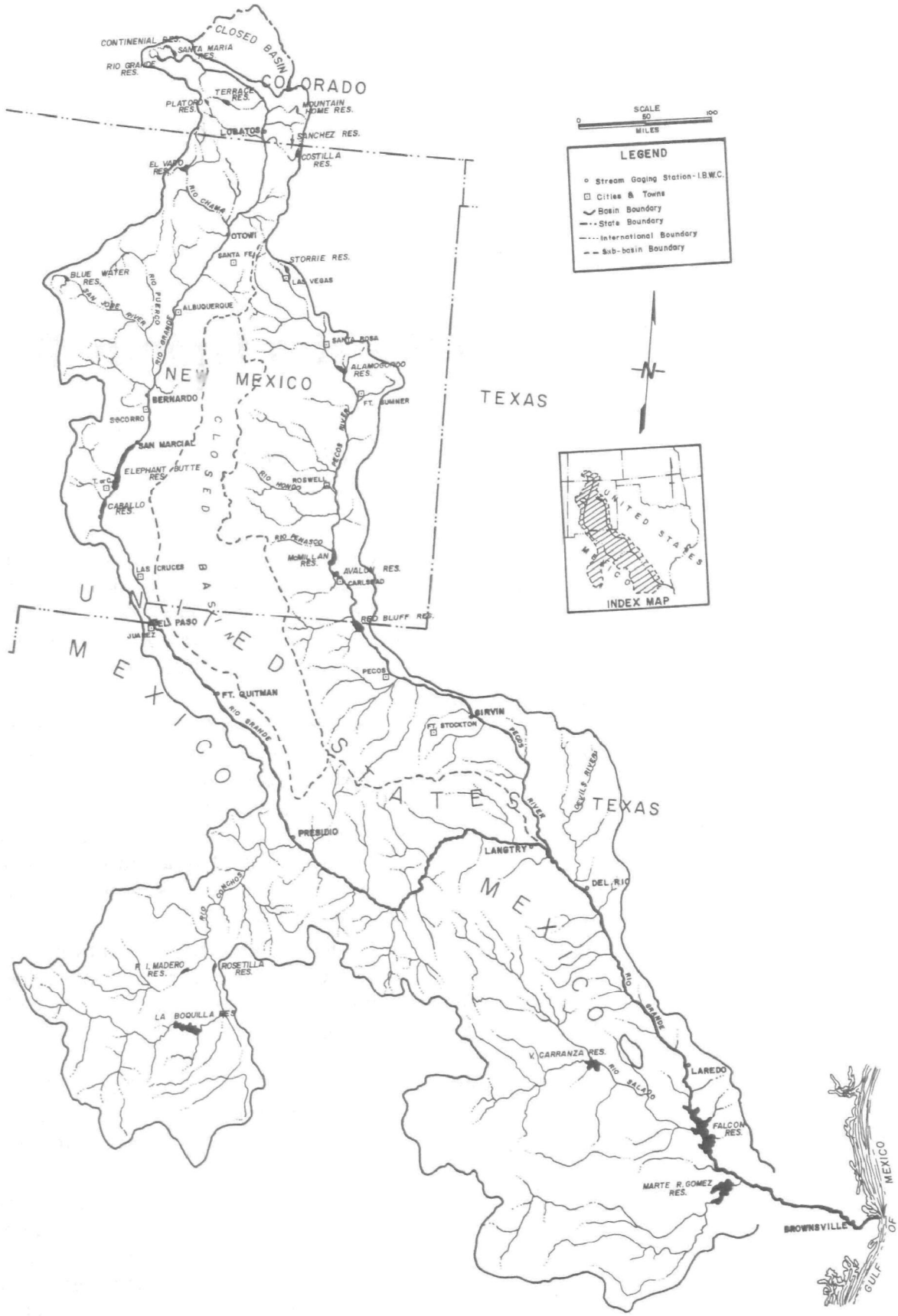

Figure 1: Rio Grande Basin

Nearly all of the water produced in the Upper Rio Grande is consumed in that sub-basin. Much the same situation prevails in the drainage area of the Pecos River, the major tributary of the Rio Grande in the United States. The lower Basin receives little flow from Colorado or New Mexico. Because of this separation, the three sub-basins will be discussed separately.

Upper Rio Grande

Physical Description — The Upper Basin drains an area of about 32,000 square miles above Fort Quitman, see Figure 2. Fort Quitman, Texas, is approximately 650 miles downstream from the river's head in Colorado and about 80 miles downstream from the City of El Paso, Texas. The Upper Basin includes parts of Colorado and New Mexico, and very small parts of Texas and the Republic of Mexico. More than 99 percent of the water comes in about equal amounts from Colorado and New Mexico.

The Upper Basin comprises three sub-areas designated as the San Luis Section in Colorado, the Middle Section in New Mexico, and the Elephant Butte Project Section of Southern New Mexico, including extreme West Texas and the adjacent river valley in the Republic of Mexico.

San Luis Valley — The San Luis Valley is a large north-tending structural depression downfaulted in the eastern border and surrounded on the west, north and east by mountains. It is a high flat mountain valley with an average altitude of about 7,700 feet. Underlying the valley is as much as 30,000 feet of alluvium, volcanic debris, and interbedded volcanic flows and tuffs. Most of the valley floor is bordered by alluvial fans deposited by streams originating in the mountains: the most extensive of these is the Rio Grande fan.

The northern half of the San Luis Valley is internally drained and is referred to as the "closed basin." The rest of the valley is drained by the Rio Grande and its tributaries. A number of small streams enter the closed basin and practically all water produced by these streams that is not consumed in irrigation is lost by evapotranspiration. In addition, all water diverted from the Rio Grande for a large irrigated acreage in the closed basin and not consumed in irrigation is also lost in the low portion of the area by nonbeneficial evapotranspiration. Mineral concentrations in the shallow groundwater in part of the closed basin range is nearly 14,000 mg/l.[2]

Total annual water supply to the San Luis Valley is about 2,500,000 acre-feet. Approximately 1,500,000 acre-feet is stream flow from snow melt in the surrounding mountains, and 1,000,000 acre-feet is from precipitation within the valley. Discharges from the valley are estimated at about 2,000,000 acre-feet per year by evapotranspiration and about 500,000 acre-feet as flow into New Mexico. The stream flow at the state line averages 445,000 acre-feet per year, and the groundwater underflow is estimated at 55,000 acre-feet.

Groundwater in the San Luis Valley is from confined and unconfined aquifers which contain at least 2 billion acre-feet of water in storage.[2] The unconfined aquifer is of modern origin and occurs almost everywhere in the valley. Recharge to the unconfined aquifer is mainly by infiltration of applied irrigation water and leakage from the distribution system. Some water percolates from the many streams flanking the valley and from local precipitation. Subirrigation is widely practiced in the valley and the phreatic surface must be brought very close to the land surface for at least part of the year.

The valley is arid, and a successful agricultural economy would not be possible without irrigation. The main irrigated crops produced are alfalfa, potatoes, barley, oats, hay, and pasture. Irrigation development began in the San Luis Valley after 1850 and the oldest water right in the valley is dated 1852. Rapid and extensive settlement occurred which utilized waters from the Rio Grande after construction started on the Denver and Rio Grande Railroad through the valley in 1879.

The Middle Section — The Middle Rio Grande Section is a land of flat dry desert floors, and rocky precipitous mountains in the north-central part of New Mexico. It includes the Rio Grande and tributary valleys from the Colorado state line to San Marcial at the head of Elephant Butte Reservoir, a river distance of about 270 miles.

The Rio Grande flows into New Mexico from a southerly extension of Colorado's San Luis Valley through a deeply entrenched channel for

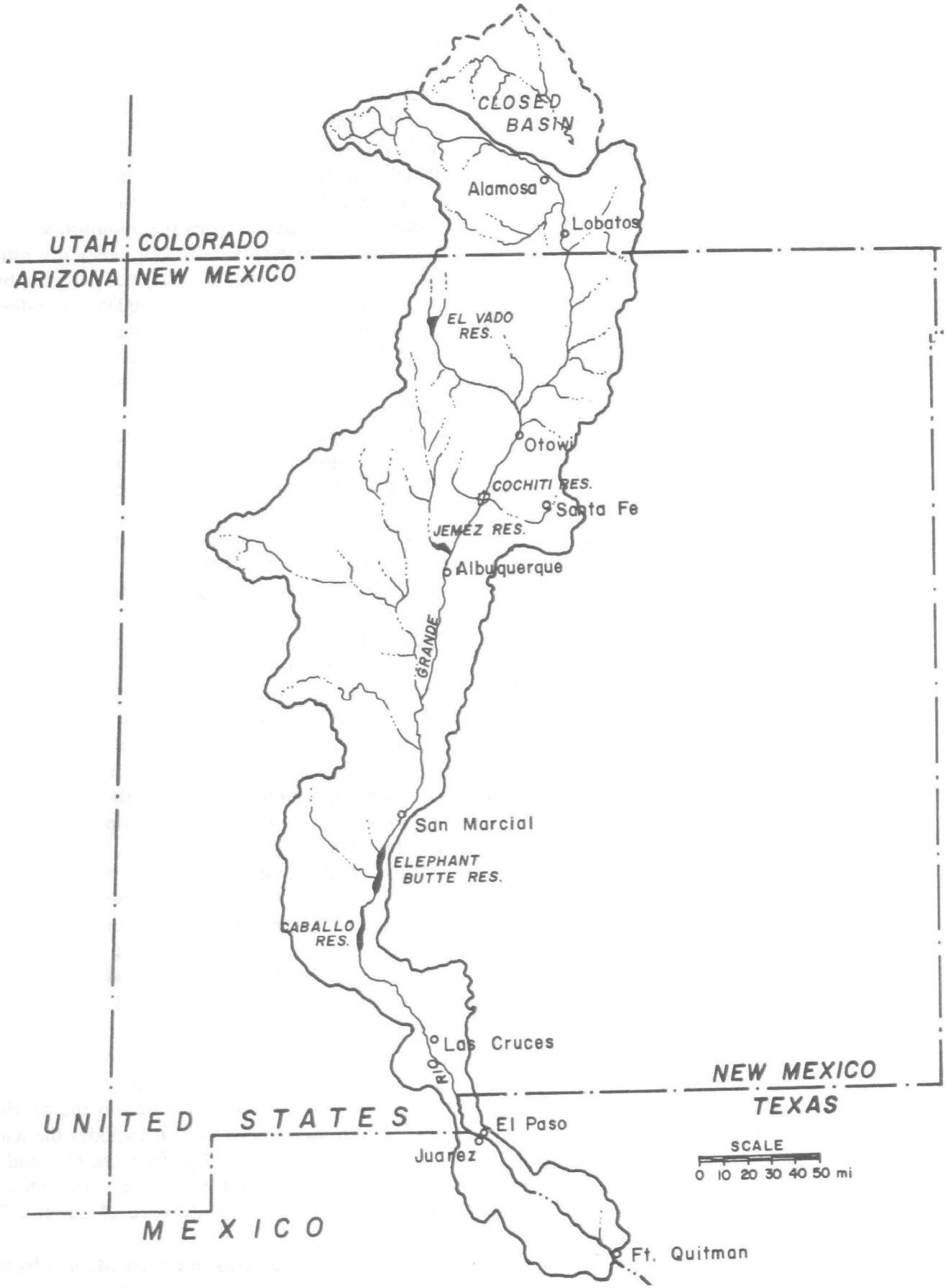

Figure 2: Upper Rio Grande

some 75 miles downstream. At the mouth of this canyon the river enters the several valleys that make up the Middle Section. These basins within the Middle Section are aligned in a generally southerly direction and consist of broad plains flanked by mountains. The basins are partially filled with Quaternary and Tertiary sediments known collectively as the Santa Fe Group. Irrigated lands lie in narrow strips from one to five miles wide on each side of the river within the basins.

The drainage area between Lobatos Bridge, Colorado, gauging station and the San Marcial gauging station above Elephant Butte Reservoir is approximately 20,000 square miles. This area comprising the Middle Section contains about 175,000 acres subject to irrigation, about 38,000 of which are on Indian lands.[1]

The average annual water production of stream flow in the Middle Section is about 1.3 million acre-feet, and the outflow at San Marcial averages about 0.9 million acre-feet. The total inflow from Colorado is about 0.5 million acre-feet resulting in about 0.9 million acre-feet consumed in this reach.

Groundwater is primarily from valley fill sediments that have been deposited along tributary streams and have filled much of the Rio Grande trough. These fills are generally stream-connected and are recharged mainly from stream flow. The status of groundwater in the basin is not well known and only generalized physical properties and water bearing characteristics are available.

The Middle Rio Grande section is one of the earliest areas in the Western Hemisphere to be occupied by man. Agriculture was first practiced here by the Anasazi Indians who evolved into the people of the Pueblo I and II eras, 700-1050 A.D. By 900 A.D. irrigation was in wide use, and 20 to 30 thousand people are estimated to have lived in 70 to 80 pueblos.[3] A severe drouth between 1276 and 1300 resulted in a large influx of agricultural peoples from the Mesa Verde of Colorado on the Colorado River. Subsequent irrigation developed until an estimated 25,000 acres were in use at the time of arrival of the first Spaniards. In 1598 Juan de Onate built the first Spanish irrigation ditch in the new world about 30 miles north of Santa Fe. By 1800 A.D. over 100,000 acres were under cultivation utilizing 70 diversion canals from the Rio Grande in this section. Rapid expansion of irrigated agriculture occurred during the late 1800's due to the railroads providing a transportation link to new markets, and resulted in about 230,000 acres being under irrigation in the Middle Section and its tributaries by 1890.

Elephant Butte Project Section — The Elephant Butte Project Section is located in that stretch of the river from San Marcial, New Mexico, to Fort Quitman, Texas, a distance of about 258 river miles. The Rio Grande between these points contains 4,335 square miles of drainage area, 1,429 of which are in the Republic of Mexico. While this reach of the river is in two states of the United States and in two nations, it is one economic and hydrologic unit separated from other populated centers of either country by vast expanses of semi-arid deserts.

Altitudes range from 4,200 feet at Elephant Butte Reservoir to 3,400 feet at Fort Quitman. Like the Middle Section, the Elephant Butte Project Section is a succession of valleys separated by canyons and narrows. Of these valleys, Rincon, Mesilla, and the El Paso Valley contain the major irrigated areas. The El Paso Valley area southwest of the river is in Mexico.

The production of water in this reach of the river is negligible. Although there are numerous ephemeral tributaries, some of which have rather large drainage areas, there are no perennial streams tributary to the Rio Grande. The Rio Grande Joint Investigation[5] estimates the mean annual surface water production for the years 1890-1935 to be 164,800 acre-feet for this area, but this is subject to a considerable amount of estimation. The flow of the Rio Grande is normally depleted in this reach and the river bed is usually dry or has only a small flow of highly mineralized water at Fort Quitman except in times of local flood.

The river alluvium in this reach constitutes a major source of irrigation water, although the quality of this water varies from place to place and some areas do not have suitable irrigation quality groundwater. Withdrawals for the irrigated lands using river water are estimated to have averaged in excess of one acre-foot per year since 1951.

Irrigation in this section of the Upper Rio Grande dates to the establishment of a mission

church in 1659 in what is now Ciudad Juarez, Mexico. This mission served local Indian tribes and provided a way station between the seats of government in Mission City, Mexico, and Santa Fe, New Mexico.

Salinity — Salinity concentrations progressively increase from the headwaters in Colorado to Fort Quitman, Texas. This increase results from salt concentration produced by stream flow depletions that increase salinity by concentrating the salt burden in a lesser volume of water, and by salt loading due to the addition of mineral salts from various man-made and natural sources which increases salinity by increasing the total salt burden carried by the river.

Most of the water in the Rio Grande is used for irrigation. This use, together with that of native vegetation and surface evaporation, is responsible for the largest depletions. Consumptive use of water for municipal and industrial purposes accounts for a much smaller depletion.

Natural salt loading is contributed by some tributaries of the Rio Grande in north-Central New Mexico, such as the Rio Chama and the Rio Puerco, that drain areas outside the Rio Grande depression and have large surface areas covered with shales and clays containing fairly soluble minerals. Man-made sources include municipal and industrial waste discharges and return flows from land irrigated by groundwater. The relative effects of the various salt concentrating and salt load factors on salinity concentrations are summarized in Tables 1 and 2.

There was a generally favorable salt balance on the Upper Rio Grande to El Paso, Texas, until the drouth starting in 1946. This drouth period, coupled with the heavy use of a more saline groundwater below Elephant Butte Reservoir starting about 1953, created some serious soil salinity problems in this reach. The problem has been further complicated due to the decrease in surface water delivered to Elephant Butte Reservoir. The 1970, 75-year mean discharge for the Rio Grande at San Marcial is 924,000 acre-feet while the ten-year moving average is 621,000 acre-feet. The twenty-year moving average would be less than this value due to the drouth in the 50's. This situation has caused serious economic loss to New Mexico, Texas, and Mexico portions of the basin above Fort Quitman. The Hudspeth District below El Paso has practically ceased to exist as an economic unit during this period.[4]

TABLE 1

Salinity Concentrations on the Upper Rio Grande 1963 — Milligrams Per Liter

Headwaters	< 100
Otowi Bridge	235
Caballo Dam	440
El Paso	870
Fort Quitman	4,000

TABLE 2

Upper Rio Grande Salt Burden 1963 — 1000 Tons

Otowi Bridge	136.2
Caballo Dam	310.3
El Paso	313.8
Fort Quitman	126.8

Colorado River water being delivered to the Rio Grande through the San Juan-Chama Project is apparently of excellent quality, but the consumptive use of this water in the Middle Section increases the dissolved solids concentration below San Marcial. Over the years, studies have been made to develop plans to recover some of the previously irrigated acreages in the closed portion of the San Luis Section. Recovery would involve a system of wells and conveyance channels in the closed basin which would deliver water to the Rio Grande, but such a program would contribute an additional salt load to the basin and further increase the salinity problems in the reach below San Marcial.

It is recommended that a salinity policy be adopted for the Upper Rio Grande that would have as its objective the maintenance of salinity concentrations below the levels presently found in the lower portion of the basin. It is further recommended that a comprehensive study be made to provide detailed information on the causes, sources, and effects of salinity in the basin.

Pecos River

For its size, the basin of the Pecos River probably presents a greater aggregation of prob-

lems associated with land and water use than any other irrigated basin in the Western United States. These involve both quantity and quality of water supplies, the problem of salinity being particularly acute; erosion and silting of reservoirs and channels; damage from floods; and interstate controversy over the use of the waters. There is an abundance of good land so that the limit of development is the availability of water of satisfactory quality. The use of the water of the river has been fully appropriated.

— National Resources Planning Board, 1942.[6]

The principal tribuary of the Rio Grande in the United States, the Pecos River, rises in the high altitudes of the Sangre de Cristo Mountains in north central New Mexico, and flows southward some 900 miles to join the Rio Grande in Texas, see Figure 3. In a distance of 160 miles, elevations in the drainage area drop from 13,000 feet in the headwaters to 4,300 feet above sea level at Alamogordo Dam. The water yield in the upper mountain areas is a function of snow pack. The average snowfall is determined by elevation, and varies from 340 inches above 12,000 feet to 85 inches at 8,000 feet.[7]

Below Alamogordo Reservoir the narrow canyon-valley sections give way to an area of wide plains bounded on the west by a chain of mountains and on the east by the escarpment of the Southern High Plains. This is generally a semi-arid area and practically all important tributaries originate in the mountains to the west. Approximately 100 miles below Alamogordo Reservoir, the Pecos Valley opens onto the Roswell Basin. This is an area 6 to 20 miles in width along the river for a distance of about 90 miles and includes McMillan Reservoir. The area of the Carlsbad project operated by the Bureau of Reclamation occupies the river valley from Avalon Reservoir about 20 miles to a point where the river again enters a narrows section near the New Mexico-Texas state line above Red Bluff Reservoir.

Below Red Bluff Reservoir the river meanders through a broad expanse of gently rolling plains. The area irrigated from the river is confined to the reach between Red Bluff Reservoir and Girvin, a distance of about 110 miles. Below Girvin the topography becomes rough and the valley becomes narrow, developing into an ever-deepening canyon section which extends to the river's confluence with the Rio Grande. At that point the river canyon is some 300 feet deep.

Surface Water

Average annual precipitation in the Pecos River basin is more than 14 inches per year. The highest precipitation occurs in the mountains and the lowest in the central river valleys, thus making irrigation essential for successful agriculture.

The National Resources Planning Board estimated the total mean annual water production from run-off available for irrigation in the Pecos River basin as 1,095,000 acre-feet.[6] This represents 4 percent of the total precipitation in the basin. Of this total, 18 percent occurs in that reach of the river below Girvin, Texas, which is below the major irrigated areas. Of the water production above Girvin, 82 percent originates in New Mexico and 18 percent in Texas.

Studies indicate that the area of highest flood potential in the state is in the southwestern part of the basin, and the Pecos River has produced many of the major floods in New Mexico. The flow of the Pecos River is partially regulated by Alamogordo, Two Rivers, McMillan, and Red Bluff Reservoirs with many smaller reservoirs in the basin area used to control sediment and runoff.

Some evidence of early man has been found in the upper Pecos basin. Projectile points from Paleo-Indian down to modern Pueblo types have been identified. Early Pueblo Indians occupied the river valley and its tribuaries throughout its course, but they abandoned the middle and lower area before 1540. Plains Indians were in this portion of the Pecos Valley when the Spaniards arrived, and their presence may account for the abandonment of the area by the Pueblo groups. When Coronado's expedition passed through the upper valley in 1540, the explorers found Pueblo Indians near the present village of Pecos. They lived in a walled, multistoried town and practiced irrigation farming by diverting water through a system of ditches.

When the Santa Fe Trail was opened in the 1820's, the Spanish were irrigating in the upper valley: these settlements expanded downstream as the Plains Indians were subdued. Settlement

Figure 3: Pecos River

in the middle valley did not take place until the Civil War and the Homestead Act of 1862. Rail transportation was installed between 1878-1909 and stimulated the rate of development. In 1891, following the discovery of flowing artesian groundwater during the drilling of a domestic well, irrigation was substantially increased in the Roswell area. Development in the Middle Section was further stimulated in the 1920's by the discovery of oil and potash.

Salinity — Quality of the water is a serious problem throughout most of the Pecos River basin. Salinity concentrations due to salt concentration and salt loading progressively increase from the headwaters to Girvin, Texas. Water high in dissolved solids is contributed to the Pecos River from springs, from irrigation return flow, and from leakage of old oilfield brine pits. Consumptive use of water by the heavy growth of phreatophytes, especially at the head of McMillan Reservoir, probably increases the concentration of dissolved solids.

Before 1963, about 420 tons daily of dissolved salts, mostly sodium chloride, were added to the river by springs and seeps along a 3 mile stretch about 17 miles below Carlsbad, New Mexico. A salvage project operated by the Bureau of Reclamation has reduced this salt load about 70 percent by pumping this spring water away from the river to an evaporation disposal area.[9]

There are between 60 and 70 thousand acres of salt cedars along the river between Santa Rosa, New Mexico, and Girvin, Texas. The growth was first noted in 1915, and by 1939 it had spread over about 14,000 acres along the river between Alamogordo Dam and the state line. The Bureau of Reclamation indicates that some 75,000 acres will be infested by the year 2010, and unless corrective action is taken, the entire supply of the Pecos River could be depleted by these plants within a few decades.[10]

The relative effects of the various salt concentrating and salt load factors on salinity concentrations are summarized in Tables 3 and 4. Some of the salt concentration has probably been due to the diminution of good quality inflow from parts of the drainage basin. Part is attributed to the development and use of water from major groundwater reservoirs in the basin as under natural conditions these groundwaters discharge to the Pecos River.

TABLE 3

Salinity Concentrations on the Pecos River
Ten Year Average — 1955-1964
Milligrams Per Liter

Headwaters	<100
Alamogordo Dam	1,420
Carlsbad	2,320
Red Bluff Dam	6,970
Langtry	1,460

TABLE 4

Percos River Salt Burden
Ten Year Average — 1955-1964 — 1,000 Tons

Alamogordo Dam	247.4
Carlsbad	154.3
Red Bluff Dam	550.6
Langtry	432.0

The fundamental difficulty is the lack of an adequate and reliable water supply to meet all of the demands that are placed on the system. The controllable part of the supply is vested mainly in the individual water-right owners. This imposes legal and administrative constraints on an already difficult physical system. Programs for solving most of the critical problems of the system have been undertaken or are contemplated.

Lower Rio Grande

The Rio Grande leaves Fort Quitman through a narrow, steep-walled canyon and continues through this rugged mountain area, flowing occasionally through small isolated valleys as it approaches the Big Bend country, see Figure 4. This region is filled with geologic phenomena such as tilted and folded strata, uplifts, and volcanic cones. Some canyons in the area attain depths of nearly 1,500 feet. Below the Big Bend country, the Rio Grande passes through a hilly section with broken terrain, narrow valleys, and broad high tablelands. After crossing the Balcones Escarpment, the river enters the Lower Rio Grande Valley.

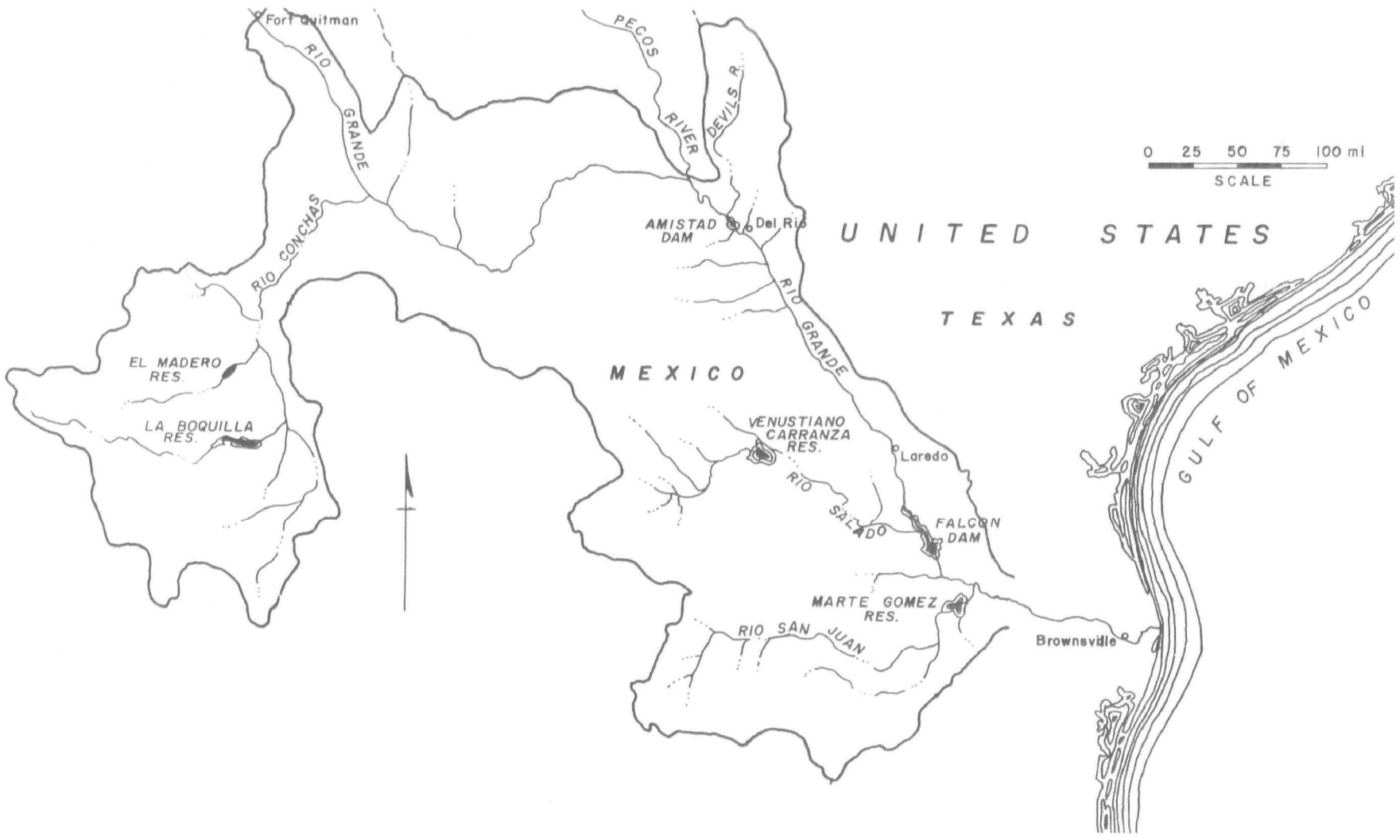

Figure 4: Lower Rio Grande

This valley extends about 100 miles upstream from the Gulf of Mexico and contains approximately 2 million acres of alluvial soil divided about equally between the United States and Mexico. It is a semitropical region which has mild winters and hot humid summers with a moderate rainfall of about 24 inches. Most of this rain falls in the early summer, making irrigation a necessity during the remainder of the year.

Five major streams join the Lower Rio Grande. About 70 percent of the water is contributed, together with several smaller streams, by three of them which originate in Mexico: these are the Conchas, the Salado, and the San Juan. The American tributaries, primarily the Pecos and Devils rivers, provide the rest. Consumptive use of the waters of the Lower Rio Grande has increased substantially in recent years. Some of this increase is due to irrigation development on the Mexican tributaries and some is due to flood control, especially Falcon Dam. The flow of the Rio Grande to the Gulf of Mexico below Brownsville prior to the construction of Falcon Dam averaged 2.6 million acre-feet: after the construction this flow has averaged about 0.6 million acre-feet per year.

Groundwater supplies provide a relatively minor part of total irrigation water; however, groundwater is used extensively when surface-water supplies are below normal. The major sources of groundwater in the region are the alluvial deposits in the river delta. This alluvial aquifer contains sizeable amounts of groundwater within a belt five to ten miles wide extending along the river and is recharged from surface drainage and seepage from the Rio Grande.

The lower valley was important in the eighteenth century as an outpost of Spanish colonizers. Reynosa and other settlements on the Mexican side were settled as early as 1749. The early settlers' attempts at growing irrigated crops were discouraged by intermittent drouths and river floods, and consequently ranching became the important activity. During the nineteenth century, the development of the valley by Anglo-Americans was stimulated by military activity and the area's strategic location on the Mexican border. The first major irrigation systems in The Lower Rio Grande were begun around 1905 by large land development companies.

Salinity — Salinity concentrations in the Lower Rio Grande are fairly constant above Falcon Dam. There is a concentrating effect below that point due to heavy consumptive use in irrigation. Some soil salinity problems have developed because of poor drainage, and this problem is expected to increase as improved irrigation management techniques are applied upstream.

SUMMARY

The Rio Grande system carries a large salt burden contributed by a variety of natural and man-made sources. Future developments will increase salinity concentrations. As salinity concentrations increase, adverse physical effects are produced which result in economic loss to the region. Additional research is necessary before adequate salinity control and management programs can be considered.

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Hydrologic Modeling for Salinity Control Evaluation in the Grand Valley

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ABSTRACT

The format and supporting information for a salinity control evaluation model for the Grand Valley is presented. The scope of the model, while developed specifically for application in the Grand Valley incorporates most of the general characteristics prevalent in irrigated agricultural areas. The objective of the model is a quantitative evaluation of a specific salinity management measure, and the comprehensive description of the ionic interchanges occurring in the soil profile has not been included.

In order to provide an additional degree of confidence in the results, the model has been designed to compare the quantities of ground water return flows through the subsurface aquifers computed by an analysis of the ground water characteristics to one using a mass balance analysis. Since both of these methods are not entirely independent, the adjustment of the model until both are predicting the same flows results in the measurable surface flows and the unmeasurable subsurface flows being complementary.

INTRODUCTION

The salinity problems associated with agricultural water use in the Grand Valley are being focused upon at the local, state, and federal level in an effort to reduce the downstream impacts. Although the need to implement effective salinity management programs in the valley is recognized, the most practical alternatives for accomplishing this requirement have not been entirely formulated. A major step in delineating the promise of available alternatives has recently been taken in the completion of the Grand Valley Salinity Control Demonstration Project. The purpose of the project was to examine canal and lateral linings as possible salinity control methods.

The evaluation of the effects of canal and lateral linings on the hydro-salinity flow system in the Grand Valley cannot be made independently of the various other factors which influence the flow system. Consequently, in order to substantiate the impacts of controlling one segment, all other phases of the hydro-salinity network must also be delineated and quantitatively

defined. This process of modeling the complete water and salt flow system involves the preparation of water and salt budgets.

A difficulty often encountered while preparing water and salt budgets is the variability in the accuracy and reliability with which the hydrologic and salinity parameters are measured. Usually the measurement precision varies with the scope of the research and the size of the locale. Because of these factors, it is helpful to the understanding of the results of an investigation if the techniques employed in computing the budgets and the simpliflying assumptions which are made are examined.

Since the hydrologic system is difficult to monitor and predict, it is impractical to expect their models to operate without some experienced adjustments. In short, the budgeting procedure is usually the adjustment of the segments in the water and salt flows according to a weighing of the most reliable data until all parameters represent the close approximation of the area. The vast and lengthy computation procedure of computing budgets is facilitated by a mathematical model programmed for a digital computer. For the purposes of this paper, the more important aspects will be extracted for discussion. A schematic diagram of a general hydro-salinity model is shown in Figure 1.

The hydro-salinity system of the Grand Valley can be divided into four general areas:

(1) Inflows representing the total water potentially available for use within the area and the dissolved minerals carried by the water. Included in this group are river, tributary, and ground water inflows, importations, and precipitation.

(2) Cropland diversions form the available supply of water diverted into the agricultural segment of the valley. From the main supply canals, small turnout structures are used to divert the water into small lateral ditches which lead to the fields.

(3) Ground water results from the seepage from canals and laterals and the water which deep percolates through the root zone into the water table region.

(4) Outflows are the flows which return to the river system or are lost to the atmosphere through evapotranspiration. Numerous routes are taken by the water to reach the river, including drainage and ground water return flows.

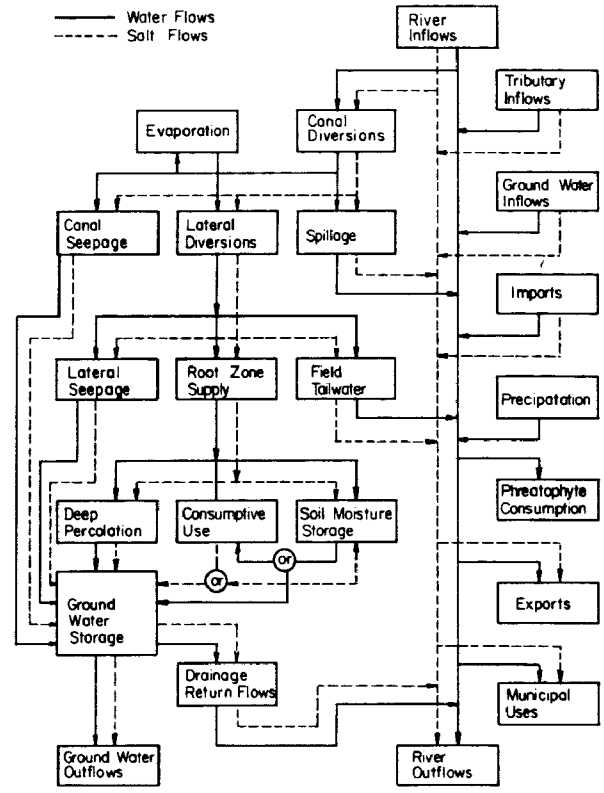


Figure 1: Schematic Diagram of Generalized Hydro-salinity Model

In the following sections, the aspects of these divisions are explored in greater detail to give a degree of insight into the real system which is to be modeled.

Inflows

River Inflows

The exclusive sources of irrigation water in the Grand Valley are the Colorado and Gunnison Rivers. Together, the two rivers represent an average combined flow of 6500 cfs from which large check type structures are used to divert the water into the principal supply canals. Owing to the increased development of the water resources in the Upper Colorado River Basin, the discharges in the rivers in the Grand Valley region are highly affected by transbasin diversions, reservoirs, power development, and irrigation. The Colorado River at the east entrance to the valley drains an area of about 8,050 square miles resulting in an average discharge of about 4000 cfs containing between

300 to 400 ppm of dissolved minerals. The river at this point also carries large sediment loads, especially during the high flow periods in the spring, which aids irrigation in the valley by reducing intake rates during the early growing season when smaller irrigations suffice. The effect of development upstream of Grand Valley is clearly noticeable in examining historical records. A large part of these conditions are related to the approximately 190,000 acres which deplete about 190,000 acre-feet of water annually from the river system (2). The Gunnison River Basin, while about the same size, uses about 350,000 acre-feet annually on about 270,000 acres. The resulting flow in the Gunnison River as it enters the Grand Valley is about 2500 cfs containing between 500 and 600 ppm of salts.

Tributary Inflows

Tributary inflows which are the ungaged water resulting from precipitation on the adjacent area in the valley, actually account for only a minor portion of the water passing through the Grand Valley. Aside from the estimated 60,000 acre-feet added by Plateau Creek, the estimated yield from the surrounding watershed is probably on the order of 55,000 acre-feet (2), (4), (5). The precipitation averages about 8 to 9 inches per year, and the intensity is usually low enough to allow the soils to simply absorb the water. The area is marked by natural washes, evidence that some periods of tributary inflows occur, but for the majority of the time, the flows in these washes are field tailwater and drainage return flows.

Imports

Importation of water from nearby mountain watersheds currently supplies the bulk of domestic demands in the valley although new treatment facilities have been built to use water from the Colorado River. In addition, several deep wells are used for domestic and commercial use. However, none of the water is used for irrigation as a rule because of the abundance of cheap river water.

Ground Water Inflows

Ground water inflows to the valley are essentially impossible to measure but should be accounted for in the water and salt budgets. Hyatt (4), using an electronic analog computer system model of the Grand Valley, indicated little or no ground water inflows to the region. His conclusion seemed well justified as both the rivers enter the valley through rocky mountainous channels.

Cropland Diversions

Canal Diversions

The source of the irrigation supply is the diversion into large canals by means of large check-type diversion dams. Distribution of the canal flows occurs in four ways: (1) diversions into the farm lateral system, (2) seepage, (3) spillage into wasteways, and (4) evaporation.

By using the natural washes as wasteways, the individual canal companies maintain regulation points along the system where control of downstream flows can be made. This practice has the advantage of being able to readily compensate for drastic events such as irrigation cutbacks due to foul weather or increased demands by periods of warmer weather. Even though this practice is not a desirable water management alternative, the long length between canal headworks and the end of the distribution system, along with the abundance of cheap water, make spillage the most employed regulation tool in the Grand Valley. One situation does exist where spillage is used to supply another segment of the system. The Grand Valley Canal spills water into what is known as Lewis Wash which is then diverted by the Mesa County Ditch. A noticeable consequence of this particular operation is the poorer quality of irrigation water being used by irrigators served by the Mesa County Ditch resulting from mixing the spillage with the drainage waters in the washes. The salinity being added to the spilled water throughout the valley is difficult to determine, but in the course back to the river system evaporation and phreatophyte consumption probably further concentrate existing salt concentrations.

Seepage from the conveyance channels enters the ground water basin directly and in the Grand Valley these flows complicate an already serious drainage problem. Most estimates of the

magnitude of the seepage losses range in the neighborhood of 20%, but considerable variability has been noted.

Lateral Diversions

The term lateral as used in this text refers to those small conveyance channels that deliver water from the company operated canals to the farmers fields. These small conveyance channels usually carry under 5 cfs, and range in size up to 4 or 5 feet of wetted perimeter. Since the lateral system in the Grand Valley is so immense, seepage from these small channels is probably much higher than from the canal system.

In a manner similar to the distribution of canal discharges, lateral diversions may be divided into four classes: (1) diversions reaching the crop root zone, (2) flows that are allowed to run off the ends of the fields during irrigation, otherwise known as field tailwater, (3) seepage losses, and (4) evaporation from the water surfaces. The nature of irrigation in the region is not conducive to efficient handling of water in the laterals as their lengths are so vast. Other factors influencing water management methods include the slope of the land, which is about 50 feet per mile in some places, and the inexpensive water supply. Numerous instances exist where laterals flow continuously with the water not being used in irrigation being simply dumped into the drainage system. A preliminary sampling of these discharges indicates some salt pickup from the soil surfaces.

Root Zone Diversions

The purpose of irrigation is to supply the root zone of crops with sufficient water to meet the evapotranspiration demands. During the process of crop water use, the dissolved minerals in the water are isolated resulting in accumulations occurring in the root zone which necessitates a leaching of these salts by an additional quantity of irrigation. There are often difficulties in irrigating farm lands because of the relative effects of the water on the plants. For example, when insufficient moisture is provided during critical growth periods, the reduction in production may be enormous. On the other hand, in most situations a small excess produces very little damage. As a result, the tendency is usually to over-irrigate. The consequences of over-irrigation, while not as severe to the farmer, are unnecessary fertilizer leaching, high water tables and drainage requirements, and large salt additions to the river systems.

The movement of water within the root zone is either lost to the atmosphere through evapotranspiration, or lost through deep percolation into the ground water basin below the root zone, or it may simply be stored within the root zone. The delineation of these flows by measurement is extremely difficult and is impractical on a large scale. Consequently, the procedure most often used is empirical computational methods.

Numerous methods of estimating evapotranspiration have been developed for agricultural lands. Probably the two most adaptable methods for the semi-arid western regions are the Blaney-Criddle method (4) and the Jensen-Haise method (6). The Blaney-Criddle method involves the determination of consumptive use as a function of mean monthly temperature and the percentage of daylight hours occurring during the month. The general equation can be expressed as,

$$U = (t \cdot p/100) \cdot (K_c \cdot K_t) \cdot (A)/12 \quad .. \quad (1)$$

Where U is the water use in acre-feet, t is the mean monthly temperature in degrees Fahrenheit, p is the yearly daylight hour percentage occurring during a month, K_t is a climatic coefficient expressed as,

$$K_t = 0.0173 \cdot t - 0.314 \quad ..... \quad (2)$$

K_c is the crop growth stage coefficient determined experimentally, and A is the acreage of a particular crop or phreatophyte.

The Jensen-Haise method was formulated from the evaluation of about 3,000 published and unpublished reports on short period measurements of evapotranspiration using soil sampling procedures during a 35-year interval in the western USA. The resulting equation is,

$$ET = K_c E_{tp} \quad ..... \quad (3)$$

in which ET is the evapotranspiration, K_c is a crop coefficient much like the Blaney-Criddle K_c value, and E_{tp} is the potential evapotranspiration in a well watered soil in a semi-arid area. The value of E_{tp} is computed by a relationship between air temperature and solar radiation,

$$E_{tp} = (0.014t - 0.37) \cdot R_s \quad ..... \quad (4)$$

where t is the temperature in degrees Fahrenheit and R_s is the solar radiation in Langleys.

In order to determine the magnitude of deep percolation losses and root zone storage, some simplifying assumptions must be made. Since vegetation is only capable of transpiring at its potential rate when the soil moisture storage is adequate, an adjustment based on the storage and irrigation supply whenever insufficient water is available must be made to the potential value. The measured values of canal and lateral diversions do not reflect the application on each field or each crop and so the assumption is made that the irrigation is made uniformly over the cropland. Thus, the water used from the root zone would only involve crop requirements and phreatophyte use would be from the moisture below the water tables. Evaluation of reported crop and soil characteristics in the area can be made to determine root zone depths and soil moisture storage capacity as they change with time (1), (3), (6), (8), (9). Once these parameters have been established for an area, a budget of root zone water can be made. The calculated total potential consumptive use is first compared with the total water added to the root zone from irrigation and precipitation. Three alternatives are assumed:

(1) If the supply to the root zone is less than the potential demand, but ample water is stored within the root zone to meet the deficit, then the use would be equal to the potential demand. Since the usual budgeting procedure is carried out on a monthly time interval, the next period of study would have an unused root zone storage that would be filled or supplemented with that period's supply. It has been assumed that whenever a deficit in root storage exists, no water is lost to deep percolation.

(2) If the sum of the supply and the available storage is less than the potential demand, the actual use is assumed to be the total quantity available. A term called consumptive use deficit is defined as the difference between potential demand and the actual use. Again, there would be no deep percolation.

(3) If the supply to the root zone is sufficient to meet the potential demand, the actual use would equal this demand. If the excess is sufficient to refill the soil moisture storage, the deep percolation would be the water above which is necessary to refill the soil moisture storage to field capacity.

An illustrative flow chart of this routine is shown in Figure 2.

Although the salt flow system is generally dependent upon the nature and magnitude of the water flows, the behavior of specific ions in the root zone and ground water basin are very complex. When the irrigation water is applied to the soils, the processes of ionic exchange, adsorption, and precipitation occur. The mathematical ability to describe these reactions has developed a long way, but in terms of evaluating the effects of a salinity control program, the expense necessary to collect sufficient data to operate such a comprehensive model is presently prohibitive. As a result, the modeling which has been done for evaluation in the Grand Valley has considered only the quantity of total dissolved solids as a parameter. In addition, the

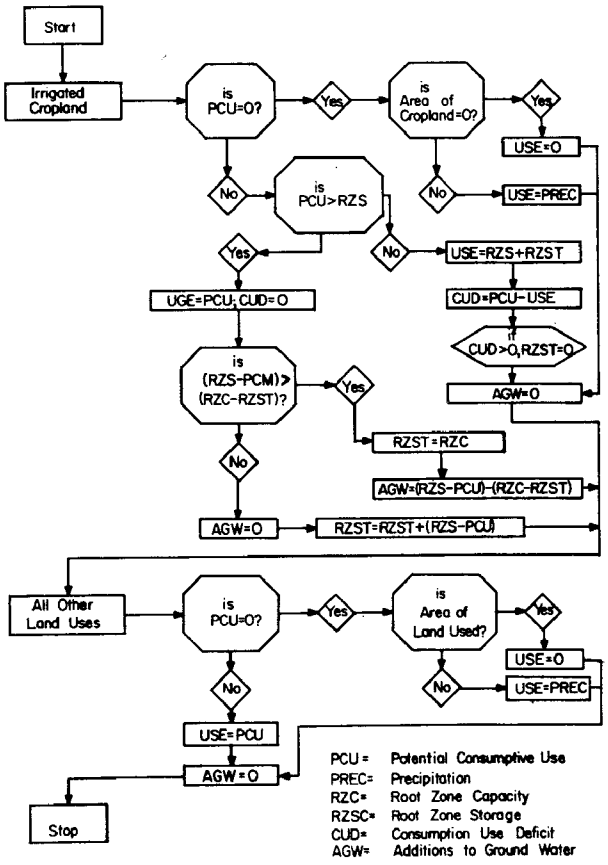


Figure 2: Illustrative Flow Chart of Root Zone Budgeting Procedure

root zone model has not focused upon the specific behavior of the various components of salinity.

These assumptions seem well justified in light of present technology. In the evaluation of a salinity control alternative, the results of the model should evaluate a net effect and predict in a quantitative manner the results of an expanded program.

Ground Water

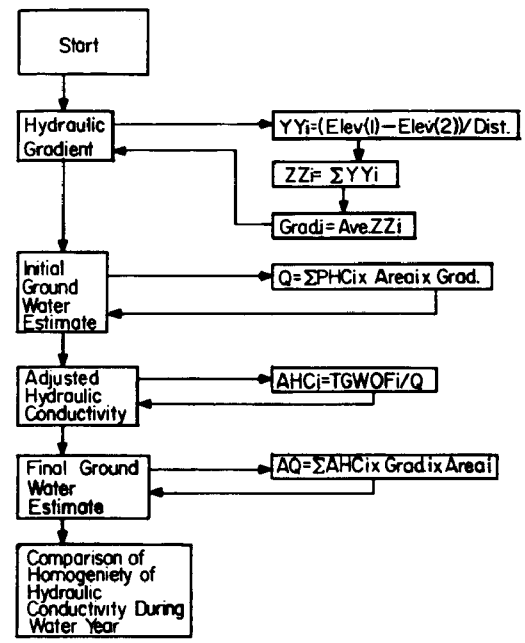
The discussion of ground water flows in this section is limited to those flows below the water table as the root zone discussion of the proceeding section involved the region above the water table. The ground water flows in the agricultural region are comprised of canal and lateral seepage as well as deep percolation. The hydraulic gradient resulting from the water inflows causes the movement of the water towards and into the river system.

The ground water discharges involve two phases: (1) drainage interception, and (2) subsurface outflows. Since the water table is often intersected by the drainage system, these flows are easily measured by flow measuring devices in these drains. The subsurface outflows cannot be measured, but with water table elevation data throughout the area, along with hydraulic conductivity measurements in the various subsurface strata, these flows can be reasonably computed. Even though considerable effort can be made to monitor the pertinent subsurface variables, the data usually obtained do not warrant a non-steady state analysis unless a ground water study is the specific objective of a project. For the purposes of this study, Darcy's steady state equation has been used, (7).

$$Q = AK\,(dh/dx) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

in which Q is the discharge, A is the cross-sectional area of the ground water flow, K is the hydraulic conductivity, and dh/dx is the hydraulic gradient in the direction of flow. During the course of the investigation, it was felt that the weakest link in the data collection was in determining the values of hydraulic conductivity; however, it seemed reasonable to assume that the relative magnitude of conductivity between one strata and another could be determined with reasonable accuracy. With this type of data, it is possible to formulate two independent methods of calculating the ground water flows and thus increase the hydrologic budgeting procedure accuracy by forcing an alignment between the two methods.

The ground water analysis illustrated in Figure 3 involves the comparison of the ground water outflow based on a mass balance arrived at



i =Refers to Its Strata
Grad. =Hydraulic Gradient
Q =Computed Ground Water Outflow
PHC =Field Values of Hydraulic Conductivity
AHC =Adjusted Values of Hydraulic Conductivity
TGWOF=Total Ground Water Outflow from Mass Balance Analysis
AQ =TGWOF

Figure 3: Illustrative Flow Chart of Ground Water Modeling Procedure

through a general budgeting procedure (inflow equals outflow minus storage changes) and computations of outflows based upon measured gradient and conductivity data. Because the model only uses relative magnitude of strata hydraulic conductivity, the values are adjusted on their relative proportion until each value of monthly ground water outflow is consistent between analyses. Then the variability of the computed values of conductivity is examined. If they become homogenous, the model represents the "best fit" between all monitored data. The computation of ground water outflow based on Darcy's equation for a number of strata can be written:

$$Q = A_1 K_1' \frac{dh_1}{dx_1} + A_2 K_2' \frac{dh_2}{dx_2} + \ldots + A_n K_n \frac{dh_n}{dx_n} \quad \ldots\ldots (6)$$

where A_n is the area of the nth strata, K_n' is the hydraulic conductivity of the nth strata, and dh_n/dx_n is the hydraulic gradient acting on the nth strata. Occasionally when no confining layers exist, the hydraulic gradients would be the same for each strata; however, in the Grand Valley an underlying cobble aquifer is partially confined and this condition does not exist. The value computed from Eq. 6 will generally not be comparable in magnitude to the expected values determined from the mass balance analysis because no need exists to keep the measured values of conductivity in proper units. Usually, conductivity is determined in in/hr, while the ground water outflows will be in acre-feet/month. To avoid confusion, these inconsistencies are compensated for in the adjustments. In addition, it is often difficult to evaluate the respective strata areas accurately. Consequently, a representative thickness can be determined and then a convenient unit width selected for the computations. If this practice is used the flows will be altered, but the adjustment can be absorbed in the adjustments to hydraulic conductivity. The adjustments to the field hydraulic conductivity measurements can be made as indicated:

$$K_i + (TGWOF \cdot K_i')/\text{value of discharge obtained from Eq. 6} \quad \ldots\ldots\ldots\ldots\ldots (7)$$

where K_i is the adjusted hydraulic conductivity, TGWOF is the ground water outflow estimate from the mass balance analyses, and K_i' is the field measurement of hydraulic conductivity.

In summary, the computational procedure for evaluating ground water flows is as follows:

(1) From field data collected on hydraulic gradients and conductivities, along with physical dimensions of the system, a value of ground water discharge can be computed using Darcy's equation.

(2) Comparison of the values obtained in Step (1) with the estimates of ground water outflows based on a mass balance analysis is used to adjust the field values of conductivity according to their relative magnitude until both methods of computing discharge agree.

(3) Compare the monthly values of adjusted hydraulic conductivity for homogeneity. If the values are found to be in error, all parameters in the hydro-salinity model are not aligned and further adjustment of various budget factors is necessary.

Outflows

The water leaving the Grand Valley, aside from evapotranspiration, includes the river outflows and ground water flows occurring beneath the gaging station. Another common form of regional outflow is exportation, but in the Grand Valley none of these flows exists.

River Outflows

The Colorado River exits from the Grand Valley in the western end with a mean annual discharge of about 6,500 cfs and a salt load of about 900 parts per million of total dissolved solids. The resulting salt contribution from the Grand Valley during most normal water years varies between 0.7 and 1.0 million tons.

Ground Water Outflows

The estimated discharge under the exit gaging station operated by the U.S. Geological Survey is shown to be small in comparison to the river flows, (4). However, the reliability of this type of an assessment should be questioned in light of the difficulty of monitoring the exact effect of the Grand Valley within acceptable accuracy.

Hydro-Salinity Model

The vast computational requirements requisite to formulating water and salt budgets, often called hydro-salinity modeling, is best facilitated by digital computers or, as in the case of Hyatt (4), by electric analog systems. The model formulated for evaluating the salinity control effects of canal and lateral linings in the Grand Valley is also somewhat general, so it is helpful to examine the computer framework under which it was formulated.

Model Operation

The mathematical model derived for this study attempted to simulate the hydrologic con-

ditions of the agricultural system in the Grand Valley, but the concepts are general and can be extended with modification to other areas which are similar in nature. The program was written in individual but interconnected subroutines which give the program a measure of flexibility during operations by separating the calculation phase from either input or output. By structuring the program in this manner, several of the subroutines become optional if their functions can be replaced by input data, or if certain outputs are not desired. This general nature of the program is illustrated in the schematic flow chart shown in Figure 4 with name and functions defined in Table 1.

The main portion of the program is used to read necessary input data and to control the order of budget calculations. There are certain advantages in separating the input, output and computational stages of a program, including:

(1) Input order is not important as the data are completely available at all stages of computation.
(2) Variable sets of data can be utilized in the model when several budgets are desired, or when some form of integration is desired. This is useful especially when an area can be broken down into smaller dependent areas.
(3) The functions of the subroutines are independent of input making each a unit that can be implemented in other programs.

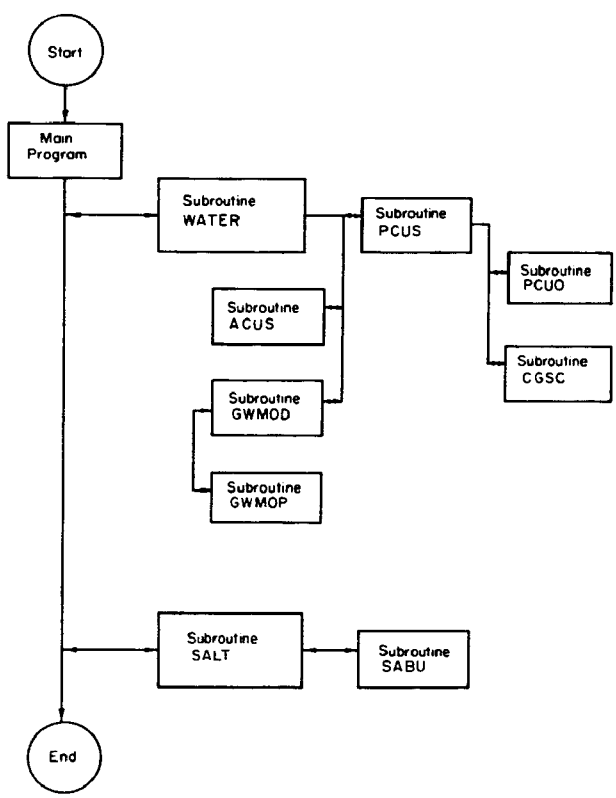


Figure 4: Schematic Flow Chart of Hydro-salinity Model

TABLE 1

Hydro-salinity model subroutine descriptions

Subroutine	*Description*
WATER	Computation of monthly and annual values of the water budget. Relatively little independent data is generated by WATER directly, since it functions primarily as a summary.
BUDO	Outputs data generated from WATER as the water budget.
PCUS	Computation of monthly and annual value of potential consumptive use for irrigated crops, dryland crops, municipal uses, industrial uses, open water surfaces, and phreatophytes.
PCUO	Outputs data generated in subroutine PCUS.
CGSC	Outputs values of crop growth stage coefficients.
ACUS	Computation of the estimated actual consumptive use and the various root zone parameters.
GWMOD	Computation of the discharges through the ground water model and adjusted strata hydraulic conductivities. When these values of conductivity approach equality, the ground water outflows are correct.
GWMOP	Output of ground water model computations.
SALT	Computation of the salt budget for the area.
SABU	Output of salt budgets.

(4) Corrections and adjustments are easily made without detailed consideration to other segments of the program.

In controlling the computational order of the program, the main program separates the calculation of the water and salt budgets. Consequently, the modeling procedure involves only the water phase of the flow system. This has been possible in this study because of the detail in which data have been collected. Once the water flow system has been simulated, the individual flows are multiplied by measured salinity concentration and converted to units of tons per month. At this point in the formation of the budgets, careful attention must be given to the salt flow system since irregularities may be present and further model adjustment is necessary. Thus, when the final budgets have been generated, the salt system, ground water system, and surface flow system must be reasonably coordinated and additional reliability is assured.

SUMMARY

The evaluation of specific salinity management schemes in the Grand Valley involves the development of models which detect and predict the quantitative effects of the program. Such a modeling effort encompasses an evaluation of the hydro-salinity system and thus indirectly evaluates the potential impacts of other possible measures.

The current hydro-salinity model for the Grand Valley is only the first step in salinity control evaluation. While its purpose has been to simply establish effects, future models should incorporate greater detail of the behavior and specific interactions of the salinity flow system in order for more comprehensive predictions of capabilities. The next development in Grand Valley modeling must not only be capable of evaluating the impact of a salinity control measure, but also to indicate its influence in a correlated program involving a broad variety of alternative salinity management alternatives.

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Sediment Control in Yakima Valley

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ABSTRACT

A study of irrigation return flows in the Roza Irrigation District in the Yakima River Basin in central Washington was initiated during the 1971 irrigation season to evaluate methodology for sediment removal from drainage waters and provide some assessment of the costs and benefits of sediment control.

Water management in furrow irrigation regimes has a significant effect on sediment concentration, nutrient content and overall water quality of return flows from such systems. Sediment concentrations in return flows under the best managed furrow irrigation systems did not meet the water quality standards for turbidity for streams of the region. Some treatment for sediment control will therefore be necessary.

Sedimentation basins alone leave much to be desired in treating return flows for subsequent discharge to streams since only a fraction of the sediment is removed by such treatment and the discharge waters still contain turbidities in excess of water quality criteria. Other alternatives alone or in conjunction with sediment basins will be needed to meet the water quality criteria.

INTRODUCTION

Sediment in streams and reservoirs is neither a new problem nor one which is peculiar to any one location in the country. However, it is becoming an increasingly important problem in many areas of the Northwest from the standpoint of potential impact on recreation and fish life, on clogging of channels, on eventual reduction of reservoir storage capacity and on the cost of treating water for subsequent use.

Sediment is sometime referred to as inert solids carried in suspension by water. Considerable evidence is available to indicate that most sediment in agricultural runoff is certainly not inert material but surface active particles which serve as adsorbing and transport media for toxic and nutrient chemicals, some radioactive materials and some pathogens.

Agriculture, in addition to its role as the largest single consumptive user of water, is a major source of sediment pollution. Therefore it has been reasoned that the ideal approach to control of sediment pollution would be through use of proper land management practices. Soil and water conservation methods can and do reduce the quality of sediment reaching waterways, but the realization of widespread effective implementation of land management techniques for the purpose of pollution control is unlikely until sufficient legal and/or economic motivation for such practices is provided. However, the technological groundwork should be laid now for eventual curtailment of sediment pollution,

especially in view of the efforts already underway to abate pollution from municipal and industrial sources.

Nature of the Problem

Control at the source seems to be the most feasible approach to curtailment of sediment pollution. Prevention by means of better water and land management practices would undoubtedly be the optimum method of combating sediment pollution arising from agricultural and urban regions. Until such practices can be promoted, interim measures are required to alleviate the existing situations in some problem areas.

A case in point is the situation which exists in the Yakima River Basin in southcentral Washington. This region is devoted almost entirely to agriculture and is one of the more extensively irrigated regions in the western United States. Irrigation constitutes such a major water use that irrigation return flow comprise nearly the entire summer flow in the lower eighty miles of the river. A study by Sylvester and Seabloom[1] indicate that irrigation return flows are the major factor influencing overall water quality of the Yakima River.

Sediment pollution has become an ever worsening problem in downstream diversion canals and in the Yakima River itself. Canal water receiving irrigation return flows often carries such a heavy sediment load that untreated water is unsuitable for irrigation. Some farmers have constructed silting basins in an attempt to remove enough of the particulate matter to render the water fit for use. However, only a portion of the sediment can be removed and the remainder still causes serious problems in pumps, sprinkler heads and pipes. It is ironic that, because of sediment pollution and the associated problems, many farmers are reluctant to convert from furrow to sprinkler irrigation. At the same time, total conversion to sprinkler irrigation would be a major step toward alleviating sediment pollution.

Economic consequences of sediment pollution are now being felt by cities and counties throughout the Yakima Valley. Benton County, located in the lower region of the Valley, spends upward to $50,000 per year to remove sediments from road ditches and bridge approaches. City residents are faced with the task of replacing sprinkler heads and flushing pipelines day after day when using irrigation water to keep lawns green and gardens blooming. Pumps have to be torn down and cleaned and city officials are faced with the never-ending task of hauling silt from flush points in the city irrigation system. Coupled with impaired recreational and aesthetic values, public reaction against sediment pollution in the Yakima Valley has reached the point where interim measures are needed to combat the existing problem until improved water and land management practices can be implemented.

Sediment Studies

A preliminary study of irrigation return flow characteristics in the Yakima Valley was initiated in 1971 to evaluate the feasibility of sediment removal from drainage waters and to provide an assessment of the costs and benefits of sediment control.

The study was aimed at determining the kinds and amounts of sediment entering drains from selected agricultural watersheds and evaluating methodology for removing these sediments from drainage waters prior to their entry into streams.

The study was conducted in the Roza Irrigation District of the lower Yakima Valley on three separate drainage basins, each representing a different concept of water management in a similar geographical region. Each drainage unit was relatively small, representing from one to three land owners with a total area of from 200 to 400 acres. Duration of the study was from the beginning of one irrigation season in spring until surface flow ceased following the final irrigation in late summer.

The study included obtaining information on water intake and return flow; on area devoted to various classes of crops; and on the use of fertilizers for each crop. It involved field measurements of intake and drainage water temperature, and collection of water samples on a biweekly basis for determination of suspended solids, turbidity, COD, ammonium and nitrate nitrogen, total and soluble phosphate, chloride, electrical conductivity and an occasional analysis for coliform bacteria. The water sample to be analyzed was immediately cooled and maintained at a few degrees above freezing until

analysis was completed. Nutrient and microbial analysis were completed within 2 days of sample collection.

Quantities of suspended sediment from each drainage outlet were characterized as to particle size, mineral composition, nutrient content and adsorption, light scattering ability (turbidity potential) and settling rates. Flocculation and sedimentation studies were conducted to measure the effectiveness of chemical flocculation and coagulation with neutral salts and/or synthetic polyelectrolytes as a means of sediment removal in agricultural waters.

Description of Study Area

Eight sampling stations on farms within the three drainage units were selected as representing the inflow and return flow water quality characteristics for the study areas.

Stations A-1, A-2 and A-3 are located within the unit designated as Drainage A occupying an area of approximately 300 acres with 80 percent being classified in the Irrigation Capability Class II representing medium textured soils on slopes of less than 2 percent gradient[2]. The sampling stations were selected to allow measurement of water quality of the irrigation water supplied to the basin; of the return flow leaving the basin; and of the return flow from one individual field of sugar beets. This basin represented a unit where excellent water management practices were carried out on land ideally suited for surface irrigation.

Stations B-1 and B-2 represents inflow and return flow characteristics of a drainage unit similar in size to drainage A but representing significantly different water management practices. Only 20 to 30 percent of the area within Drainage B falls in the Irrigation Capability Class II, the remaining being classified as Class III and IV, representative of medium textured soils on slopes of greater than 2 percent. This unit represents water management practices where operators apply significantly more water to similar crops on land less than ideally suited for surface irrigation.

Drainage unit C is a 200 acre unit similar in soils and topography to unit B but where all the surface drainage water from the unit is treated in a large sediment basin having a detention time of approximately 2 hours prior to discharge to adjacent canal. Station C-1 represents inflow water to the unit while stations C-2 and C-3 were located at the inlet and outlet of the sediment basin to assess the effect of such basins on the overall water quality of return flows.

Irrigation in all units was by furrow application with crop rotations consisting of field crops (sugar beets, mint and potatoes) five years out of six and cereal grains to complete the rotation.

Intake of water (diversion from the Roza Canal) for use on the irrigated units averaged about five and one-half feet depth during the six months from April to September. An additional three to four feet of water were applied to units B and C from a drainage source adjacent to the units. An equivalent of about two feet depth was discharged from unit A and five to 6 feet depth discharged from units B and C as return flow in the drains.

There is no way to estimate influent or effluent seepage and there is some inherent error in the flow measurements, so that the inflow-return flow balance may be of question although it was considered sufficient for the purpose of this study.

Return Flow Characteristics

Average values for the water quality parameters measured throughout the irrigation season are presented in Table 1. Inflow quality characteristics were sufficiently uniform such that the three stations A-1, B-1 and C-1 were compiled together and reported as applied water.

From the values shown, it is evident that water and land management factors do have a significant influence on quality parameters of irrigation return flows. However, at this point the relationship is not clear due to the large variations in many of the measured parameters. Much of the variation noted in Table 1 is related to the range in suspended solids concentration and the related parameters of turbidity, COD and total phosphorus from each drainage unit. This reflects the inherent difficulty of sampling watersheds for sediment discharge since many factors affect the suspension, transport and deposition of sediment from the point of origin to the place of sampling.

It is evident that furrow application of irrigation water does have a significant influence on

TABLE 1
Irrigation and Return Flow Water Quality Average of Biweekly Sampling for Irrigation Season

Station	*Temp*	*NO_3-N*	*Soluble PO_4-P*	*Total PO_4-P*	*COD*	*Total Salts*	*Suspended Solids*	*Turbidity*
	°C	(			mg/l			) JTU
Applied Water	19.4	0.2	0.1	1.1	8.8	70	91	29
A-2	25.5	0.4	0.5	34.2	162.2	70	7850	2500*
A-3	20.0	0.4	0.3	22.6	64.2	74	2800	900*
B-2	22.2	2.5	0.3	16.1	24.0	79	751	250*
C-2	20.0	0.6	0.3	34.8	75.8	79	3350	1300*
C-3	19.3	0.4	0.3	23.2	26.8	83	770	400*

*approximate values due to high concentration of suspended solids.

the water quality of surface drains. Water returned from furrow application is greatly enriched compared to its quality incoming. The principal degradation relates to increases in suspended solids and the related parameters of turbidity, total phosphorus and COD.

Treatment of return flows in sedimentation basins affords considerable removal of suspended solids and related contaminants as noted from sampling stations C-2 and C-3. From a water quality standpoint, such treatment leaves much to be desired in treating water for subsequent discharge to streams since water discharged from the basin still contained turbidity values of over 400 JTU units and total phosphorus concentrations of over 20 mg/1. Such values are far in excess of what is recommended for discharge to Class B waters of the region[3].

Sediment Control Measures

Much of the sediment carried in irrigation return flows in the Yakima Valley never reach the river or major canals but are deposited adjacent to the field of origin or in the small drainageways serving individual or small groups of operators. This does not negate the significance of the problem, however, since sediment in transport depletes the land resource from which it comes and sediment deposition creates unsightly and troublesome accumulations of material in nearby drains and structures and may be quite costly to the downstream operator. The fraction of fine material not deposited in adjacent structures may still be of such nature to create substantial water degradation in the major rivers and canals.

With improved soil and water management, sediment yields in the Yakima Valley can be reduced but it is virtually impossible to reduce erosion in furrow irrigation systems to the extent that sediment and related contaminants in return flows will meet water quality standards recommended for the region. To irrigate most efficiently, water must be applied uniformly to all parts of the field. With surface irrigation it is impossible to irrigate every spot uniformly, but present techniques will permit operators to approach this ideal. In practice, the irrigator finds that the rate of irrigation for proper application varies from irrigation to irrigation and from year to year. Soil characteristics, cultivation, moisture, crop, climatic and many other conditions all influence the water intake rate of the soil. This variability probably causes the irrigator the greatest difficulty and requires an excess of water to be applied to offset intake rate variances within the field. With such water application where the soil is necessarily a medium for transporting water to other parts of the field, suspension of particles is an inevitable result of such a system.

As a practice which greatly reduces the load of sediment in drainage waters, sprinkler irrigation is finding increased favor in the Yakima Valley. One of the greatest advantages of the sprinkler irrigation method is that it overcomes

the difficulty of varied intake rate since the water is applied at a design rate somewhat lower than the intake rate of the soil. The water management problem is greatly simplified and little or no surface return flow occurs. One deterrent to conversion to sprinkler irrigation in the Yakima Valley, in addition to the cost involved, is the problem of sediments in the supply water currently available. Plugging of sprinkler heads, abrasion of pipe and wearing of pumps will be a major problem where surface and sprinkler systems are being operated simultaneously.

One alternative to conversion to sprinkler systems would be the installation of basins or ponds to intercept and collect drain waters for return to the head ditch with no external surface discharge. The same problems of pump and pipe abrasion, channel clogging and basin sedimentation would still be inherent to this system but would have the effect of requiring each operator to treat the problem which his individual operation creates and would probably make many operators take a close look at the efficiency and management of his irrigation system.

It appears to be most impractical to construct sediment basins with sufficient detention time for natural settling to produce waters meeting recommended quality criteria. Detention times in the order of two to three days would be necessary to produce waters of less than 50 units of turbidity for drainage waters of the lower Yakima Valley. Considerable reduction in basin capacity can be achieved by the use of chemical additives in conjunction with sediment basin to create forced settling of suspended solids.

Some preliminary studies have been conducted with a great number of synthetic organic polyelectrolytes and several inorganic salts to determine the effectiveness of each in facilitating sediment flocculation and removal. The results of the best of each type of chemical are shown in Figure 1. The results are reported as percent turbidity removed versus dose rate after a one hour settling period following chemical addition. The sediment size fraction used in this study was the less than 0.05 mm diameter particles which account for approximately 70 percent of the total suspended load in return flow waters. Some of the cationic and non-ionic polymers at dose rates less than 1 mg/1 appear to be as effective as the standard flocculants at dose

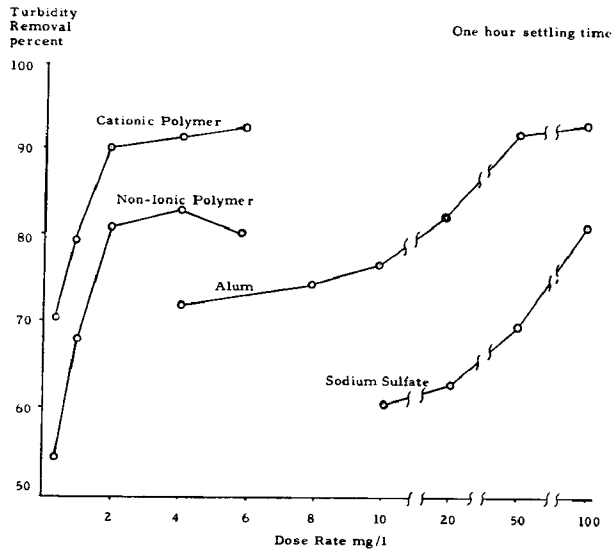

Figure 1: Percent Turbidity Removed by Chemical Flocculants

rates up to 100 mg/1. The cost of chemical application for flocculation and sedimentation appear to be prohibitive at this stage but studies will continue to evaluate the cost of application as well as the total effects on water quality.

SUMMARY

Sediment pollution has become an ever worsening problem in downstream diversion canals and in the Yakima River itself. Canal water receiving irrigation return flows often carry such a heavy sediment load that untreated water is unsuitable for sprinkler irrigation. Coupled with impaired recreational and aesthetic values, public reaction against sediment pollution in the Valley has reached the point where interim measures are needed to combat the existing problem until improved water and land management practices can be implemented.

Treatment of drainage waters in sedimentation basins does afford considerable removal of suspended solids, total phosphorus and COD from such waters. From a water quality standpoint, such treatment leaves much to be desired for discharge to streams since waters discharged from the basins still contained turbidity values in excess of 400 JTU units and total phosphorus concentrations of over 20 mg/1.

To produce return flow waters meeting the recommended quality criteria, established by the Washington State Department of Ecology, other alternatives to natural settling must be implemented. These alternatives appear to be:

1) installing practices which greatly reduce the load of solids in drainage waters (sprinkler irrigation for example); 2) use of basins as interception ponds to collect drain waters for return to the head ditch with no external discharge; or 3) use of chemical additives in conjunction with settling basins to create forced settling of solids and reduce detention time requirements. Each or some combination of these or other management programs may be needed, but implementation should be initiated soon in view of the efforts already underway to abate pollution from non-agricultural sources.

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Treatment of Irrigation Return Flows in the San Joaquin Valley

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ABSTRACT

Agricultural tile drainage in portions of California's San Joaquin Valley must be disposed of because of their brackish nature. It is planned to collect this tile drainage and dispose of it in the San Francisco Bay System. The only constituent of the tile drainage that might create problems in the receiving waters is nitrogen. The nitrogen is essentially all in the nitrate form.

Two methods of nitrogen removal were studied and found to be feasible. These are bacterial denitrification and algal production and harvesting (algae stripping). Operating conditions, design criteria and costs were developed for both methods. Denitrification was studied both in deep ponds and packed columns.

Denitrification reduced the nitrate concentration from 20 mg/l to less than 2 mg/l throughout the year. It was necessary to add organic carbon to the process to achieve this efficiency. Algae stripping reduced the nitrate concentration from 20 mg/l to 2 to 4 mg/l depending on the time of the year.

Studies are now being conducted of a symbiotic method of nitrogen removal. This method combines algae or plant growth and bacterial denitrification in one pond. Preliminary results indicate that cost of the symbiotic method may be one-quarter to one-third the cost of either bacterial denitrification or algae stripping.

Studies are also now being conducted on the use of reverse osmosis techniques for desalination of the tile drainage. If the reverse osmosis studies are successful, the complete reclamation process will be studied in pilot scale. This will include boron removal and brine disposal.

INTRODUCTION

In recent years an ever increasing emphasis has been placed on nitrogen removal techniques, both for reasons of public health and the control of eutrophication. The subject studies were instituted because of the possible eutrophying effect of the discharge of large quantities of agricultural tile drainage into the San Francisco Bay System. The tile drainage to be disposed of results from the irrigation of large portions of California's San Joaquin Valley that have been classified as drainage problem areas

This paper was presented at the National Conference on Managing Irrigated Agriculture to Improve Water Quality in Grand Junction, Colorado, May 16-18, 1972.

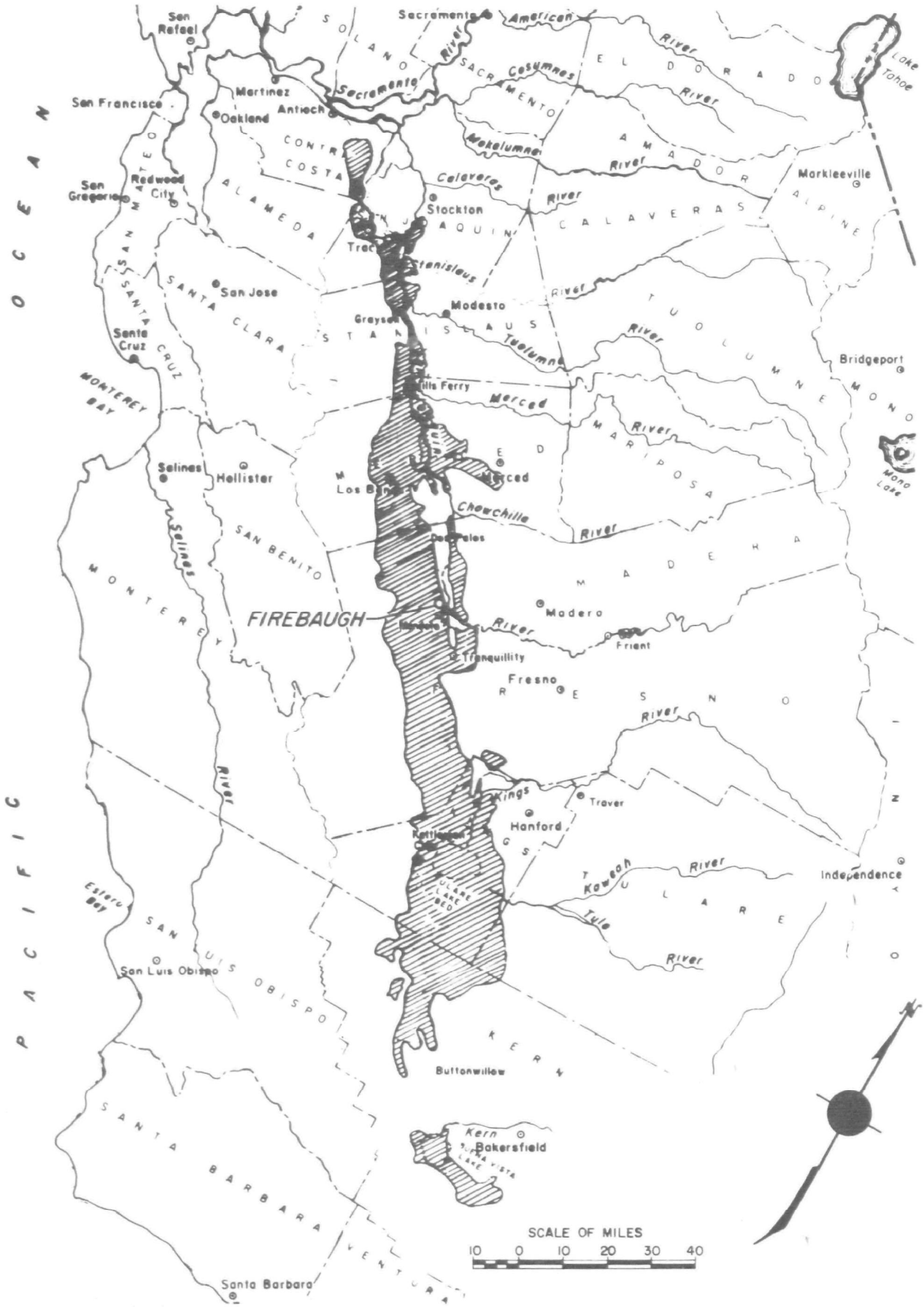

Figure 1: Existing and Potential Agricultural Waste Water Disposal Problem Areas. San Joaqui ı Valley-California

(Figure 1). Of the over 7 million acres (2.8 million ha) of irrigable land in the Valley, approximately 1.7 million acres (0.7 million ha) have been classified as existing or potential drainage problem areas — lands where brackish high water tables have or will become a problem[1].

Most of the saline agricultural wastewater that is presently being generated within the Valley is discharged to the San Joaquin River. As the quantity of this waste increases, due to the increased availability of water for irrigation, the waste load on the river would reach a point where downstream users would be deprived of a usable water supply.

For this reason, a system is now under construction to collect much of the saline drainage and transport it from the Valley. The system will serve 300,000 acres (120,000 ha) of the drainage problem area. It is being built by the U.S. Bureau of Reclamation (USBR) to handle primarily the wastewater from the Federal San Luis Service Area. California's Department of Water Resources (DWR) is also aware of the drainage problem and is making plans to serve those areas outside of the Federal San Luis Service Area. The predicted quality of the waste to be carried by the San Luis Drain is presented in Table 1[2]. It is estimated that by the year 2000 there will be 500,000 acre-feet (6.2 x 10^8-cu m) of tile drainage to be disposed of annually. (This is only about 4 percent of the water to be applied to the Valley in the same period.) The peak flows, during the summer irrigation season, are expected to reach 700 mgd (2.65 x 10^6 - cu m/day).

Prior to the study reported herein, the DWR and USBR had investigated disposal of tile drainage for several years. Of all the alternatives studied, they concluded that the most economical and safest method of disposal would be a gravity concrete-lined canal, or drain, that would discharge into the upper reaches of San Francisco Bay[3]. They further concluded that the only major constituent of the drainage that could create problems in the receiving water is nitrogen. A 1967 Environmental Protection Agency (EPA), then Federal Water Pollution Control Administration (FWPCA), study of water quality problems which could result from the drainage water concurred with the earlier study[4]. The FWPCA concluded that problems would not occur if the nitrogen content of the subject waste could be reduced to 2 mg/l or less.

The DWR, USBR, and FWPCA joined together to determine if a method of nitrogen removal for tile drainage could be developed or if the costly alternative of ocean disposal would have to be adopted. In order to evaluate possible methods of nitrogen removal under field conditions, the Interagency Agricultural Wastewater Treatment Center was established. It is located near Firebaugh, California (40 miles west of Fresno) in one of the existing drainage problem areas. This paper presents a comparison of the various treatment methods studied at the Center.

Treatment Techniques

Ninety-five percent, or more, of the nitrogen in tile drainage is in the nitrate form. Therefore, the problem of reducing the nitrogen content of tile drainage becomes one of removing nitrate-nitrogen. Two basic methods of nitrate removal were investigated: bacterial denitrification, and algal biomass production and harvesting (algae stripping). Bacterial denitrification was studied in both anaerobic filters and deep ponds. A symbiotic method (combination of photosynthetic and bacteriological in one pond) of nitrogen removal is now being studied. In addition to the nitrate removal studies, desalination is being studied at the Treatment Center.

Bacterial Denitrification

Bacterial denitrification is a process in which bacteria utilize highly oxidized anions for the oxidation of organic matter[5]. The overall process can be expressed stoichiometrically, as a two-step or three-step reaction. Nitrate (No_3^-) is reduced to nitrite (NO_2^-) and then from nitrite to molecular nitrogen (N_2) with or without the intermediate formation of hyponitrite (N_2O_2). The process can be shown to be thermodynamically sound (capable of producing energy for organisms utilizing it)[6]. Several commonly occurring facultative bacteria are denitrifiers, for example, *Bacillus brevis*[1]. The occurrence of bac-

[1]One of the three bacteria of the *Bacillus* genus which are cultured commerically to produce polypetide-type antibiotics.

terial denitrification in existing sewage treatment plants is well documented and several pilot-scale units have been built and successfully operated for denitrification[7,8,9,10]).

Unless biodegradable organic material is present in adequate quantity, effective denitrification will not take place. Most agricultural tile drainage has a low organic content. Therefore, methanol was added to the waste prior to entry into the anaerobic filters and deep ponds operated at the Center[11].

The main factors, with regard to bacterial denitrification, requiring study were: the general feasibility of the process, detention time, methanol requirement, and operating efficiencies under field conditions.

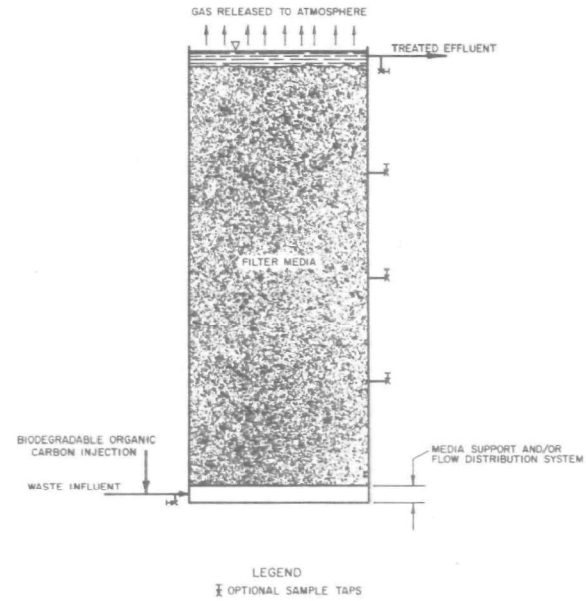

Figure 2: Schematic Diagram. Upflow Anaerobic Filter Denitrification Process

Anaerobic Filters

In the anaerobic filter the waste is passed through a packed column-type reactor (a vessel containing an inactive medium). The filter medium provides a solid support for the denitrifying bacteria. The advantage of the filter is that the solids retention time of the unit is longer than the hydraulic detention time and, therefore, there is no need for the recycling of solids[12]. Anaerobic filters can be operated with upflow or downflow configurations, as long as the unit is kept anaerobic (or nearly so). All of the filters operated at the Center have been upflow units (Figure 2).

Four different sizes of anaerobic filters have been used: 4-, 18-, and 36-inch (10-, 46-, and 91-cm) diameter[13] and 10-feet by 10-feet (3-m x 3-m) square. The 10-feet by 10-feet filter has a false bottom (of the type used in water treatment rapid sand filters) with an 8-inch (20-cm) plenum and a 6-foot (1.8-m) bed depth. The primary purpose for building this filter was to investigate the effect of scale-up on process efficiency due to changes in the hydraulic regime.

Deep Ponds

The feasibility of bacterial denitrification in deep ponds under field conditions was determined in 3-foot (0.9-m) diameter simulated deep ponds[14]. Once the process was shown to be feasible, two large ponds were constructed as shown schematically in Figure 3. The larger of the two ponds constructed at the Center is 200 x 50-feet (61-x 15-m) and has a floating cover. The smaller pond is 50-x 50-feet (15-x 15-m) and is not covered. Both ponds are approximately 14-feet deep (4.3-m). Through the parallel operation of these two units, it was possible to evaluate the significance of wind mixing, and algal growth on process efficiency. The solids retention time and hydraulic detention time are the same, therefore, the controlling parameter in pond operation is the regeneration time of the bacterial population. To increase the solids retention time, recycle is necessary. If an adequate residence time is not provided, effective denitrification is not maintained.

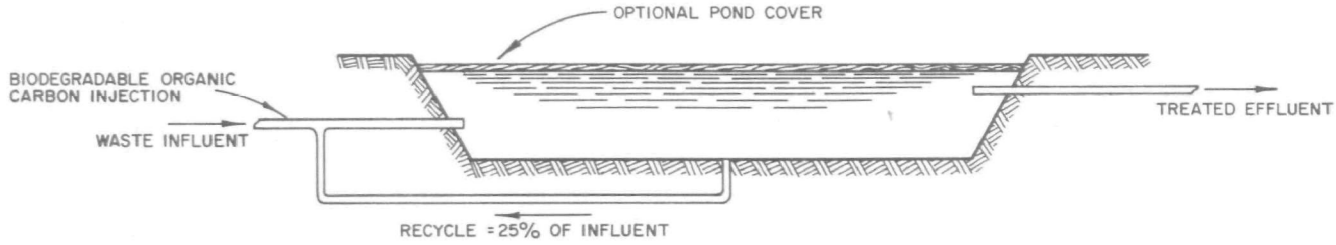

Figure 3: Schematic Diagram. Deep Pond Denitrification Process

Algae Stripping

Research on the treatment of domestic and industrial wastes in photosynthetic systems has been studied for a number of years[15]. As a result of the findings of such studies, it has become apparent that nutrients are assimilated by algal cells in significant amounts and, hence, are removed as part of the operation.

Figure 4 is a schematic diagram of algae stripping. It is immediately evident, upon observing any ponded tile drainage, that algae definitely grow in this type of waste. The main problem in the process is not the mere growing of algae, but the optimization of growth factors to maximize their nitrate uptake rate. Some of the factors that must be investigated before the algal growth system could be evaluated were: growth pond depth, hydraulic detention time, recirculation, mixing, pH, and nutrient addition. All of these factors must be optimized before a photosynthetic system can be designed. Once the algae have been grown; the problem of separating them from the waste becomes paramount. Flocculation, sedimentation, flotation, and microscreening are all processes that were evaluated to determine the least costly technique.

Three types of growth vessels were used at the Center: a light box, small-scale growth ponds (miniponds), and a 1/4-acre (0.10-ha) large-scale rapid growth pond[16]. The light box was used for the preliminary screening of factors such as pH and nutrient addition. These results were then verified in the miniponds. In addition to varifying light box results, miniponds were used to study detention times, mixing, water depth, and climatic conditions. Final testing was conducted in the large-scale rapid growth pond. The pilot-scale growth pond also served as the primary source of algal-laden waste for the separation studies.

The harvesting studies were divided into three categories — separation, dewatering, and drying. The majority of the work that was done on separation has consisted of jar tests to evaluate various flocculants. Pilot-scale separation techniques studied included: centrifugation, microscreening, filtration, and flocculation and sedimentation. The following dewatering and drying equipment were investigated: cylindrical and basket-type centrifuges, a vacuum filter, sand drying beds, and flash drying.

Symbiotic Method

During the study of the algae stripping and denitrification methods, there were indications that under certain conditions photosynthesis and bacteriological denitrification could occur in the same pond. This phenomenon occurred both when algae and emergent vegetation were the plant material. The addition of methanol was not required for the symbiotic reaction. It has been theorized that the decomposition of the plant material provided the organic carbon necessary for the bacteriological denitrification. A two-year study was started in July of 1971 to define the mechanisms and nitrogen pathways in this process and to determine the efficiency, operational procedures, and costs of the process.

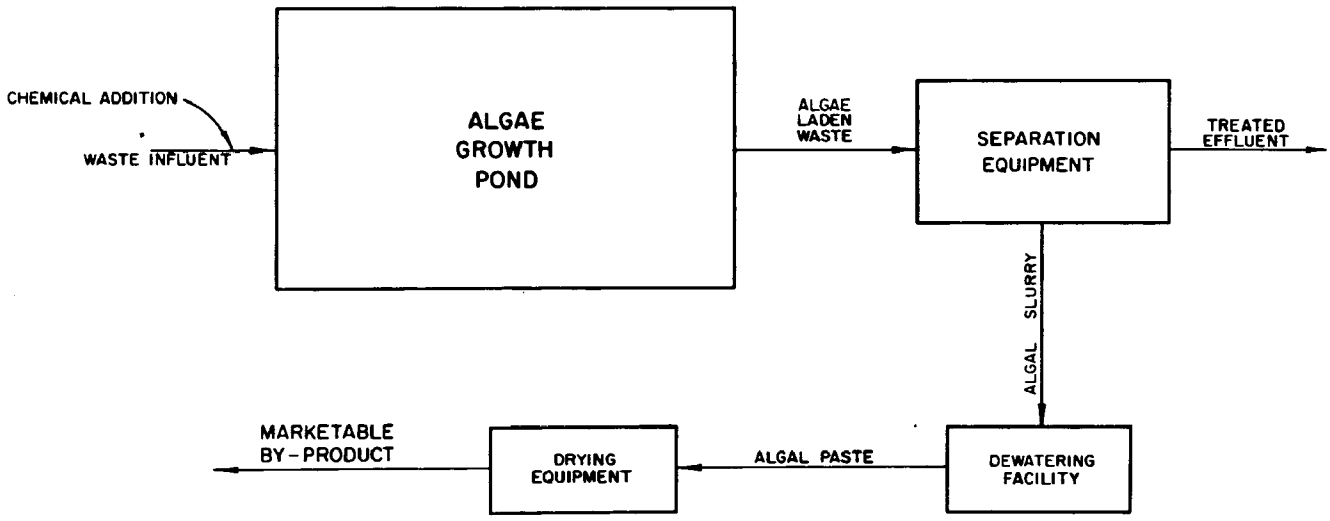

Figure 4: Schematic Diagram. Algae Stripping Process

Desalination

In July 1971, reverse osmosis studies were started on the agricultural wastewater. It is planned to study different configurations of reverse osmosis. If the reverse osmosis studies demonstrate that the process will operate efficiently and economically, complete reclamation studies will be instituted as an alternative to nitrogen removal and disposal to San Francisco Bay. The reclamation studies, if needed, will include pilot-scale operation of reverse osmosis and boron removal facilities and demonstration of brine disposal techniques.

Analytical Techniques

The routine analyses used to monitor the operation of the various units at the Center are summarized as follows:

ROUTINE ANALYSES PERFORMED AT THE INTERAGENCY AGRICULTURAL WASTEWATER TREATMENT CENTER

Analysis	*Technique*
Nitrate-Nitrogen	Brucine Method and/or Selective Ion Electrode
Nitrite-Nitrogen	Standard Methods, 12th Edition[17]
Total Kjeldahl Nitrogen	Kjeldahl Method
Ammonia Nitrogen	Distillation Method
Organic Nitrogen	Kjeldahl Method
Orthophosphate	Stannous Chloride Modification
pH	Glass Electrode
Alkalinity	Standard Methods, 12th Edition
Dissolved Oxygen	Winkler Method
Suspended Solids	0.45μ Glass Paper, 103°C
Volatile Suspended Solids	0.45μ Glass Paper, 600°C
Optical Density	450μ, 5 cm Cell
Electrical Conductivity	Galvanic Cell
Algal Cell Counts and Identifiers	Sedgewick-Rafter Cell
Methanol	Gas Chromatograph, Carbowas Column, Flame Ionization Detector

Most samples were normally collected between 8:00 and 9:00 AM and analyzed immediately. Some samples were taken in the afternoon to gather information on changes that may occur during the peak photosynthetic period. Diurnal studies were also conducted, as the need arose.

In addition to chemical analyses, several physical parameters were monitored. Water temperatures were monitored daily with maximum-minimum thermometers and periodically with 8-day recording thermographs. The influent pressure required for an anaerobic filter to maintain a constant hydraulic detention time was monitored with varying frequency throughout the study. Flows were calibrated volumetrically. In addition tracer studies using the chloride ion as a tracer were run to determine the actual hydraulic regime of the different units. Pre-and postinjection density corrections were made using sodium sulfate. The tracer studies were analyzed using the volume apportionment technique[18,19].

Influent Quality

The tile drainage used for the investigation reported in this paper came from a drainage system that was in existence when the Center was constructed. This system, which serves approximately 400 acres (160-ha), was chosen because of its proximity to land available for construction of the Center and the quality of the drainage, which was considered to be quite "typical". The range of constituent concentrations in this drainage are as follows:

CHARACTERISTICS OF TILE DRAINAGE USED AT THE INTERAGENCY WASTE-WATER TREATMENT CENTER

Constituents	*Range of Concentrations mg/l*
Total Dissolved Solids	2500-7600
Salts	
Sulfate	1500-3900
Sodium	620-2050
Chloride	310-640
Calcium	160-390
Magnesium	70-230
Bicarbonate	280-330
Boron	4-15
Potassium	4-11
Nutrients	
Nitrogen	5-25
Phosphate	0.13-0.33
Pesticides	0.001
Others	
5-Day BOD	1-3
COD	10-20
DO	7-9

The variations are seasonal and due primarily to irrigation applications and rainfall. With the exception of the variation in nitrogen concentration, it was decided that all other constituents should be allowed to vary naturally. Sodium nitrate was used to maintain an average influent nitrate-nitrogen concentration of approximately 20 mg/l, the predicted average nitrogen concentration of the waste in the San Luis Drain.

Discussion

Figure 5 illustrates the predicted seasonal variations of flow and nitrogen concentration. The distribution of flow was determined through a monitoring program and computer simulation[3]. The nitrate-time relationship was developed from data collected by the DWR in a special three-year water quality monitoring program[20]. Figure 6 is a summary of westside San Joaquin Valley air temperature data from three stations in the general area in which a treatment plant might be constructed (between Los Banos and Tracy, California)[21]. These figures are presented to illustrate the fact that the majority of the waste load will occur during the warmer

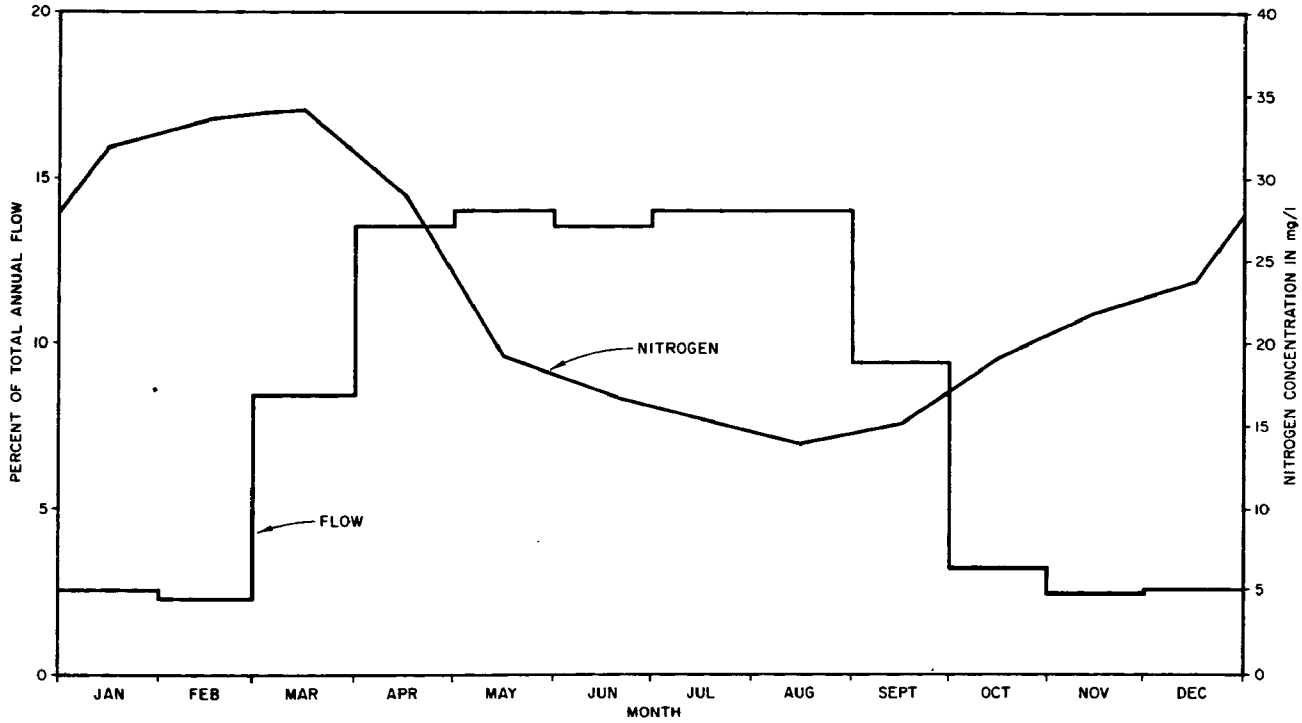

Figure 5: Predicted Seasonal Variation of Tile Drainage Flow 8 Nitrogen Concentration from San Joaquin Valley, California

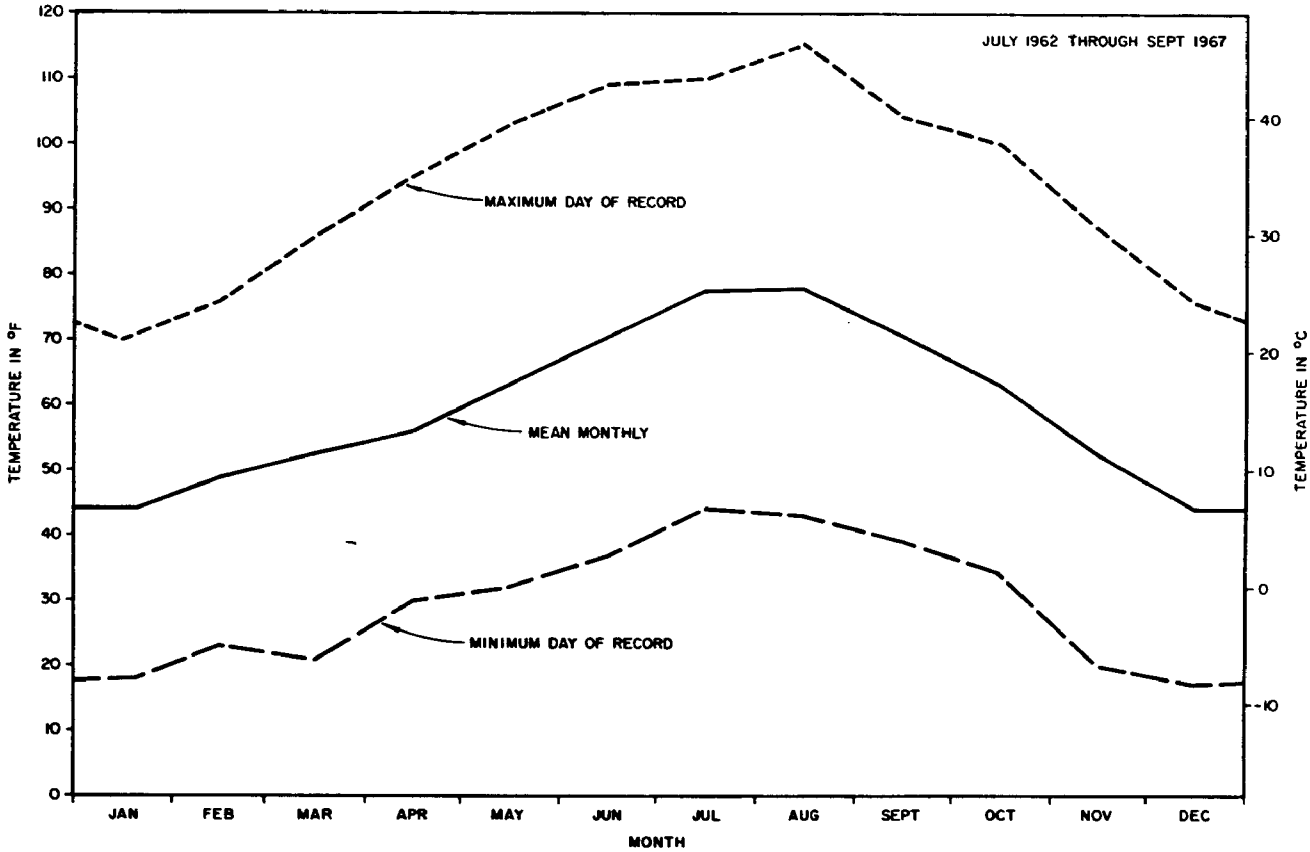

Figure 6: Annual Air Temperature Variation on the West Side of the San Joaquin Valley, California

summer months. Seventy percent of the annual nitrogen load, in pounds per day (grams/day), will arrive at the plant between April 1 and September 30. The significance of this lies in the fact that all of the nitrogen removal systems being evaluated at the Center are biological systems, and are temperature and/or light sensitive.

Operational data will be presented for each system to illustrate individual operating criteria, etc. The individual systems will then be compared.

Anaerobic Filter

The data from experiments designed to investigate the significant media size, texture, and sorptive quality are summarized below[13]. Based on the results of an initial feasibility investigation, all filters operated to generate this data had hydraulic detention times (based on void volumes) of 2 hours. Medium surface texture, size, and sorptive quality have no apparent affect on removal efficiencies. After an extended period of continuous operation the bacterial mass within filters containing media with diameters of less than 1-inch (2.54-cm) built up to the point where the required influent pressures (as high as 60-psig) rendered them uneconomical.

NITROGEN REMOVAL EFFICIENCIES FOR FILTER DENITRIFICATION UNITS CONTAINING VARIOUS MEDIA

Medium	*Nitrogen Removal Efficiency, Percent*		
	Min.	*Max.*	*Average*
Activated Carbon	89	99	96
Washed Sand	84	97	93
5/16″ Coal	80	98	93
5/16″ Volcanic Cinders	85	98	94
3/8″ Aggregate	82	97	94
5/8″ Volcanic Cinders	87	97	91
1″ Coal	81	98	93
1″ Volcanic Cinders	89	97	96
1″ Aggregate	89	98	94

The data gathered from the long-term operation of three filters containing 1-inch diameter media are summarized in the following table.

SUMMARY OF LONG-TERM PERFORMANCE OF FILTERS CONTAINING 1-INCH DIAMETER AGGREGATE

Detention Time Hrs.	*Days of Operation*	*Percent Nitrogen Removal*			*Required Influent Pressure, psig*		
		Min.	*Max.*	*Average*	*Min.*	*Max.*	*Average*
0.5	275	40	91	68	3.5	11.8	7.2
1.0	240	64	97	88	3.2	9.6	5.4
2.0	244	79	97	91	3.5	9.7	6.2

For about the first 150 days of operation, the required influent pressure fluctuated within a narrow range. There did not appear to be any need for backwashing, etc. After that time, an upward trend appeared. Investigations were conducted to determine the best technique to reduce the pressure. Backwashing with a combination of air and water appears to be the best method of cleaning the filter.

The temperature of the influent to the units varied from a high of 22° to a low of 10° Centigrade. There were some indications of a relationship between temperature and nitrogen removal efficiency; however, the relationship was far from obvious. By grouping the nitrate and nitrite removal data for samples taken at different depths within a filter, the reduction in efficiency becomes more apparent as illustrated in the next table.

PROFILE DATA GROUPED BY PERCENT OF FILTER REQUIRED FOR 80% OR GREATER $NO_3 + NO_2$ REDUCTION

(1-inch diameter aggregate media, 2-hour hydraulic detention time)

Percent of Filter Used	*Average Influent Temperature °C*
25% or less	14.5
25% to 50%	12.8
50% to 75%	11.9

As the temperature of the influent dropped, the percent of the filter bed required for the same degree of treatment increased. The 6-foot bed depths used for this investigation and the range of temperatures encountered were such that the effect was not reflected in the overall treatment efficiencies of the units. This information is only qualitative, since steady-state conditions were not reached at any given temperature.

The following equation was developed by McCarty to express the concentration of methanol required for denitrification[11].

$$C_m = (1.90\ N_o + 1.77\ N_1 + 0.67\ D_o)^1$$

C_m = required methanol concentration, mg/l

C_r = consumptive ratio (determined experimentally)

C_r = total quantity of organic carbon source consumed during denitrification divided by the stoichiometric requirement for denitrification and deoxygenation

N_o = initial nitrate-nitrogen concentration, mg/l

N_I = initial nitrite-nitrogen concentration, mg/l

D_o = initial dissolved oxygen concentration, mg/l

The average consumptive ratio calculated from the data gathered at the Center equals 1.47 mg/l with a standard deviation of + 0.367. The fairly large standard deviation claculated for the consumptive ratio is more likely due to inherent difficulties in field studies than fluctuations in system requirements. With the development of an automatic methanol control system, which would respond to changes in influent and effluent quality, this variation should be drastically reduced. The methanol requirement for a typical influent containing 20 mg/l of nitrate-nitrogen and 8 mg/l of dissolved oxygen calculated by equation[1] equals 64 mg/l.

Deep Ponds

The initial field studies of bacterial denitrification in deep ponds were conducted in the Fall of 1967[14]. In these studies, units were operated at various detention times with and without pond covers. Adequate denitrification took place in ponds with detention times as low as 5 days.

Data gathered from the large ponds, which started operation in the Fall of 1968, are summarized in Table 2. Covered ponds have consistently outperformed uncovered ponds. There are two primary reasons for this. Large algal populations develop in uncovered ponds and the resultant high dissolved oxygen concentration inhibits denitrification. The second reason is that more of the influent is short-circuited through the unit because of wind mixing and temperature variation in an uncovered pond. The high nitrogen removal efficiencies recorded for the uncovered pond when operated with a 10-day detention time was probably caused by the formation of a natural partial cover. The cover was composed of decayed algal and bacterial cells floating on the surface of the pond. Some type of covering is necessary for sufficient denitrification to take place.

There were numerous mechanical equipment breakdowns associated with these units; therefore, it is impossible to accurately predict the minimum detention time possible. However, a ten-day detention time, with 25% recycle, and a pond depth of 14-feet (4.27-m) have been shown to be effective for covered pond summertime operation (Table 2) and is used in this paper.

The methanol requirement for pond denitrification follows the same equation developed for filter denitrification. The average consumptive ratio for deep ponds has been found to be statistically equal to that found for anaerobic filters, within the accuracy possible under field conditions.

Based on the feasibility and operational studies conducted at the Center, the cost of both methods of bacteriological denitrification (anaerobic filters and deep ponds) is estimated to be about 90 dollars per million gallons.

Algae Stripping

The results of the algae stripping studies are divided into three subsections; growth, harvesting, and algae utilization.

Growth. Light box studies conducted early in the investigation indicated a serious phosphorus limitation in tile drainage. The addition of approximately 2 mg/l of phosphorus was found necessary. This was further confirmed in studies in the miniponds.

Once the required phosphorus addition was determined, work began on optimizing nitrate assimilation. Of all the nutrient additions investigated, iron and carbon were the only two that have significant effects on assimilation. The optimum amount of iron that should be used has been found to be approximately 2-3 mg/l. A seasonal variability in the iron requirement was indicated and 2-3 mg/l appears to be a maximum requirement. A mixture of carbon dioxide (5%) and air improved nitrate assimilation. Carbon dioxide studies in the miniponds indicated that carbon additions enhanced growth only during the summer months.

Physical parameters which have been studied that affect the process are: water depth, mixing, and hydraulic detention time. Water depths of from 8- to 16-inches (20.3- to 40.6-cm) have been studied in combination with various detention times and mixing schedules. The following data summarizes nitrogen removal data for several miniponds operated to study the significance of these parameters.

This table is intended to show the effects of physical parameters only. The low efficiencies resulted because the other factors that affect growth were not optimized. For summertime operation a design depth of 12-inches (30.5-cm) and a detention time of 5-days has been found to be adequate. Because of the difference between summer and winter temperatures and light a 13- to 15-day detention time is required in the winter. Mixing was found not required for optimum growth when carbon was added to the system.

Harvesting. Oswald, et. al., determined that flocculation and sedimentation was the most economical and efficient method of algae separation at the time of their study[22]. Consequently, the first work done on separation at the Center involved jar tests. The following flocculants were investigated: alum, lime, ferric chloride, ferric sulfate, and various polyelectrolytes. Better than ninety percent removal of algae cells from the liquid has been achieved with alum, lime, ferric sulfate, and several polyelectrolytes.

NITRATE REMOVAL EFFICIENCY OF ALGAE STRIPPING GROWTH UNITS AS RELATED TO PHYSICAL PARAMETERS

Detention Time				*Depth*			
Days	*Nitrate Removal in %*				*Nitrate Removal in %*		
	Max.	*Min.*	*Average*	*Inches*	*Max.*	*Min.*	*Average*
2.5	75	43	59	8	98	71	83
5.0	80	59	75	12	87	74	79
8.0	82	74	78	16	87	61	75
10.0	90	80	85				

The most economical flocculant used was ferric sulfate.

A shallow-depth sedimentation unit with inclined tubes in the sedimentation chamber consistently removed 95 to 97 percent of the suspended solids. The algal slurry from this unit contained 1 to 2 percent suspended solids. A second concentrating device, a Sanborn rapid sand filter also removed about 95 percent of the suspended solids and produced an algal slurry containing 1 to 3 percent solids. Other units (microscreen, upflow clarifier, and centrifuges) were tested as concentrating devices but were not found to be as effective or reliable as the sedimentation and rapid sand filter systems.

A vacuum filter using a multifilament nylon belt produced an algal cake containing about 20 percent solids from an influent with about 0.3 to 3 percent solids. A self-cleaning centrifuge produced an algal product with about 10 to 12 percent solids and removed up to 95 percent of the influent algae (influent concentrations ranging from 500 to 30,000 mg/l). This centrifuge was found to be more effective than either a solid bowl or nozzle type of unit.

The algae were normally dried in the open atmosphere to about 85 to 95 percent solids, a concentration which allowed for safe storage of the material. One algae sample containing about 15 percent solids was spray dried. No problems were experienced in attaining the desired level of moisture in the product.

Algae Utilization. At peak flows more than one million pounds (4.5 x 10^5-kg) of dry algae will be produced each day. The use of algae as a protein supplement in the feed formulations for sheep and hogs has been shown to be feasible[22]. A study investigating the use of algae for poultry feed determined that in addition to the value of the protein content, a benefit is derived from the presence of significant quantities of Xanthophyll[23]. (A carotenoid which is used to increase the color of egg yolks and bird flesh to enhance market value.) Other possible uses for algae include soil conditioning or fertilization. Depending on use, algae have been found to have a value of between 80 and 160 dollars per ton (912 kg).

Based on the studies conducted at the Center, the estimated cost of nitrogen removal by algae stripping is about 100 dollars per million gallons. This includes all phases of algae stripping: growth, separation, dewatering and drying. The cost estimate also includes income from the sale of algae as a by-product at 60 dollars per ton.

Symbiotic Nitrogen Removal

The USBR operated a ten-acre test in a rice paddy configuration with water grass as the emergent vegetation. This test plot had many operational problems, but the effluent consistently contained less than 2-3 mg/l of nitrogen. At the Treatment Center two miniponds were operated in a symbiotic mode with algae as the plant material. These miniponds nearly always achieved the effluent object of 2 mg/l. Preliminary cost estimates based on these two operations were 25 to 35 dollars per million gallons. These costs are much lower than bacterial denitrification and algae stripping and led to the

present symbiotic studies at the Treatment Center. Units are being operated to determine if deeper ponds can be utilized and what detention times are required. The units under study are still in the shake-down period and the results are still erratic.

Desalination

A tube-type reserve osmosis unit is being tested at the Center. The results to date indicate that the total dissolved solids can be reduced from 4,000 mg/l to 600 mg/l at 600 psi with a flux of 20 gallons per square foot per day. This datum is based on the first set of membranes which covered a range of curing conditions. A second set of membranes have been installed based on the first series of tests and long term operation will now be tested.

Comparison of Methods

The pilot-scale studies at Firebaugh have demonstrated that three methods can remove ninety percent of the nitrogen (mostly nitrate) in agricultural wastewaters. Differences in the biological systems and physical configurations of the processes result in many differences between the methods.

Anaerobic filters operate efficiently with the shortest detention times of the three methods studied, one hour, because of the concentrating and containing of bacteria within the units. Algae are not as readily washed out of ponds as bacteria. Therefore, algae growth ponds operate at a five-day detention time compared to ten-days for deep pond denitirfication. For a design flow of 700 million gallons per day, the relative surface areas would be 37-acres (15-ha) for filters, 1,400-acres (570-ha) for denitrification ponds and 10,700-acres (4,300-ha) for algal growth ponds. All three treatment methods require some chemical additions. The detrification systems require methanol. The algal system will require phosphorus, iron, and carbon for growth and ferric sulphate for separation. Algae stripping requires more mechanical equipment than bacterial denitrification. Chemical feed pumps for methanol addition, influent pumps for anaerobic filters, and recycle pumps for deep ponds are the major pieces of mechanical equipment required for bacterial denitrification. Because of the low dissolved oxygen content of wastes that have been treated by these processes, it may be necessary to reaerate the effluent prior to discharge. Algal stripping will require phosphorus, iron, and carbon dioxide feed systems; separation equipment; dewatering equipment; drying equipment; and equipment to handle to algae to prepare it for marketing. The foregoing information is summarized below.

COMPARISON OF NITRATE REMOVAL METHODS FOR ONE MGD OF AGRICULTURAL WASTE CONTAINING 20 MG/L NITRATE NITROGEN

	Bacterial Denitrification		
	Filters	*Deep Ponds*	*Algae Stripping*
Detention	1 hour	10 days	5 days
Chemical Addition	Methanol	Methanol	Phosphorus Iron Carbon Dioxide Ferric Sulfate
By-product Produced	None	None	1 ton
Surface Area of Treatment Unit	2,300 ft.	2.0 acre	15.3 acre
Equipment Requirements	Chemical feed; influent pumps; aeration	Chemical feed; recycle pump aeration	Chemical feed; Separation; dewatering; drying; by-product handling

Each of the methods has special operational requirements. The solids level in denitrification ponds and algal growth ponds must be maintained at a level high enough to achieve the necessary nitrogen removal efficiency. The solids level in the filters must be maintained low enough to prevent clogging and excessive head loss through the units. The chemical feed rates have to be carefully monitored to provide the required additive concentrations for the biological cultures, as economically as possible. The three methods are temperature sensitive, and as temperatures vary throughout the year, detention times will have to be adjusted. The separation procedures may vary throughout the year as the nature of the algal culture changes.

Algae stripping is the only method that produces a by-product. Approximately one ton of dry algae will be produced for each million gallons per day of waste treated. The value of the algae produced will be between 80 and 160 dollars per ton.

Estimated costs for bacterial denitrification and algae stripping are between 90 and 100 dollars per million gallons for each treatment method

SUMMARY

1. Bacteriological denitrification is the best method of removing nitrogen from agricultural wastewater in the San Joaquin Valley at this time. It meets the effluent objective of 2 mg/1 nitrogen and involves less operation than algae stripping.

2. Bacteriological denitrification (both in anaerobic filters and deep ponds) and algal stripping have several advantages and disadvantages.

3. The high cost (90 to 100 dollars per million gallons) for denitrification and algae stripping have instigated studies of a symbiotic method of nitrogen removal and reclamation of the wastewater.

TABLE 1

ESTIMATED CONCENTRATIONS OF CHEMICAL SUBSTANCES IN SAN LUIS DRAIN WATERS

Substance	*1970 Conditions mg/1*	*2020 Conditions mg/1*
Total Dissolved Solids	7,000	3,000
Salts		
Sulfate	3,000	700
Sodium	1,500	700
Chloride	1,200	900
Calcium	300	100
Magnesium	200	50
Bicarbonate	200	100
Potassium	20	10
Boron	10	3
Nutrients		
Total Nitrogen	20	20
Total Phosphate	0.15	0.15
Pesticides	0.001	0.001
Others		
5 Day B.O.D.	1-3	1-3
C.O.D.	10-20	10-20

TABLE 2

NITROGEN REMOVAL-DETENTION RELATIONSHIP FOR DEEP POND DENITRIFICATION

Number of Days of Operation			*Nitrogen Removal In Percent*					
Detention Time Days	*Uncovered Pond*	*Covered Pond*	*Uncovered Pond*			*Covered Pond*		
			Min.	*Max.*	*Avg.*	*Min.*	*Max.*	*Avg.*
7.5	-	34	-	-	-	67	92	80
10	61	31	60	93	77	75	98	88
15	30	35	30	95	56	88	94	91
20	31	40	54	84	71	84	94	90

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Examination of Agricultural Practices for Nitrate Control in Subsurface Effluents

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ABSTRACT

This paper outlines the results of a total nitrogen balance study on the Santa Ana Basin in Southern California and shows the flux of nitrogen between the atmosphere, land surface, soil, and ground water for this 356,000 acre area. These fluxes are then discussed with respect to the effect of agricultural production and fertilizer use on the amount of nitrogen available for leaching. Recommended fertilizer and water application rates in this irrigated basin are proposed based on the current level of fertilizer technology and production practices.

INTRODUCTION

Although there is a wide range of opinion about the effect of irrigated agriculture on our environment, particularly as it relates to the quality of irrigation return flows, it must generally be agreed that our research and engineering efforts have to be augmented if we are to measure and manage our water resources as currently demanded by society. Agricultural production techniques have traditionally involved practices made to guarantee or achieve maximum biological production per acre. Except for the establishment and maintenance of a favorable salt balance within an irrigated basin, we have seldom anticipated the results of our actions on the total environment as they slowly accrue over decades of years, nor have we made very many attempts at measuring and understanding the impact and consequences of these production practices in terms other than crop yields.

One consequence of considering crop yields as the only goal of a production oriented research program coupled with an ever-increasing population educated to emphasize animal instead of plant protein in its diet has been an increased requirement for nitrogen fertilizers from chemical sources. Past applications of farm-site nitrogen fertilizers and the detection of nitrate-nitrogen in ground water has focused attention on the deep percolation of soluble forms of nitrogen. Viets[1] has summarized and evaluated some of the evidence pro and con regarding water quality in relation to farm use of fertilizer. His review and an earlier effort[2] attest to the assertion that measurements of and information about the exact fate of applied nitrogen fertilizers are not available.

The scope of the nitrogen problem can be best placed in context by briefly examining the total nitrogen picture before narrowing our field of vision. According to Bartholomew and Clark[3], a global overview of the distribution of nitrogen

reveals that 98.03% of the total supply is held essentially immobile in the lithosphere of the earth while 1.96% is found in the atmosphere. Hence, the amount of nitrogen available in terrestrial and aquatic life forms together with soil organic matter capable of being managed by man's activity is only about 0.01% of the global supply. This seemingly small percentage figure represents 1.8 x 10^{11} English tons of elemental nitrogen and is that a mount on which all life depends.

To assess the importance of this nitrogen pool to irrigated agriculture, we must first examine its influence on a specific basin. Moreover to be able to ascertain the effects of irrigation and related agricultural practices on the retention and redistribution of nitrogen not only in soil but also in drainage and return flow waters, it is essential to recognize the magnitudes of all sources and sinks of ntrogen and the potential rates of transfer from one location to another. In other words, an understanding of the various processes involved in the so-called nitrogen cycle treated comprehensively by Bartholomew and Clark[3] must be quantified and coupled with processes of water management.

The principal purpose of this paper is to review a recent effort[4] made to ascertain the magnitude of agricultural contributions of nitrate-nitrogen in ground water supplies in the upper Santa Ana Basin in California. In addition to the guidelines established from that effort, recommendations will be given for potential irrigation practices and future research activities based upon analyses of field-measured water and solute behavior.

Santa Ana Basin Study

Only a limited number of areas are suitable for a detailed analysis of the magnitude of agricultural contributions of nitrate-nitrogen in ground water supplies. Such studies require accurate and regular measurements over long periods of time of such information as ground water quality, land use patterns, rates of nitrogen fertilizer, waste disposal from humans, cattle and poultry, water application rates, and water use. The upper Santa Ana Basin located in Southern California was chosen as the site of this type of an investigation because necessary information was available. The basin comprises 356,000 acres overlying 900-foot thick water bearing sediments. The basin is surrounded by mountains and is drained by the Santa Ana River. This river is impounded at the egress from the basin by Prado Dam.

In an attempt to assess the impact of agriculture on the nitrate-nitrogen in ground water supplies in the Santa Ana Basin the total nitrogen pools and fluxes were first determined. The pools (sources and sinks) and fluxes (rates of transfer from sources to sinks) of nitrogen, are presented in 4 zones (Figure 1), those in the atmosphere, land surface, surface six feet of soil, and in the substrata. The magnitude of each flux is given in thousands of tons of nitrogen per year next to each arrow representing the various transport pathways. These fluxes were determined by evaluating the various mechanisms or processes in the nitrogen cycle, nitrogen contents of natural and man-made substances, land use, and hydrologic data.

Specifically for the Santa Ana Basin, the atmosphere loses about 4,600 tons of nitrogen per year, of which 2,100 tons returns to the land surface nitrogen pool in rain, dry fallout, and sorption of ammonia (Precip.). The remaining 2,500 tons is returned by symbiotic and nonsymbiotic fixation. The atmosphere gains 9,000 tons, 6,400 tons of gaseous nitrogen from volatilization from fertilizer applications and combustion products emitted by motor vehicles, boilers, etc., (Combustion) and 2,600 tons from denitrification in the soil zone (Gas Losses). Because the total atmospheric gains above the basin exceed the losses, there is 4,400 tons available for export by the atmosphere to other areas of the world.

In addition to bulk precipitation and soprtion, the land surface receives about 5,200 tons of nitrogen per year in the water supply (200 tons from streamflow and imported water and 5,000 tons from pumped ground water. The return-flow waters from urban and agricultural irrigations amount to 700 tons. Water analyses at Prado Dam, the only ground water drainage pathway from the basin, indicate 800 tons left the basin in the surface water.

A net total of 17,400 tons of nitrogen per year are distributed on the land surface from municipal sewage and solid wastes (3,900 tons), industrial sources (100 tons), manures from feedlot

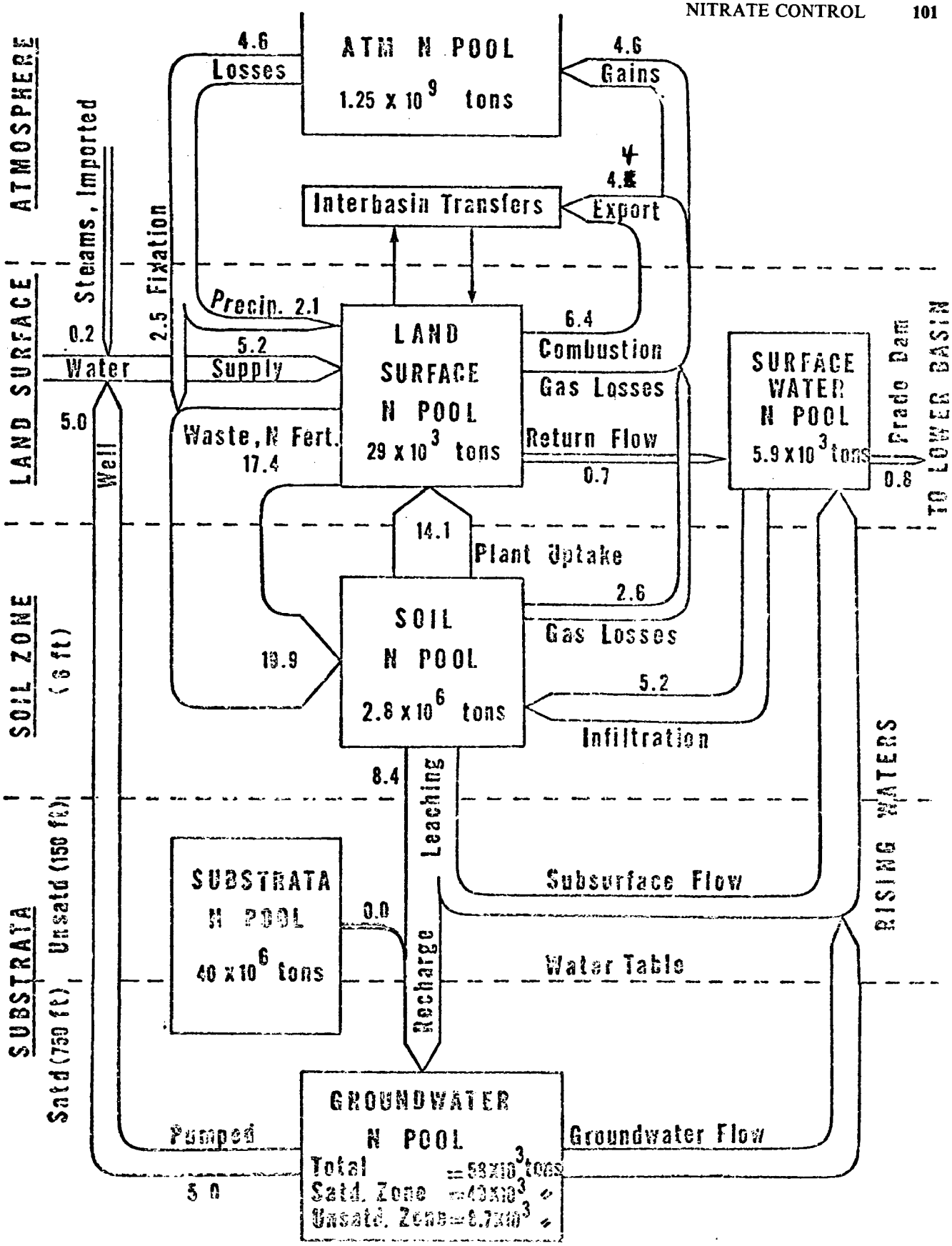

Figure 1: Nitrogen Pools and Fluxes for the Santa Ana Basin Based on the Level of Development in 1960. The Basin is 356,000 acres in Extent and Assumed to Have 6 feet of Soil and 900 feet of Substratum. The Mass of Nitrogen in Pools is in Tons. The Flux of Nitrogen between Pools (numbers for arrows) is in Thousands of Tons of Nitrogen per Year.

and dairy cattle (3,200 tons), precipitation (2,100 tons), and chemical forms of nitrogen fertilizer (8,100 tons).

The total flux of nitrogen transferred to the soil nitrogen pool is 25,100 tons per year. This amount accrues from fixation from the atmosphere (2,500 tons), nitrogen from the water supply (5,200 tons) and nitrogen transferred to the soil from the land surface, including precipitation and sorption (17,400 tons).

The soil, in turn, loses about 2,600 tons of nitrogen per year to the atmosphere by denitrification and about 14,100 tons to plant uptake. This calculation leaves 8,400 tons potentially available for leaching to the substrata, accumulating in the soil, and/or plant uptake in succeeding years.

If we assume that all 8,400 tons of nitrogen per year potentially available for leaching is completely nitrified to nitrate and leached by about 300,000 acre-feet of water percolating beyond the soil zone, the resultant nitrate concentration in the percolating water would be about 80-100 ppm in the unsaturated zone. This estimate is unrealistic, however, for several reasons: 1) nitrogen in the soil does not exist wholly in the nitrate form; 2) nitrogen waste loads contain organic nitrogen compounds, which may take years to degrade completely to nitrate; 3) nitrate can be assimilated by microbes if the carbon-nitrogen ratio of the waste load or the humus in the soil is high. A more realistic concentration level of nitrate in the recharge water would probably be 40 to 50 ppm basin-wide, with perhaps 100 ppm or more in localized disposal sites.

Following this overview of the nitrogen cycle for the basin, an effort was made to identify locations of high nitrate concentrations in the ground water. After identification of problem areas was complete, a program to determine the cause of these nitrate accumulations was begun. Finally guidelines were established for controlling nitrate accumulations stemming from agricultural practices.

At locations of high nitrate concentrations (45 to 90 ppm nitrate and higher) measured in well waters today, early water analyses (1919-1937) confirmed that nitrate concentrations were low, ranging from only 2 to 22 ppm nitrate. Time sequence studies of nitrate concentrations in well waters revealed that they increased during the last 40 years and were in general agreement with the increasing amounts of nitrogen (concentration times volumetric flow rates) observed in the Santa Ana River passing through Prado Dam between 1950 and 1970.

To determine the cause of these nitrate increases, the major nitrogen inputs into the basin were considered — agricultural fertilizers and wastes from dairy cows, poultry and humans. Other recognized sources of nitrogen were native or fossil nitrogen accumulated under natural conditions (before agricultural development) and nitrogen fixed from the atmosphere by leguminous plants, nonsymbiotic microorganisms and electrical storms, and internal combustion engines. These nitrogen sources were related to early and present day land use patterns and to the movement of nitrogen on the basis of examination and analysis of nitrogen transformations, soil permeability, irrigation water use, and surface and ground water hydrology.

An examination of changes in fertilizer use and vegetation patterns with regard to citrus, other fruit crops, nut crops, field crops, and turf grass reveals the impact of land use and technology on agricultural practices.

Early studies (before 1950) on nitrogen fertilizer use by citrus in California indicated that maximum returns required applications of 100 to 350 pounds of nitrogen per acre annually. Since long-term fertilizer experiments at the University of California Citrus Experiment Station indicated annual needs of about 300 pounds of nitrogen per acre for maximum returns, many growers adopted this as a minimal rate. Analyses of nitrogen fertilizer use on citrus in Riverside and San Bernardino County portions of the Santa Ana Basin since 1930 (Figure 2) indicate a steady utilization of fertilizer until 1950 and then a rapid decrease that begins around 1950 and stabilizes approximately ten years later. This precipitous decrease is due to both a changing land use pattern and a changing fertilizer use. During this period there was a reduction in citrus acreage due to population growth in the area and a reduction in fertilizer use because of the development of leaf analysis as a guide to citrus fertilization. Experiments (circa 1950) showed that 100 to 150

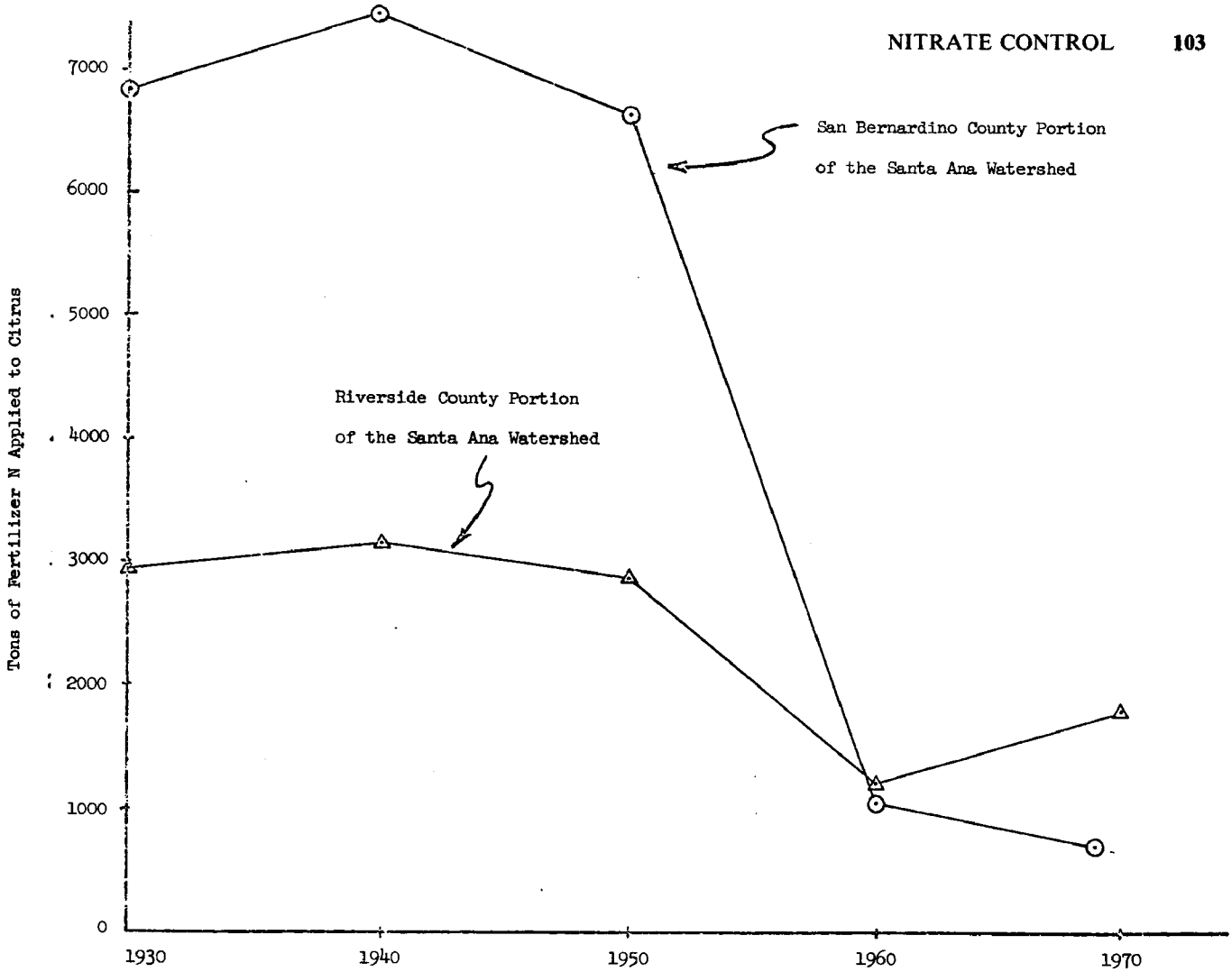

Figure 2: Tons of Nitrogen Applied as Fertilizer Yearly to Citrus in the Santa Ana Basin Between 1930 and 1970

pounds of nitrogen per acre from chemical sources gave yields equal to those from higher rates using leaf analysis. Presently 85-90% of the citrus acreage in the Upper Santa Ana Watershed is fertilized according to leaf analysis programs. The consequences of this changing fertilizer use on the tons of nitrogen fertilizer subject to leaching is shown in Figure 3. These graphs were prepared using the assumptions: a) citrus acreage data is valid; b) 15,000 pounds of fruit were produced per acre annually; c) 300 pounds of nitrogen applied per acre annually prior to 1950, and 75 pounds of nitrogen applied per acre annually in San Bernardino County and 150 pounds in Riverside County in subsequent years; d) 2.5 pounds of nitrogen are removed per ton of fresh fruit; and e) 20% of applied nitrogen is lost by volatilization or denitrification.

Similar studies to the citrus utilization of nitrogen fertilizer were conducted on the 15 or more principal noncitrus fruit and nut crops in the basin. This acreage is dominated by grapes with annual rates of nitrogen fertilization ranging from 60 pounds per acre for grapes to 300 pounds per acre for strawberries. Over the period from 1950 to 1970, fertilizer nitrogen applied to these crops has decreased from 1800 to 600 tons per year, owing primarily to acreage reductions lost to urbanization. Field crops, noncitrus fruit crops, and turf grass were considered to not contribute appreciably to nitrogen increases in the ground waters of the basin. Vegetable acreages combined with nitrogen fertilization studies revealed that in 1930, 12 pounds of nitrogen per acre was available for deep percolation below the root zone, and by 1969, that value had increased nearly tenfold to 107 pounds per acre.

In addition to fertilizers, agriculture can introduce nitrogen from organic wastes produced by people and animals. The amount of nitrogen

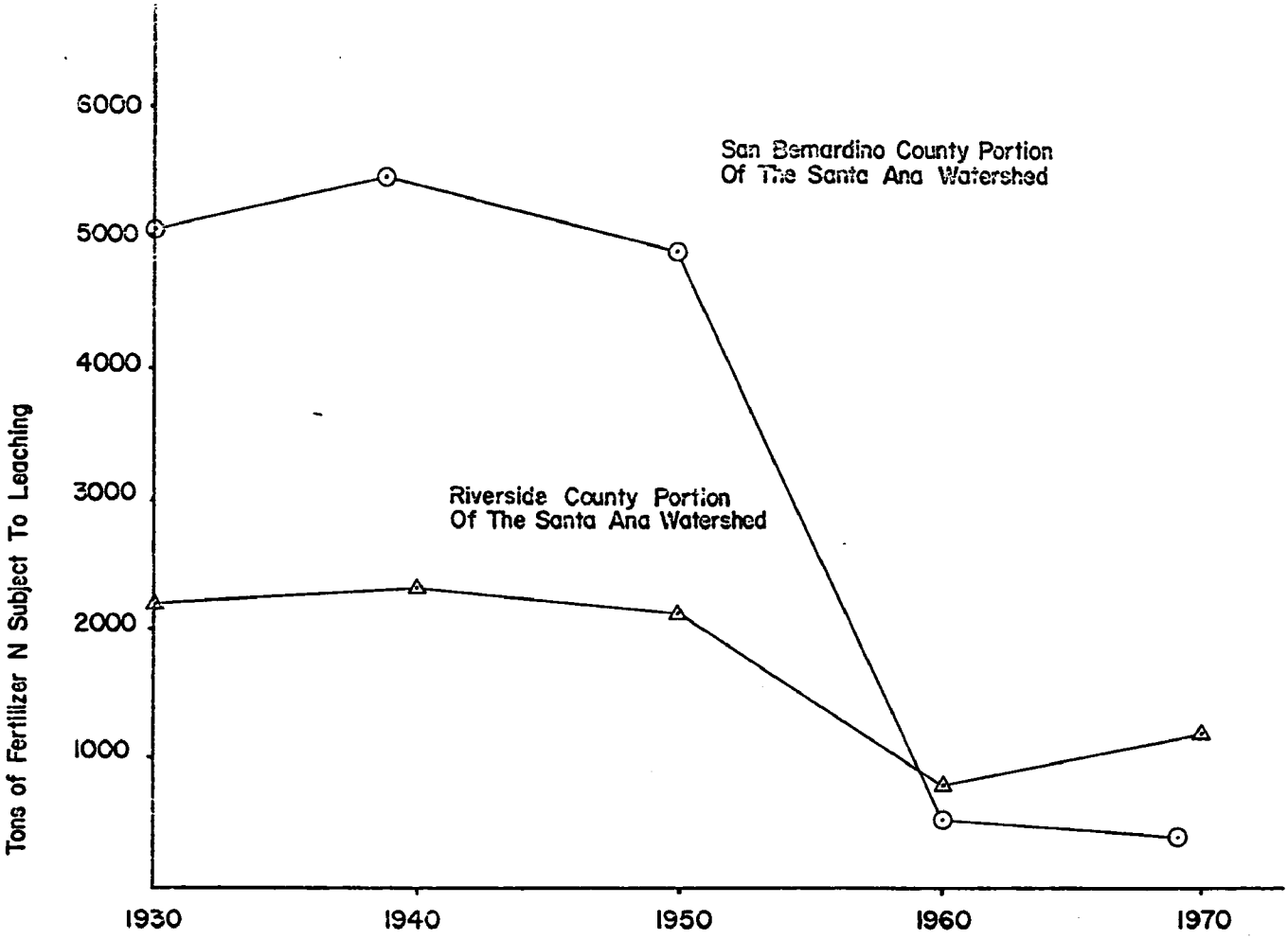

Figure 3: Annual Amount of Nitrogen from Fertilizer Available for Leaching in the Santa Ana Basin between 1930 and 1970

produced in this manner in the basin increased from 4 million pounds in 1930 to 30 million pounds in 1970.

Inasmuch as any significant contribution of nitrogen reaching the ground water in the basin from agriculture is likely to be associated with crop fertilization, water use, and manure disposal, recommendations for reducing the potential of nitrate pollution relative to fertilization and water use focus on rates of fertilization, timing of fertilizer applications, type of fertilizer, evapotranspiration requirements, and leaching fraction.

All crops require nitrogen for growth. In the Santa Ana Basin, naturally occurring soil nitrogen reserves are too low to produce yields high enough for substained commercial agriculture production. Except with legume crops, which utilize atmospheric nitrogen through conversion by legume bacteria living on their roots, supplemental fertilizer nitrogen must be applied to all crops if agriculture is to continue in the basin.

The rates of nitrogen application required for good yields and good quality vary from crop to crop. Citrus and vegetables are two crops to which nitrogen is applied at rather high rates and which may, under inefficient management, result in appreciable excessive nitrogen additions to the underground water supply. The recommendation for citrus is to use leaf analysis as a guide to nitrogen fertilization and to apply the fertilizer in one application in the winter. Leaf analysis integrates the effects of many factors into one figure — the nitrogen concentration in a specific type and age of leaf. These guides were developed to permit maximum yield at lowest cost, so the great reduction in pollution potential is an extra benefit. A further reduction in the suggested optimum nitrogen

level in leaves might improve the fruit quality of oranges and further reduce the pollution potential. Such a program is likely to reduce yields slightly, but that could be counterbalanced by improved fruit quality. Analyses of field experiments for vegetables indicate that maximum yields will require 120 to 300 pounds N/ac, the rate varying with crop, and applied in two or more applications. Grower practices on the average result in greater applications than necessary. For annual crops (vegetables and field crops) split applications of fertilizer are to be encouraged — one-fourth to one-half of the nitrogen needs of the crop applied at or near planting time and the remainder at the main period of most rapid growth.

Fertilizing of tree crops or spring-planted annual crops in late-summer and fall is inefficient, and excessive deep percolation losses of nitrogen to underground water supplies may result from rainfall and normal fall-winter irrigations or irrigations made in preparation for planting. The most critical period for tree crops is generally bloom time. Recommended to ensure maximum yields is a single nitrogen application timed sufficiently ahead of bloom to assure high nitrogen at bloom. High nitrogen at bloom will usually be enough to supply crop needs for the rest of the season.

The use of a relatively new group, slow-release fertilizers, offers some interesting possibilities of reducing nitrogen losses below crop root zones by releasing nitrogen rates that match crop needs more closely. Although some promising materials have been developed recently, their use is still primarily on an experimental basis. Desired goals with slow-release fertilizers must await improvements in formulations and more extensive field testing.

Animal manures can be thought of as a form of slow-release nitrogen. About one-half the nitrogen in manures is released during a cropping period of two to three months. Recommendations for use of manures include the following: 1) Apply well ahead of planting. 2) Disc or otherwise incorporate the manure at leat six inches deep into the soil. 3) Irrigate adequately or let winter rainfall wet to leach detrimental salts away from germination zone of the crop to be planted. 4) A light supplemental nitrogen application may be needed near planting time if crops are planted in the cool season, since nitrogen release from manure is slower in cool weather. 5) Do not apply bulk manure to growing crops, because of plant disease problems, fly problems, and other generally undesirable effects. 6) To reduce deep percolation losses, disposal of dairy wash water or waste effluent by irrigation (either surface ditch, pipe, or sprinkler) should be timed to apply quantities consistent with crop or soil requirements for water and nitrogen.

Soil analysis and/or plant tissue analysis can be helpful in timing fertilizer applications by evaluating nitrogen needs or crop response to nitrogen application at a given time. Soil samples (or soil solutions extracted by soil-solution probes) taken below crops can be analyzed to evaluate losses of nitrogen resulting from various timings of fertilizer applications.

The actual amount of nitrogen reaching underground waters is important, but the primary concern is generally the concentration of nitrate. The concentration in the soil water can be varied by changing either the quantity of nitrogen or the volume of irrigation water applied. Control of nitrogen pollution may require not only reduced rates of fertilization but application of water in excess of crop needs (evapotranspiration) sufficient that waters percolating downward will dilute the nitrogen to an acceptable concentration. Evapotranspiration can be calculated from various empirical formulae, measured indirectly, or measured directly by weighing lysimeters. These values of evapotranspiration may be used as a guide to crop needs and as a mesaure of irrigation efficiency. Another way of estimating the quantities of water moving downward is based on the leaching fraction. The leaching fraction is the volume of water that moves past the root zone, expressed as a fraction of the irrigation water entering the soil at the surface. A leaching fraction[5] of 0.20 to 0.50 is common (20 to 50% of the water entering the soil during irrigation percolates beyond the reach of roots and becomes drainage water). The leaching fraction for well-drained soils may also be estimated more directly by comparing the concentration of a constituent such as chloride in the irrigation water with the chloride in the soil solution below the root zone. For example, if chlorides in

the soil solution below the root zone are 5 me/1, and the chlorides in the water are 2 me/1, the leaching fraction is 2/5 = 0.40 or 40%.

Future Research Effort

Accurate appraisals of the major known facts pertaining to nitrogen balance in a basin, field, plot or greenhouse pot have eluded soil scientists and engineers owing to insufficient development of technology and the previously-held limited objective of determining the percentage nitrogen recovery from fertilizer additions in the crop only. In the field, both gaseous losses of nitrogen to the atmosphere and leaching losses below the root zone too often have been lumped together without a direct measure of either. Without the use of tracers, an accurate measure of gaseous losses is precluded. On the other hand, although they remain more or less untested, field techniques are available for examining the rates of water moving below the root zone. In addition to those mentioned in the previous paragraph, soil water flow may be ascertained by *in situ* measurements of the unsaturated hydraulic conductivity coupled with those of the hydraulic gradient.[6] Assuming that water soluble nitrogen forms move with the water, measurements of their concentrations, accompanying the measured soil water flow, yield estimates of rates of nitrogen appearance in irrigation return flows. Although such techniques are advantageous in that they do not depend upon knowing the physical, chemical and biological processes occurring in the root zone, they do involve temporal and spatial integrations plagued with several degrees of uncertainty[7]. Research effort resolving these uncertainties will undoubtedly increase in the near future.

Knowledge concerning the forms, amounts, transformations and importance of organic and inorganic soil nitrogen compounds has been accumulating for more than a century. Yet, for a laboratory soil column, much less for a field, research has not been sufficient to allow a quantitative description or prediction of biochemical reactions of nitrogen and the resulting concentration distributions within soil profiles. In nature, and especially under irrigated agriculture, nitrogen and other beneficial and potentially harmful solutes are subjected to a downward translocation at the same time that they may be absorbed by plants or undergo microbiological transformations. If we are to identify agricultural practices which affect the amount of surface-applied fertilizers and salts and the time required for them to reach the ground water, we must begin to examine the biochemical course of events within soil profiles both as a function of time of flow and depth in the soil. Field techniques, like those described by Marcura and Malek[8] and by McLaren[9] for laboratory samples, must be developed to ascertain values of physical, chemical, and biological parameters essential for microbial activity. These techniques together with qualitative information already at hand regarding soil texture, depth of profile, crop requirements, growth characteristics, and others will provide better guidelines for fertilizer management.

Soil scientists as well as plant scientists and irrigation engineers are relatively unfamiliar with management techniques for identifying and controlling the concentration of the soil solution once it has moved beyond the root zone. This is especially true for deep, well-drained alluvial soils having water tables at considerable depths. It is often assumed that below the root zone in the absence of microbial activity, nitrate concentrations are not diminished except by dilution with water containing little or no nitrate. How does dilution actually take place if a pulse of nitrate-laden water is displaced by an irrigation with water relatively free of nitrates? This question is not easily resolved, and it is especially complex when other less desirable salts must be leached preferentially.[10] The characterization of solute mixing and displacement coupled with the unsaturated hydraulic properties of the vadose zone remains obscure, yet essential, to long-term, rational irrigation basin management.

When the concepts expressed in the above paragraphs have been integrated and connected to theoretical developments of ground water management by hydrologists, the technology of managing nitrate in potentially saline irrigated basins will be well advanced and more mature than it is today. Until that time, agricultural practices for nitrate control in subsurface effluents will depend largely on guidelines established by studies similar to those in the Santa Ana Basin.

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Grand Valley Salinity Control Demonstration Project

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ABSTRACT

The Grand Valley Salinity Control Demonstration Project was formulated to evaluate the salinity control effectiveness of canal and lateral linings. Introduction of water into the highly saline environment of the soils and aquifer in the Grand Valley results in excessive salinity contributions to the Colorado River. Consequently, by reducing these ground water inflows by a program of canal and lateral linings, significant reductions in the Grand Valley's salt contribution could be achieved.

Ponding tests were made at the beginning of the project in order to establish the initial conditions regarding seepage rates, as well as finalizing the construction recommendations. While the results of seepage measurements in the canals do not indicate potentially high losses, results of some preliminary lateral seepage rate measurements show very high rates. Approximately 8 miles of canals and 5 miles of laterals were lined.

INTRODUCTION

Because the salinity problem in the Colorado River Basin is rapidly becoming acute, measures must be taken concerning various salinity control alternatives if future development is to occur. But most measures which could be considered may be found to be very poorly conceived unless a thorough understanding of the physical, economic, and social conditions in each area is gained. The attitudes of local people are important management considerations and for the most part these attitudes are easily traced to the events surrounding the development of the area. In addition, it is necessary to be aware of the natural characteristics of an area so that restrictions are not imposed which would destroy an area as a functional community. And finally, the institutional structure of an area should be known in order to effectively implement control measures.

Probably the most significant salt source resulting from irrigated agriculture in the upper basin is the Grand Valley area (Fig. 1) in west central Colorado. Consequently, this valley was selected for study in order to evaluate irrigation water conveyance lining as a possible salinity control practice.

The primary source of salinity is from the extremely saline aquifers overlying the marine deposited Mancos Shale formation. The shale is characterized by lenses of salt in the formation which are dissolved by the water from excessive irrigation and conveyance seepage losses when it comes in contact with the Mancos shale for-

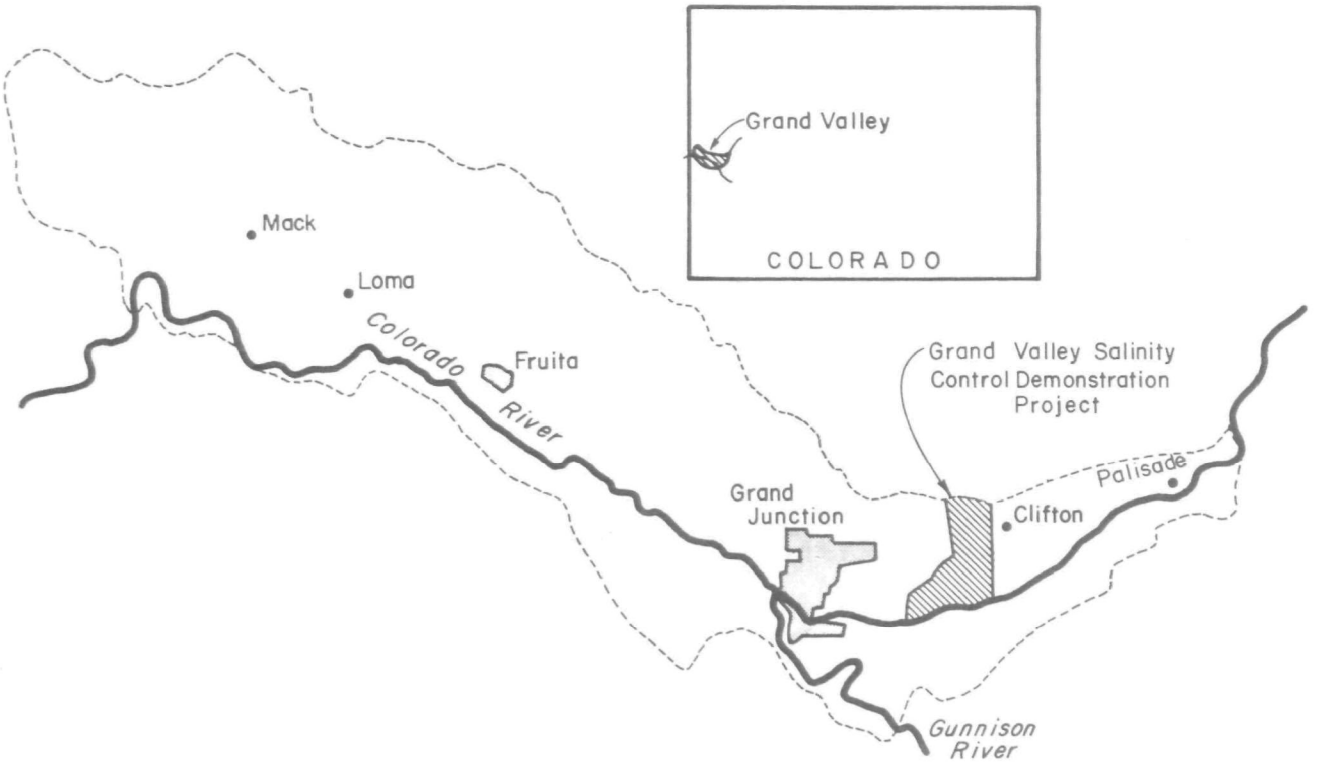

Figure 1: The Grand Valley, Colorado

mation. The introduction of water through these surface sources deep percolates into the shallow ground water reservoir where the hydraulic gradients it produced displace some water into the river. This displaced water has usually had sufficient time to reach chemical equilibrium with the salt concentrations of the soils and shale.

Aside from the numerous studies in the Grand Valley to evaluate local conditions, this effort, the Grand Valley Salinity Control Demonstration Project, is the first study conducted in the area to determine the effect of a salinity management practice on the conditions in the basin. The project was funded on a matching basis (70% Federal and 30% local) by the Environmental Protection Agency in conjunction with the Grand Valley Water Purification Project, Inc., which consists of representatives from the Grand Valley Water Users Association, Palisade Irrigation District, Mesa County Irrigation Company, Grand Valley Irrigation Company, Redlands Water and Power Company, and the Grand Junction Drainage District. The project was undertaken in order to further the development of pollution control technology in the basin. The objectives of the project include:

(1) Demonstration of the feasibility of reducing salt loading in the Colorado River system by lining conveyance channels to reduce unnecessary ground water additions.
(2) Extension of the results of this study to the problem in the upper basin.

The project is comprised of three study areas selected for their different characteristics commonly found in the valley. Area I, shown in Fig. 2, was chosen as an intensive study area in which the bulk of the investigation was to be made and also includes most of the construction effort. This area was established to study in detail the results of conveyance linings on the water and salt flow systems in an irrigated area. The intensive study area was selected for its accessibility in isolating most of the important hydrologic parameters, but had the important advantage that it allowed five irrigation companies to participate in one unit. Area II was selected because it represented a different land form several miles west of Area I along a short section of the Grand Valley Canal where high seepage losses had resulted in a severe drainage problem. Area III is located along a section of the Redlands First Lift Canal, which is supplied from the Gunnison River and was selected to evaluate the effect of different drainage and soil types. Both Areas II and III were to be studied with sufficient data to confirm the results in

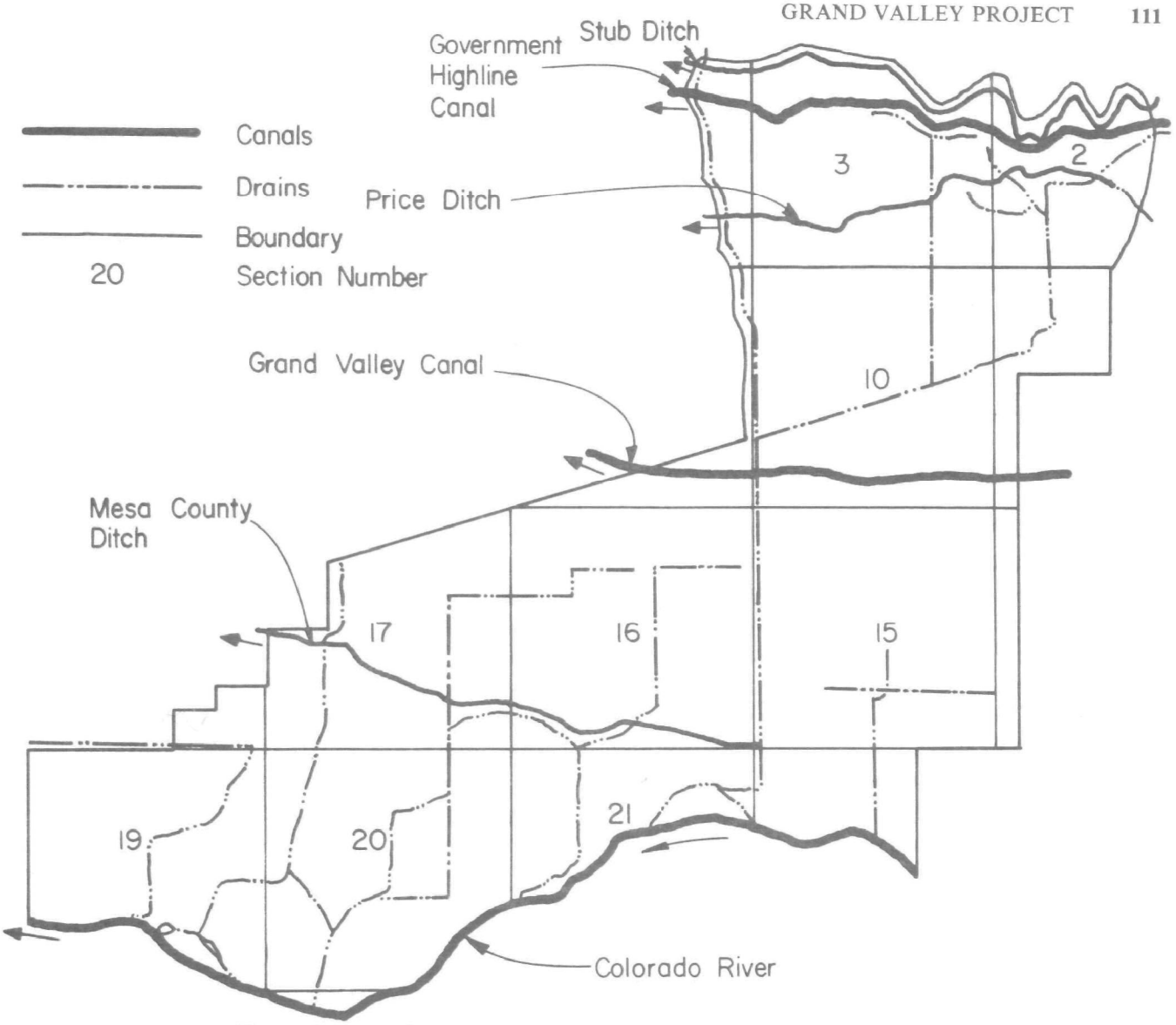

Figure 2: Intensive study area, Area I, of the Grand Valley Project

Area I and involved a minimum number of observations.

The procedure outlined for execution of the project consisted of a two-phase study. Phase 1 was planned to evaluate the conditions in the study areas prior to the construction of the lining. These results have been reported (6). Phase 2 consisted of re-evaluating the conditions after the lining had been completed, which will be reported in the following paper. In both cases, the study was conducted to collect and analyze sufficient data to define in detail both the water and salt flow systems.

Description of the Grand Valley

Exploration and Settlement

Although numerous hieroglyphics and abandoned ruins testify to the occupation of the Colorado River Basin long before settlement began, the first people encountered in the Grand Valley were the Ute Indians. The first contact these peoples had with white men was recorded in 1776 when an expedition led by Fathers Dominiquez and Escalante passed north of what was later to be Grand Junction and across the Grand Mesa (3). The region was subsequently visited by fur trappers, traders and explorers. In 1839 one such trader named Joseph Roubdeau built a trading post just upstream from the present site of Grand Junction.

In 1853, Captain John W. Gunnison led an exploration party into the Grand Valley from up the Gunnison River Valley in search of a feasible transcontinental railroad route (1). As Captain Gunnison and his party traversed the confluence of the Colorado and Gunnison Rivers, an error was made by the expedition recorder as

to the proper naming of the rivers. Beckwith referred to the Gunnison River as the Grand River and the Colorado River as the Blue River, or "nah-un-Kah-rea" as it was known to the Indians. The mistake was later corrected, however, since the Colorado River was known as the Grand River as early as 1842 (2). Field surveys conducted by Hayden (4) in 1875 and 1876 found only the Ute Indians in the valley, and skirmishes with some of the hostile Utes cut short the 1875 expedition. As a result of the Meeker Massacre of 1879, the Utes were forced to accept a treaty moving them out of Colorado and onto reservations in eastern Utah. After the completion of the Utes' exit in September 1881, the valley was immediately opened up for settlement with the first ranch staked out on September 7, 1881 near Roubdeau's trading post. Later that year on September 26, George A. Crawford founded Grand Junction as a townsite and formed the Grand Junction Town Company, October 10, 1881. On November 21, 1882, the Denver and Rio Grande Railroad narrow-gage line was completed to Grand Junction via the Gunnison River Valley and thus assured the success of the settlement.

Water Resource Development

Early exploration did not conclude that the Grand Valley had much potential for agriculture since the terrain appeared very desolate. A great deal of appreciation for this judgment can be acquired just passing through the area and noting the landscape outside the agricultural boundaries. In 1853, Beckwith described the valley as, "The valley, twenty miles in diamater, enclosed by these mountains, is quite level and very barren except scattered fields of greasewood and sage varieties of artemisia—the margins of the Grand (Gunnison) and Blue (Colorado) Rivers affording but a meager supply of grass, cottonwood, and willow." Soon after the settlement began, it was realized that the climate could not support a non-irrigated agriculture. As a result, irrigation companies were organized to divert water from the river for irrigation.

Geology

The plateaus and mountains in the Colorado River Basin are the product of a series of uplifted land masses deeply eroded by wind and water. However, long before the earth movements which created the uplifted land masses, the region was the scene of alternate encroachment and retreat of great inland seas. The sedimentary rock formations underlying large portions of the basin are the result of material accumulated at the bottom of these seas. In areas similar to the Grand Valley area, the upper parts contain a large number of intertonguing and overlapping formations of continental sandstone and marine shales, as shown in Fig. 3.(8). The lower parts are mostly marine Mancos shale and the Mesa Verde group of related formations. This particular geology is exhibited in about 23 percent of the basin in such common locations as the Book Cliffs, Wasatch, Aquarius, and Kaiparowits Plateaus, the cliffs around Black Mesa, and large areas in the San Juan and Rocky Mountains. Many of the interior valleys attracted settlers such as the valleys in the

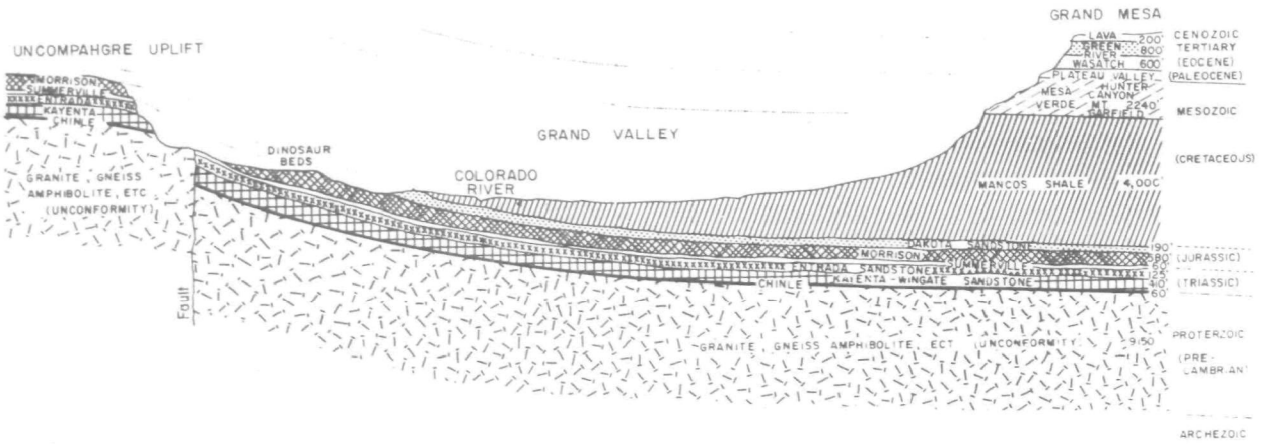

Figure 3: General geology of the Grand Valley

vicinity of Price, Vernal, and Green River, Utah; Rock Springs, Wyoming; and Grand Junction, Delta, and Montrose, Colorado (5).

The geology of an area has a profound influence on the occurrence, behavior, and chemical quality of the water resources. In the mountainous origins of most water supplies, a continuous interaction of surface water and ground water occurs when precipitation in the form of rain and melting snow enter ground water reservoirs. Eventually, these quantities of ground water return to the surface flows through springs, seeps, and adjacent soil in regions downstream. A further consequence of such a flow system is the addition of water from streams to the ground water storage during periods of high flows and the subsequent return flows during low flow periods. The resulting continuous interaction of surface water and ground water allows contact with rocks and soils of the region which cause their chemical characteristics to be imparted to the water.

The interior valleys of the basin, the Grand Valley being a good example, do not receive large enough amounts of precipitation to significantly recharge the ground water storage. Usually, the water bearing aquifers are buried deep below the valley floor and are fed in and along the high precipitation areas of the mountains. Shallow ground water supplies are predominately the result of irrigation. Although the water in the consolidated rock formations of the valley region does not contribute to the stream flows as is the case in higher elevations, it does have a pronounced effect on water quality. High intensity thunderstorms bring surface runoff in contact with the rocks and soils, which then acquire certain chemical ions from the native materials. The long erosion by rivers and streams has deposited alluvium along certain lengths and thus serves to produce an interchange of water in these areas.

Soils

The physical features describing the test area are similar to those of the whole of Grand Valley. The soils in the area were classified by the Soil Conservation Service in cooperation with the Colorado Agricultural Experiment Station (8) in 1940.

The desert climate of the area has restricted the growth of natural vegetation, thereby causing the soils to be very low in nitrogen content because of the absence of organic matter. The natural inorganic content is high in lime carbonate, gypsum, and sodium, potassium, magnesium, and calcium salts. With the addition of irrigation, some locations have experience high salt concentrations with a resulting decrease in crop productivity. Although natural phosphate exists in the soils, it becomes available too slowly for use by cultivated crops and a fertilizer application greatly aids yields. Other minor elements such as iron are available except in those areas where drainage is inadequate. The soils in the test area are of relatively recent origin as they contain no definite concentration of lime or clay in the subsoil as could be expected in weathered soils. Some areas in the valley have limited farming use because of poor internal drainage which results in water logging and salt accumulations.

Lying on top of the Mancos shale and below the alluvial soils is a large cobble aquifer extending north from the river to about midway up the test area. The importance of this aquifer with respect to the drainage problems of the area has been demonstrated by a cooperative study in 1951 between the Colorado Experiment Station in conjunction with the Agricultural Research Service (ARS) (7), which evaluated the feasibility of pump drainage from the aquifer.

Land Use of Study Area

Evaporation and transpiration from crops, phreatophytes, and other land uses results in a loss of salt-free water to the atmosphere and a deposition of salt in the soil profile. The magnitude of these losses depends on the acreage of each water use. As a part of a valley wide evaluation, the various acreages of land uses in Area I were mapped and the acreages for each land use for Area I are shown in Table 1, while the irrigated acreage for each irrigation company is listed in Table 2 (10). One of the most quoted statements in the literature concerning the Grand Valley is that approximately 30% of the farmable area is unproductive because of the ineffectiveness of the drainage in these areas. Examination of the results presented in Table 1 indicates that 70% of the study area can be classi-

TABLE 1

Land use in 1969 for Area I

Classification	*Acreage*	
Corn	487	
Sugar Beets	1	
Potatoes	8	
Barley	255	
Oats	14	
Wheat	9	
Alfalfa	545	
Cultivated Grass Hay	141	
Pasture	476	
Native Pasture	387	
Orchards	349	
Idle	559	
Other	6	
		3237
Farmsteads	258	
Residential	61	
Urban	85	
Stock Yards	8	
		412
Water Surfaces	70	
		70
Cottonwoods	6	
Salt Cedar	268	
Willows	70	
Rushes	10	
Greasewoods	333	
		687
Precipitation Only	225	
		225
	TOTAL	4631

fied as irrigable land, however only 52% can be considered productive. It should be noted that the use of the term productive relates to those areas producing cash crops such as corn, beets, grains, orchards, alfalfa, etc.

Climate

The effects of the mountain ranges in the Upper Colorado River Basin have much more influence on the climate than does the latitude. The movement of air masses is disturbed by the mountain ranges to the extent that the high elevations are wet and cool, whereas the low plateaus and valleys and dryer and subject to wide temperature changes. A common characteristic of the climate in the lower altitudes is hot and dry summers and cold winters. Moist Pacific air masses can move across the basin, but dry polar air and moist tropical air rarely continue all the way across the basin. Movement of both types of air masses is obstructed and deflected by the mountains so that their effects within the basin are weaker and more erratic than in most areas of the country.

Most of the precipitation to the basin is provided from the Pacific Ocean and the Gulf of Mexico whose shores are 600 and 1000 miles from the center of the basin, respectively. The air masses are forced up to high altitudes and lose much of their precipitation before entering the basin. During the period from October to April, Pacific moisture is predominant, but the late spring and summer months receive moisture from the Gulf of Mexico.

The monthly distribution of precipitation and temperature for Grand Junction is shown in Fig. 4 (9). The climate in the area is marked by a wide seasonal range, but sudden or severe weather changes are infrequent due mainly to the high ring of mountains around the valley. This protective topography results in a relatively low annual precipitation of approximately eight inches. The usual occurrence of precipitation during the growing season is in the form of light showers from thunderstorms which develop over the western mountains. The nature of the valley location with typical valley breezes provides some spring and fall frost protection resulting in an average growing season of 190 days from April to October. Although temperature have ranged to as high as 105° F, the usual summer temperatures range in the middle and low 90's in the daytime to the low 60's at night. Relative humidity is usually low during the growing season, which is common in all of the semi-arid Colorado River Basin.

Irrigation

The system of irrigation most common to the area is surface flooding either by borders or furrows. The study area itself is located in the narrow eastern part of the valley which has a relief of about 50 feet per mile sloping south towards

TABLE 2

Summary of 1969 land use under each irrigation company in Grand Valley

Canal System	*Cropland Acreage*	*Domestic Acreage*	*Industrial Acreage*	*Water Surfaces*	*Phreato-phytes*	*Prec Only*	*Total*
Grand Valley Irrigation Company	29,722	5,540	682	798	6,340	3,591	46,678
Grand Valley Water Users Association	25,169	1,629	0	635	6,554	10,429	44,416
Orchard Mesa Irrigation District	7,694	1,363	0	135	850	964	11,006
Palisade Irrigation District	4,306	547	0	37	177	337	5,404
Mesa County Irrigation District	608	32	0	31	51	51	773
Redlands Water & Power Company	3,046	885	0	63	1,202	1,235	6,431

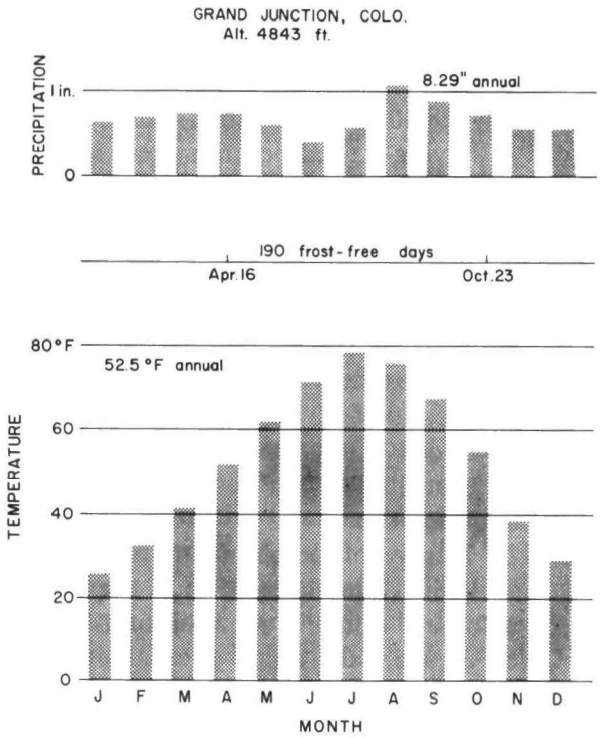

Figure 4: Normal precipitation and temperature at Grand Junction, Colorado

the river. As a result, care is taken to prevent erosion in most cases by irrigation with small streams. Most farms in the area are small and have short run lengths. However, the small irrigation stream allows adequate application. The quantity of water delivered to the farmer is plentiful so the usual practice is to allow self-regulated diversions.

Conveyance System

The delivery system in the valley is divided into the canal and ditch subsystem and the lateral subsystem. The distinction is made primarily on the basis of responsibility. The canal companies and irrigation districts divert the appropriated water right from the river and deliver it to the canal turnout, but they assume no responsibility for the water below this point. The lateral network, which originates at the canal turnout, is managed by cooperative actions of the individual users served by the turnout.

Canal System

The canals and ditches in the Grand Valley are shown in Fig. 5. Discharge capacities range from above 700 cfs in the Government Highline Canal to 30 cfs in the Stub Ditch, and these figures diminish through the length of each canal or ditch. The lengths of the respective canal systems are approximately 55 miles for the Government Highline Canal, 12 miles for Price, Stub, and Redlands Ditches, 110 miles for the Grand Valley system, and 36 miles for Orchard Mesa

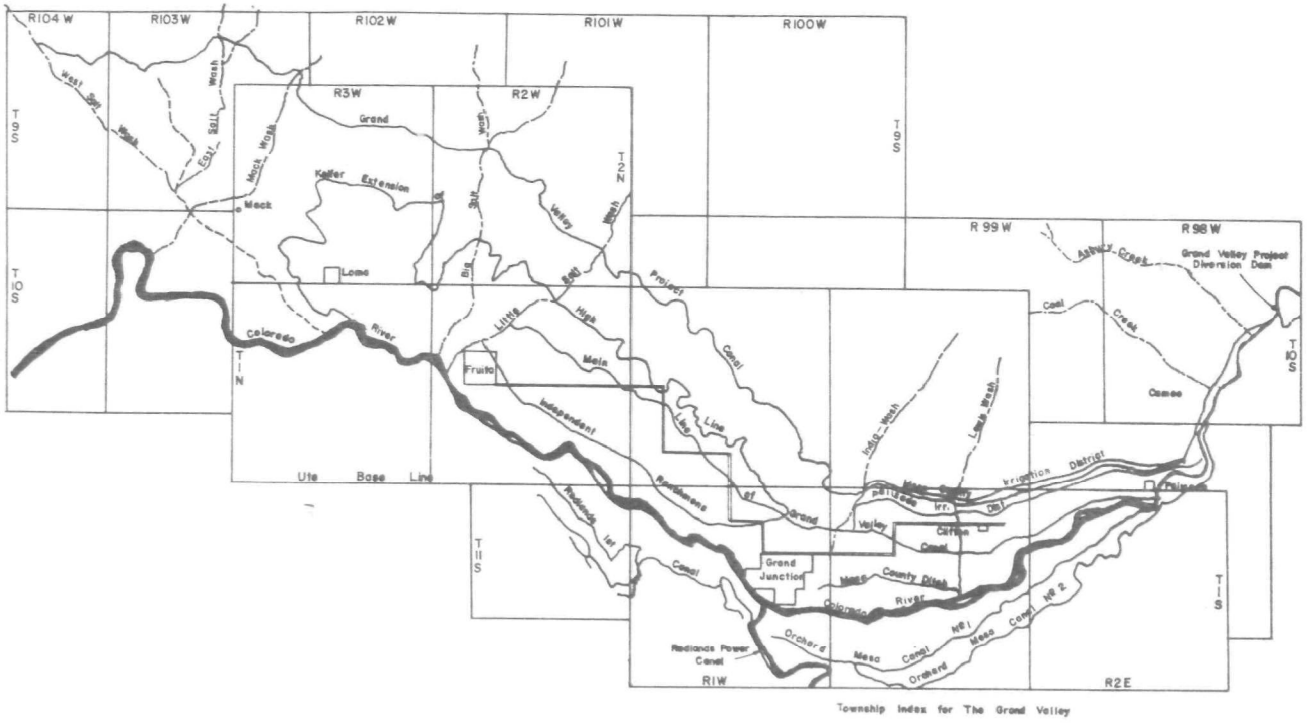

Figure 5: Grand Valley canal distribution system

Canals. In the following parts of this subsection, individual aspects of the canal system will be examined.

The management of the canals and ditches in the area varies between canals and also changes with the water supply. For example, it can be noted that during periods when river flows become small, restrictions are placed on the diversion from the Government Highline Canal. This is possible because the flows are measured and recorded at each individual turnout in that system, and it is a necessity as their water rights are junior to others. On the other hand, in most instances along the other canals, no measurements are taken because little shortage is experienced. Another practice used extensively in the region is regulating canal discharges by varying the amounts of spillage into the natural wasteways and washes. Neither of these practices, poor measurement and spillage, are conducive to salinity control.

The dilemmas being faced by the irrigation officials are numerous but can be traced to one factor. When the demand for irrigation was realized and the canal alignments located, the expected demand for water was based on the total area of land under the canal. However, when the acreages of roads, homes, phreatophytes, etc., are deducted, the water available for each acre is significantly increased. For example, under the Grand Valley Canal are 44,774 acres of which only 28,407 are irrigable. Consequently, instead of having a total before system losses of 5.76 acre-feet per acre, there is more than 9 acre-feet per acre. The result is a two-fold problem:

(1) With a considerable excess of water as appropriated stating that the water is to be used exclusively for irrigation, it is very economical to be wasteful. Thus, how does an irrigation official justify stringent management control to the people he serves?

(2) The history of development in the western United States has always shown water to be a valuable commodity to an area and as such, the rights one has are to be protected. Under the common water law, rights not historically diverted are lost. Consequently, the Grand Valley must divert its rights for fear of losing them.

In short, it is not the practice of agriculture to be wasteful, but the laws regulating the use of water dictate that a user either be wasteful or give up a valuable right.

Canal Seepage

The initial phase of the study involved the determination of the seepage rates from the canals and laterals in the test areas, Area I, II and III. As noted previously, the ponding technique was employed to assure the reliability of the results. The first tests were conducted on all canals in Area I except the Grand Valley Canal. The lengths evaluated included a 2.6 mile section of the Stub Ditch, 2 miles of the Government Highline Canal, 1.9 miles of the Price Ditch, and 2.2 miles of the Mesa County Ditch. In addition, the tests were made along the ½ mile length of the Redlands First Lift Canal in Area III. The 0.15 mile length of the Grand Valley Canal in Area II was not evaluated because of the high seepage losses being evident, and the construction costs for dikes and tests in relation to the costs of the lining would have resulted in the testing being more expensive than the lining. A summary of the test results is shown in Table 3, indicating only moderate seepage rates in Area I and a relatively high rate in the Redlands First Lift Canal. The average seepage rates were approximately 0.15 $ft^3/ft^2/day$ (cfd) in the Stub, Price, and Mesa County ditches; 0.25 cfd in the Government Highline Canal; and an average rate of 0.40 cfd in the Redlands First Lift Canal.

Although size and location of the water table may be significant factors influencing seepage rates, the results seem to contradict those of previous investigations. The water table depths in the area of the Stub Ditch, Government Highline Canal and the Price Ditch are similar, but the large canal has a noticeably large seepage rate, yet it is much more affected by the shale. Nonetheless, it seems justified to conclude that seepage rates in the Grand Valley canals probably vary between 0.15 and 0.40 cfd. Extending these results to the entire valley, the estimated conveyance losses attributable to seepage probably range between 25,000 and 65,000 acre-feet annually, which would mean that between 4% and 10% of the annual diversion is lost by seepage from canals.

Because the influence of the water table would serve to reduce canal seepage, the location of linings in the low lying areas may not be as effective as in the upper elevations in the valley. In the principal study area, the water table is higher than the bottom of the Grand Valley Canal in many places, and consequently these reaches probably pick up rather than lose water.

Linings

Based upon the results of the ponding tests, two modifications to the original plan were recommended and incorporated in the project. The first was the lining of the Government Highline Canal in Area I should be made on the downhill bank of the last mile in the study area. The objective of this change from a complete perimeter lining as originally proposed was to make an evaluation of the effectiveness of the downhill lining which should prove to be useful for future projects. The second modification involved reducing the construction scheduled for the drainage system to two small surface problems in the area and the remainder of these funds being spent on lateral linings. The linings which were made in the canal system are illustrated by the darkened lengths in Fig. 6. The cost estimates of the final plans are tabulated in Table 4.

The construction along the Stub Ditch, which consisted of the standard trapezoidal slip-form concrete lining, is shown in Fig. 7. The location of the Stub Ditch, which runs to just east of Grand Junction, is along the extreme northern edge of the irrigated area of the valley, characterized by rapid and numerous undulations in the topography, thereby causing the canal alignment to assume a very winding path. Along the path of the Stub Ditch, there is often close proximity to the Government Highline Canal as indicated in Fig. 7. The linings in the Price Ditch system in Area I and the Redlands First Lift Canal in Area III are of the same nature as the Stub Ditch linings.

The other commonly used type of lining in the area is the gunnite material used for the Mesa County Ditch, as shown in Fig. 8. It is of some interest to note the white covered field in the background; a good illustration of the alkalinity resulting from poor drainage. This type of lining has several advantages to the local irrigation companies since they are already equipped to do the work and the limited preparation for the linings does not tie up too many people. This same procedure was also used along the short section of the Grand Valley Canal in Area II and the downhill bank lining of the Government Highline Canal in Area I.

TABLE 3

Results of ponding tests on canals in Area I and II.

Canal	*Pond*	*Length (ft)*	*Mid-station*	*Avg. Wetted Perimeter (ft)*	*Seepage Rate (cfd)*	*Q* Acre-ft / Season*
Mesa County Ditch	1	1300	6+50	11.81	0.12	8.46
	2	1075	18+37	12.12	0.13	7.78
	3	1367	30+57	12.14	0.12	9.12
	4	1227	43+55	11.20	0.15	9.40
	5	1025	54+82	10.40	0.15	7.13
	6	1316	66+52	12.22	0.17	12.40
	7	1250	77+85	12.42	0.18	12.80
	8	1449	92+85	12.34	0.13	10.62
	9	1184	106+02	12.59	0.13	8.59
					Total	86
Government Highline Canal	1	4925	28+37	54.92	0.25	310.70
	2	5278	79+39	59.18	0.25	358.30
					Total	669
Price Ditch	1	1930	10+67	15.91	0.12	16.67
	2	1960	30+60	16.41	0.13	19.00
	3	2000	50+00	10.01	0.11	19.20
	4	2035	70+17	12.22	0.11	12.40
	5	1865	89+67	14.12	0.16	19.20
					Total	86
Stub Ditch	1	2175	11+62	10.53	0.15	15.60
	2	2150	33+25	12.34	0.13	15.60
	3	2600	52+06	10.84	0.15	19.40
	4	2300	81+50	13.50	0.12	17.10
	5	2275	104+37	11.69	0.13	15.80
	6	2375	127+62	10.68	0.22	25.60
					Total	109
Redlands First Lift Canal	1	1213	6+06	15.30	0.45	38.20
	2	1318	19+02	14.38	0.35	31.80
					Total	70

*Based on 200-day season.

TABLE 4

Recommended construction program

Map Designation	*Company Name Canal Name*	*Type of Lining*	*Length (mi)*	*Perimeter (ft)*	*Area (yd^2)*	*Unit Cost ($/$yd^2$)*	*Misc. Costs* ($)*	*Total Cost ($)*
Area I								
A	Grand Valley Irrigation Co. Mesa County Canal	Gunnite	2.2	14	17,500	3.25	2,100	58,975
B	Palisades Irrigation Dist. Price Ditch	Slip Form	1.9	15	16,720	3.25	1,900	56,240
C	Grand Valley Water Users Assn. Govt Highline Canal	Gunnite	1.0	15+	8,800	3.50	5,800	36,600
D	Mesa County Irrigation Co. Stub Ditch	Slip Form	2.5	10	14,700	3.25	3,500	51,275
E	Grand Junction Drainage Co.							
	Open Drains	Slip Form						4,000
	Closed Drains	Tile						16,000
	Laterals	Slip Form						110,815
Area II								
F	Grand Valley Irrigation Co. Grand Valley Canal	Gunnite	0.15	15+	1,320	3.50	4,000	8,620
Area III								
G	Redlands Water and Power First Lift Canal	Slip Form	0.5	12	3,500	3.25	1,600	11,475
						TOTAL		354,000

*Costs of pre-construction and post-construction ponding tests above amounts in CSU contract, plus costs of installing headgates, etc.
+Downhill bank lining, only.

The construction of the small drainage improvements in the project is illustrated in Fig. 9. The figure indicates the utility of such a design for a farming area in that it only temporarily disrupts farming operations in the vicinity and avoids the land area occupation encountered in locations using an open drainage system.

An often overlooked aspect of the lining program is the installation of appurtenances to the land and to rehabilitate the system in general. Two examples are shown in Fig. 10, showing first a box-type culvert arrangement to convey surface runoff from adjacent lands over the Stub Ditch to avoid destruction of the lining. The second (lower) picture shows a typical circular slide gate turnout along the Price Ditch. These additions to the canal allow and promote better management of diversions being made into the lateral system.

In addition to the canal lining, a modification was made to the original proposal to allow participation in the project by individual farm owners by setting some funding aside for lining of laterals. A summary of lateral lining which has been constructed, all of which is in Area I, is listed in Table 5, as follows:

TABLE 5

Size and length of lined laterals

Description	*Length*
*14″ trapezoidal	5,941′
12″ trapezoidal	11,435′
10″ trapezoidal	624′
6″×10″ rectangular	1,478′
12″×10″ rectangular	1,987′
12″ buried pipe	978′
8″ buried pipe	2,111′
6″ buried pipe	950′
Total	25,504′
	4.83 miles

*Note - The first dimension listed in the description refers to the bottom width of the lateral, except where pipe was used.

Figure 7: Slip Form concrete lined section of the Stub Ditch

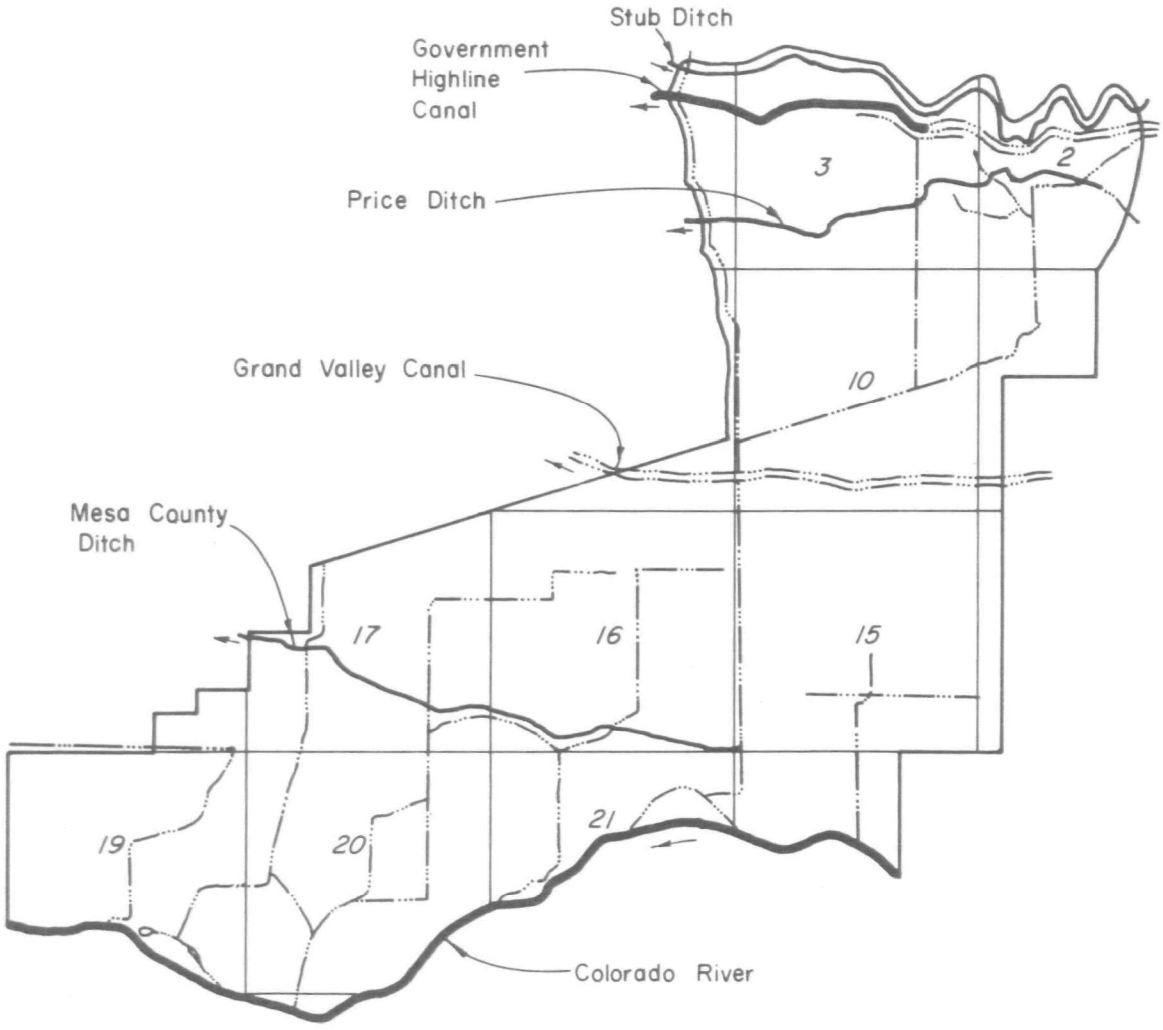

Figure 6: Location within Area I of the linings that were constructed

Figure 8: Gunnite lined section of the Mesa County Ditch

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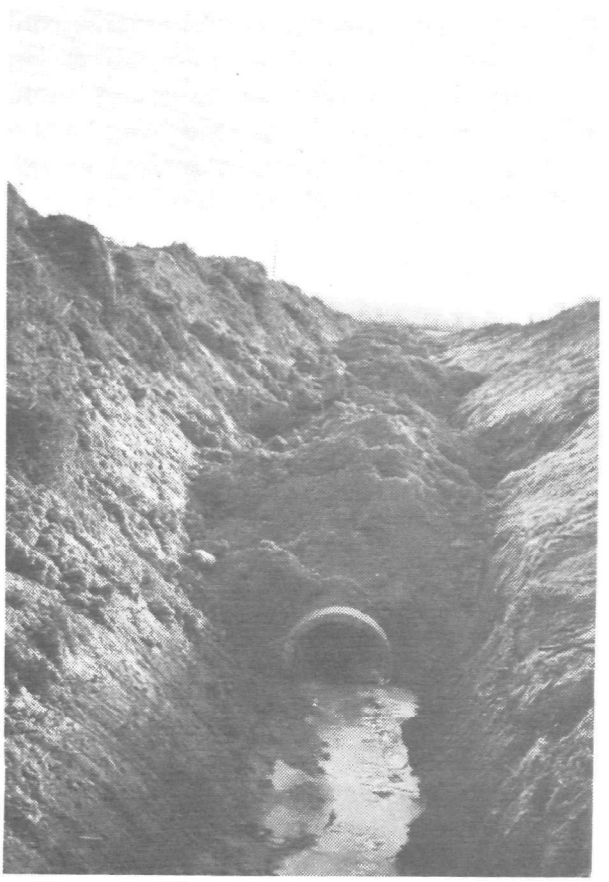

Figure 9: Tile drain line in the study area

Figure 10: Special purpose structure built as part of the lining work

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Salinity Control Measures in The Grand Valley

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ABSTRACT

Introduction of seepage and deep percolation losses to the saline soils and aquifers, and the eventual return of these flows to the river system with their large salt loads, make the Grand Valley in Colorado one of the more significant salinity sources in the Upper Colorado River Basin.

The Grand Valley Salinity Control Demonstration Project was formulated to evaluate the salinity control effectiveness of canal and lateral linings for reduction of seepage losses into the ground water.

The results indicate that the linings, even though seepage rates are relatively low, are feasible based solely upon salinity damages downstream. However, it is concluded that the major impact of conveyance channel linings and system rehabilitation is the improved water control necessary for achieving more efficient water management practices on the farm, which is the key to salinity control.

INTRODUCTION

Salinity is the most pressing problem facing the future development of water resources in the Colorado River Basin (Figure 1). Because of the progressive deterioration in mineral quality towards the lower reaches, the detrimental ef-

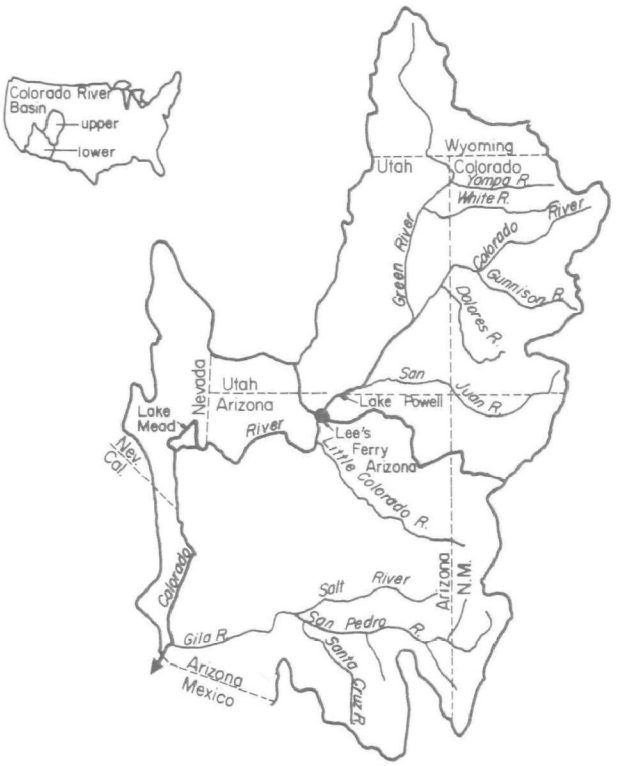

Figure 1: The Colorado River Basin

fects of using an increasingly degraded water are first seen in the lower basin. As a result of the continual development in the upper basin, most of which will be diversions out of the basin to meet large municipal and industrial needs, water ordinarily available to dilute the salt flows will be deleted from the system, causing significant increases in salinity concentrations throughout the basin. The economic penalty resulting from a use of lower quality water will be primarily incurred by those uses in the lower system.

In order to alleviate this problem, the upper basin must concern itself with the aspect of salt loading in the river system from municipal, industrial, agricultural and natural sources. The other aspect, which is the salt concentrating effects, is related to consumptive use, evaporation, and transbasin diversions. Although several methods of controlling salinity, such as phreatophyte eradication and evaporation suppression on reservoirs are desirable, the most feasible solutions are in reducing inflows from mineralized springs and more efficient irrigation practices. In any case, the salinity management objectives in the upper basin must necessarily be concerned with a reduction in the total salt load being carried to the lower basin in order that the detrimental salinity effects anticipated from further development can be limited.

The major emphasis on reducing the salt inputs from the upper basin must be placed on effective utilization of the water presently diverted for irrigation by comprehensive programs of conveyance channel lining, increased irrigation efficiency on the farm, improved irrigation company management practices, and more effective coordination of local objectives between the various institutions in the problem areas. Salinity is no longer a local problem and should be considered regionally by the local people. In irrigated areas, it is necessary to maintain an acceptable salt balance in the crop root zone which requires some water for leaching. However, when irrigation efficiency is low and conveyance seepage losses are high, the additional deep percolation losses are subject to the highly saline aquifers and soils common in the basin and result in large quantities of salt being picked up and carried back to the river system.

A need exists to quantify the high input areas and examine the management alternatives available to establish the most effective salinity control scheme. A first important step in this regard has been taken in the Grand Valley with the Grand Valley Salinity Control Demonstration Project. The purpose of this paper is to present a summary of the important findings of the study.

Summary of Previous Research

Although the first engineering investigations in the region were made to determine the feasibility of developing more irrigated land, almost every study since has been related to salinity in some way. The early settlers were able to dig shallow fresh water wells, but as irrigation continued, the groundwater became too saline for any use. Not until low lying lands began to show signs of high water tables and older apple orchards began to fail was the necessity for salinity investigations realized. With the saline soil conditions and natural composition of the soil producing a very low internal drainage capacity, the lapse between first irrigation and the following salinity crisis was about twenty years. This seemingly protracted period would have been greatly reduced if the expansion of the irrigated acrease to the higher regions had been accomplished earlier.

Drainage

Although many early settlers attested to the seriousness of the drainage problems in the low lying lands of the valley, the conditions were alarming by about 1914. In 1908, D. G. Miller, Senior Drainage Engineer, Bureau of Public Roads and Rural Engineering, initiated an eight-year investigation of the problem covering the irrigated acreage now served by the Grand Valley Irrigation Company (7). The objective of the study was to point out the contributary causes of the high water table condition in the valley, and to emphasize the necessity of drainage as a remedy. Observations were made throughout the region to determine water quality of both soil abstracts and groundwater, water table elevations, and the effects of high water table conditions.

The early manifestations of injury due to alkalinity in the Grand Valley were first realized when regions in the more mature apple orchards began to fail. Almost invariably, when the older trees died younger trees would still grow owing to their shallower rooting system. Eventually, not even field crops could be produced. Soon after the causes of crop failure had been somewhat determined, several farms were selected in the valley where the influence of the Mancos Shale could be studied. In addition, water samples were taken from wells that had been drilled to the shale. Samples were also collected from 1,000 feet of drainage tile connecting six wells drilled into a water bearing strata in the Mancos Shale.

The conclusions formulated from this research had much to do with the organization of the Drainage District in 1924. Some of the pertinent results of the study include:

1. Drainage in the Grand Valley, because of the magnitude of the problem, must be a regional undertaking in three types of drainage. These are (1) relief of the pressure condition existing in the cobble aquifer, (2) interception of canal and lateral seepage and excessive irrigation from irrigated land in the higher parts of the valley, and (3) lateral drainage of the water logged soils in locations where natural drainage is entirely deficient.
2. The positive hydraulic gradients in the aquifer are significant in numerous locales, but rarely sufficient to bring the water within three to six feet of the surface. Consequently, high water tables were probably the result of the excessive irrigation and seepage.
3. The analysis of soil samples and groundwater samples showed a definite and direct relation between the quantities of nitrate in the samples and the total soluble salts. The percentage of nitrate increases as samples get closer to the shale. As a result, the solution of the alkaline problem, irrespective of the source of the nitrates, will eliminate the problem completely. Further, those salts that do remain in the soils can be easily ammended by standard methods.

In early 1946, an investigation was launched by the Soil Conservation Service on the "Willsea" farm west of Grand Junction (3). Piezometer readings indicated the presence of a vertical gradient of 0.48 ft/ft. Since an open drain on the north side of the farm had little effect on the problem, it was decided to drill an 8" well into the cobble to test pumping as a drainage relief. On April 15, 1947 a pump test was conducted by the SCS personnel. Pumping at the rate of 100 gpm had only very local effects, thereby indicating the need for a larger pump and certain well improvements. The possibility of pump drainage was clearly evident and aroused support for a more detailed study. In 1948, an agreement with the Drainage District and the Soil Conservation Service was formalized which initiated a test program in the area. The conclusions reached from this study include:

1. Analysis of the piezometer data indicated that the pump produced a decline in the water table near the well of approximately 0.10 inch per day, which decreased to 0.03 inch per day at a radius of about ½ mile.
2. It was observed that the pumping produced greater and more rapid changes in the aquifer pressure. The fact that the dense clay layer overlying the cobble restricted flow into the cobble from the soil was stated as the reason for the relative slow effect on the water table.
3. When the pump test was conducted, it was noted that a "hole" in the clay layer existed in the radius of the influence of the pump. It was through this hole that the water above the cobble entered the aquifer. Consequently, a drainage well in any part of the lower valley can be successful only if openings exist in the upper confining stratum which will allow the groundwater above to enter the aquifer.

Canal and Lateral Seepage

A complementary investigation to drainage is evaluation of the sources of the excess groundwater. Several experiments have been conducted in the valley starting in 1954. The first was a cooperative enterprise between the Colorado Agricultural Experiment Station and Agri-

cultural Research Service, USDA (1). An eight-mile length of the Grand Valley Main Line Canal was isolated. Both inflow-outflow and seepage meter measurements were taken. The results indicate an average loss rate in the section of about 2 acre-feet per day per mile of canal (0.30 cfd). Later, on July 12, 1955, A. R. Robinson (8) conducted a similar seepage loss investigation on the Government Highline Canal, but little is known of the results. In 1958, Salomonson and Frasier investigated lateral seepage on several 200-foot sections (4). These tests utilized the ponding method of analysis and indicated a loss rate of 0.40 acre-inch/day/mile.

Summarizing the results of these studies:

1. Seepage rates in the canal were significantly higher where the canals were located in the alluvium material. In the shale cuts, the seepage rates were noticeably lower, probably owing to quantities of groundwater interception.
2. Results show that an average of about 5 acre-feet per month per mile of canal through the test area would alone exceed the internal drainage capacity of the soils.

Farm Efficiency

It has been concluded by most investigators in the area that excess irrigation is the primary cause of the drainage problem in the lower valley. To quantify the magnitude of these contributions, efficiency studies were conducted in 1954 and 1955 by the Colorado Agricultural Experiment Station (1), and by the U.S. Bureau of Reclamation (9). The earlier studies determined that an average of 7.4 acre-inches excess was being applied seasonally, but the farms were located in a small area. In order to provide more reliable data and to provide a basis for extending the results to the valley, the 1955 study involved six new farms between Grand Junction and Fruita which were irrigated by the Government Highline Canal and the Grand Valley Canal. The results of this study indicate a significant amount being applied in addition to consumptive use and leaching requirements. A result showed that an excess as high as 23.7 acre-inches per acre was being applied annually. The Bureau of Reclamation study was conducted from 1965 through 1968 on three locally operated farms about 10 miles west of Grand Junction. Careful consideration was given to the parameters affecting the farm efficiencies being attained, as well as the efficiencies that could be attained. The fields ranged in slope from 0.7 to 1.5 percent, and in irrigation runs from 250 to 1252 feet. In addition, all three operators practiced different farming methods to some extent, which gave the investigators an opportunity to observe the effect of farming methods on irrigation efficiency. The results indicate the following general conclusions:

1. The nature of irrigation in the area in the early part of the season is not conducive to efficient irrigation as the process of "wetting across," or getting the seed bed properly moistened between furrows requires larger furrow streams and long run periods.
2. Careful observation of efficient water use not only significantly improved yields, but also required less fertilizer.
3. Control of the Western Cutworm in sugar beet fields by keeping a moist soil is seen to decrease efficiency. Since drainage was not a problem in this area, this practice was common and economical.
4. Consideration of such factors as leaching and salt loads during critical growth periods, as well as soil tilth, not only improved yields, but also affected irrigation efficiency.

Regional Hydrologic and Salinity Studies

The increasing salinity problem in the Colorado River Basin has necessitated the collection and analysis of data on water and salt flows in order to evaluate the contributions from various sources. Although several interested governmental agencies have conducted short term studies in the basin, the primary source of data is the U.S. Geological Survey's stream monitoring system. One of the most comprehensive efforts to summarize and analyze this data was made by Iorns, Hembree, and Oakland (6) for the period between 1914 and 1957 and adjusted to the 1957 conditions. The study was inclusive of the entire Upper Colorado River Basin, but for the purposes of this report only the section dealing with the Grand Valley area has been extracted. Because the location of the exiting gag-

ing station is below the confluence with the Delores River, some of the data is not uniquely representative of the Grand Valley.

Some of the results of this study provide an interesting overview of the basin wide implications caused by water use in the Grand Valley. An extraction of part of the data is shown schematically in Figure 2, showing the fraction of flows for water and salt that flow in the Grand Valley related to the total flows at Lee's Ferry, Arizona. The effect caused by water resource development in the basin above the Grand Valley was shown to be an increase from 178 to 592 ppm in the Gunnison River Basin and from 272-382 ppm above Grand Valley along the main stream. The net effect of man's activities through the Grand Valley were determined to be a salinity increase of 256 to 547 ppm. The total salt loading to the Colorado River from the Grand Valley averaged about 750,000 tons during the period, although when adjusted to the 1957 conditions the value was set at 440,600 tons. In terms of tonnage contribution per acre, the salt pickup would be between 5 or 6 and 8 tons per acre depending on the time period used.

The wide fluctuation in salt pickup through the Grand Valley is shown in the USGS report (6) to be related to the river discharge. This poses an interesting source of salinity control speculation. For example, during the period from about 1930 to 1942, the average was 860,000 tons pickup per year, in 1943 to 1951 the average pickup was 745,000 tons, and in 1951-1957 period, the addition was only 490,000 tons of salt pickup annually. The significance of this is that during each of these periods the annual river discharge was decreasing, which would somewhat indicate that during water short years the farm efficiency increased, thereby resulting in dramatic salinity reductions.

The 1963-1967 water years were selected for study by the Colorado River Board of California (2) and other governmental agencies in order to appraise the salinity sources in the basin, as well as evaluate the future impact of water resource developments on mineral water quality. The results pertaining to the Grand Valley, in particular, indicates the salt pickup to be about 8 tons per acre per year, which is the result Hyatt (5) established for the 1963-1964 years (Figure 3). Both of these references are useful data sources for examination of the Upper Colorado River flow system.

Experimental Design

The evaluation of canal and lateral linings as feasible salinity control measures depends to a large extent on the success of isolating and measuring the various segments comprising the water and salt flow systems discussed in the previous section. The primary emphasis of the Grand Valley Salinity Control Demonstration Project took place in Area I, the intensive study area shown in Figure 4. Since the purpose of the project was to demonstrate canal and lateral linings for salinity control, the main advantage of this site is that it involved a large number of the irrigation companies in the valley. Areas II and III included one additional company, but were selected for their different land conditions. The principal test area also represented an area in which hydrologic conditions could be studied in reasonable detail and in which the local effects of poor water management were significant.

The instrumentation in the study area indicated by Figure 4 provides valuable data concerning many of the important water and salt movements. While some of the parameters can be measured directly such as drainage discharges, lateral diversions, water quality, and precipitation, others cannot and must be investigated indirectly. These budget parameters relate mostly to groundwater movement and are monitored for changes using such techniques as piezometers, wells, and soil sample analyses.

Instrumentation

The area I instrumentation has provided valuable data for analyzing the hydrology of the area. The data collected from these locations were used to delineate the canal and lateral diversions, drainage outflows, water table and aquifer pressure fluctuations, and water quality at the various locations. In order to gain a clearer picture of the type and limitations of data gathered from each type of measurement, it is useful to examine them individually.

The hydrostatic pressures and gradients in the region of alluvium between the cobble aquifer and the water table were studied using nu-

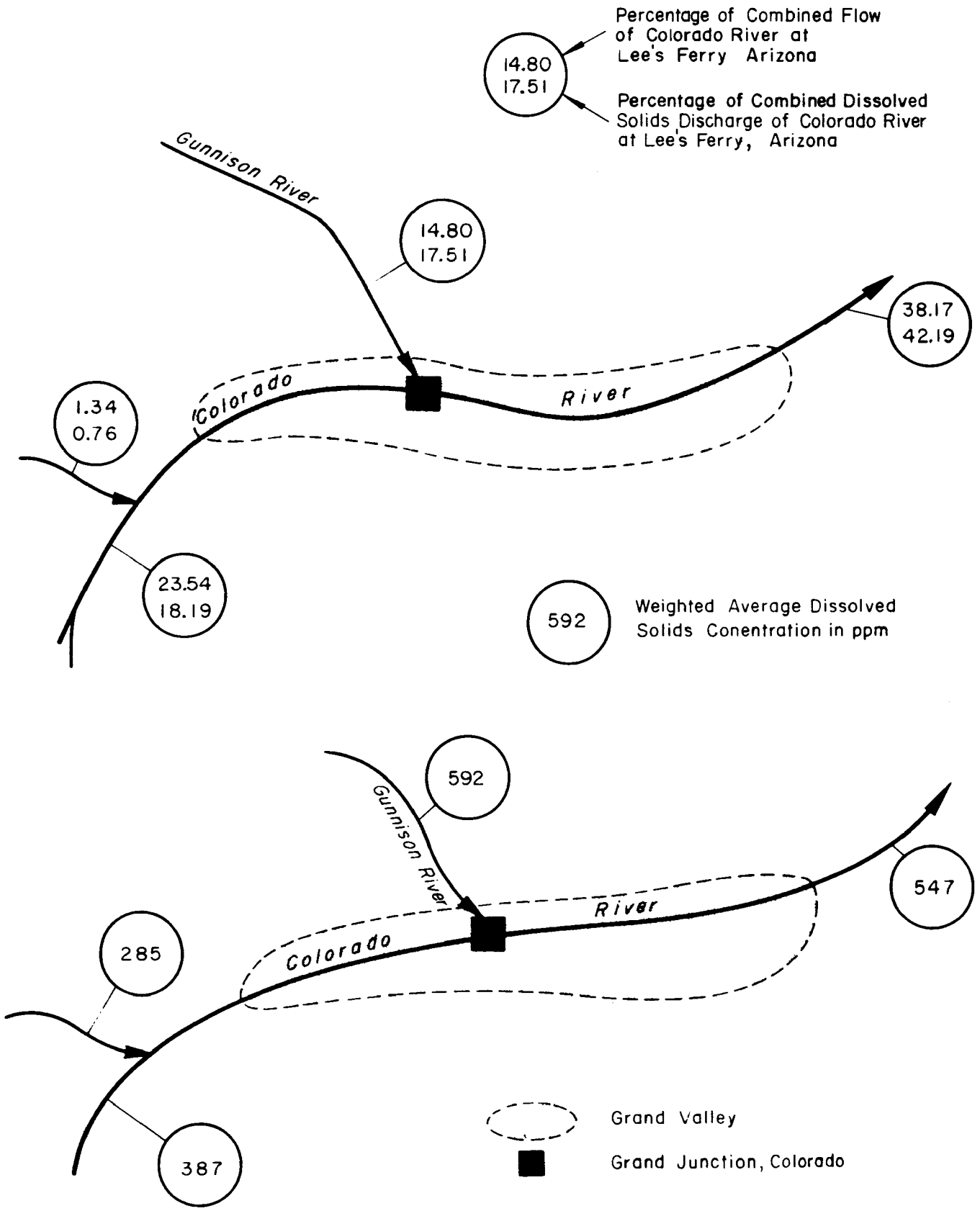

Figure 2: Water Quality in Grand Valley

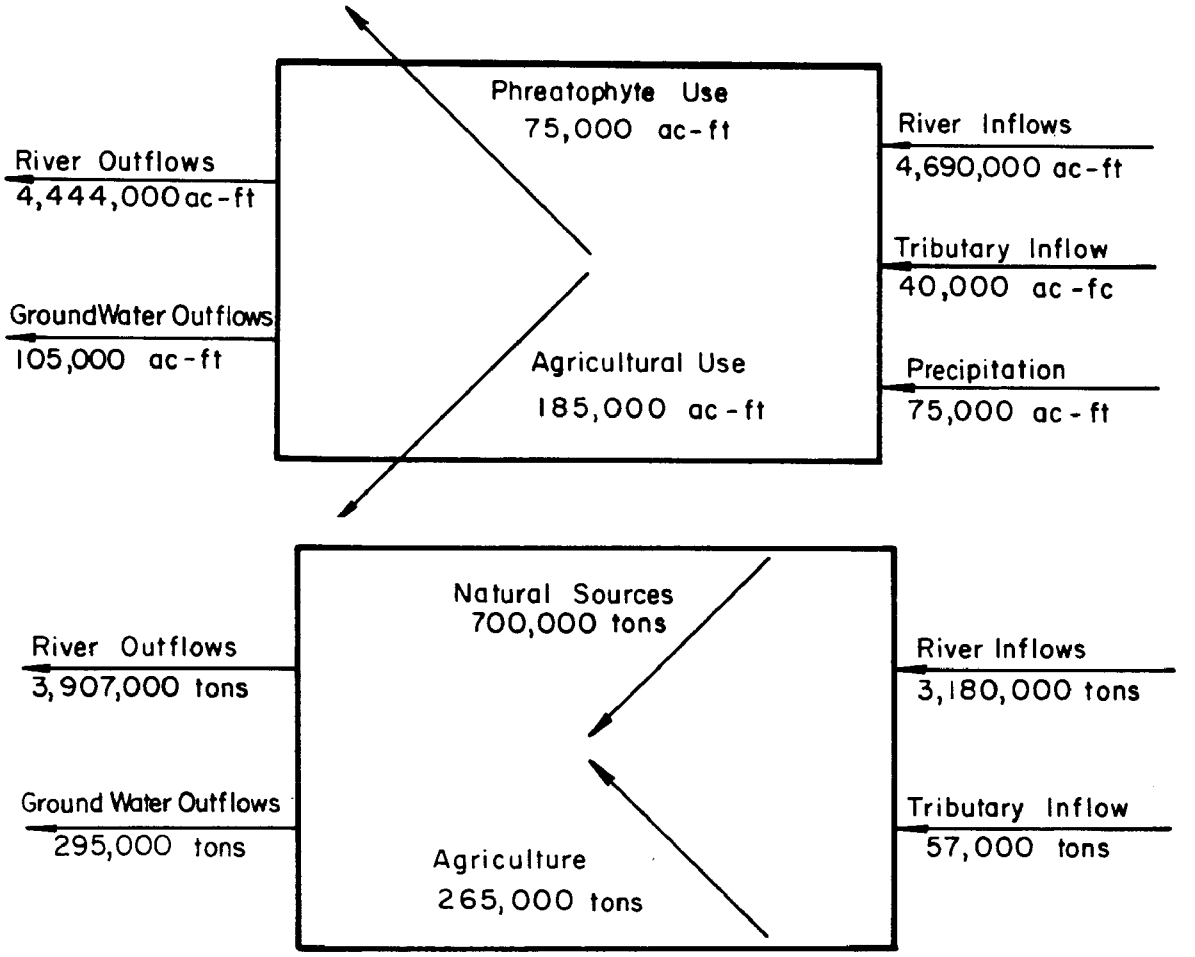

Figure 3: Schematic Water and Salt Budgets for the Grand Valley During 1963-64 Water Years

merous clusters of ⅜ inch steel pipe piezometers. In each cluster, which contained three to seven piezometers, the depths that each extended were varied so the vertical hydraulic gradient could be evaluated. The small pipe sections were placed using a jetting technique and the same apparatus could also be used to periodically flush the pipes to insure reliable readings. The small pipes were also used to evaluate hydraulic conductivity of the subsurface strata.

Due to the limitation of the piezometer depths, the examination of the movement of water and salt in the cobble aquifer was conducted by drilling two-inch steel pipes into it. The function of these instrument points has been essentially the same as that of the smaller piezometers. The larger diameter better facilitates the collection of water samples and are somewhat easier to read.

The drillers log from each installation located the topography of the subsurface strata to and including the Mancos Shale. In addition, a few of the pipes were initially continued a small distance into the shale formation indicating the presence of small aquifers within the shale. Because the number and distribution of these larger piezometers is small, all pipes were installed in the overlying cobble strata and the influence of water inside the shale has been assumed small.

The small Parshall and Cutthroat flumes used in this study have not only been used for monitoring drainage discharges as shown in Figure 5, but have also been used extensively as part of the special studies on farm efficiency, lateral seepage, and lateral diversions. At the most important locations in the area, flumes with continuous stage recorders have been installed in order to minimize the error in evaluating these discharges. Since both of these type flumes are most accurate when critical depth occurs in the flume, attention to these conditions was made upon installation and continually monitored throughout the study.

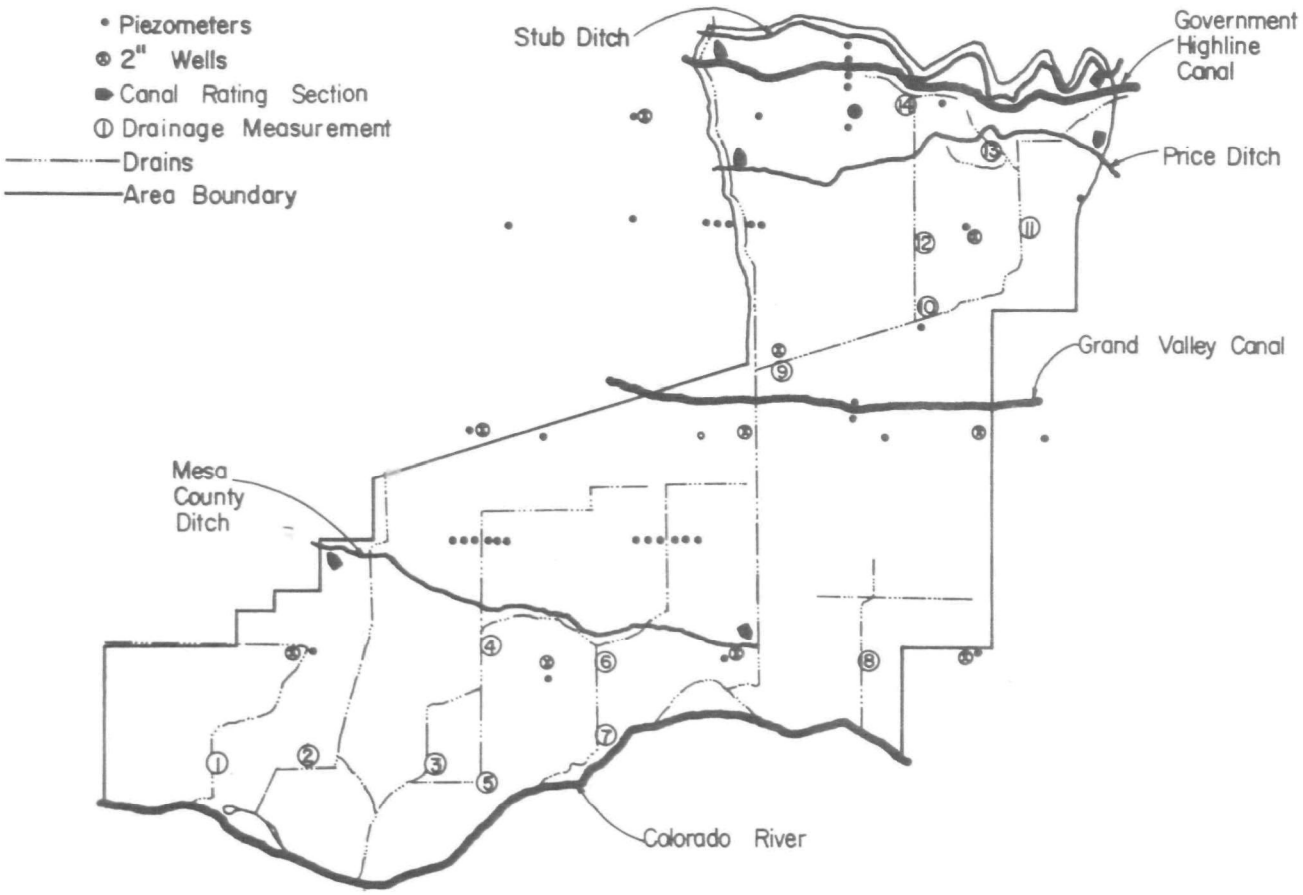

Figure 4: Location of Instrumentation in Area I

An essential item in the analysis was the determination of the magnitude of the quantities of water diverted from the canals into the lateral system for irrigation. This was accomplished in two ways:

1. The smaller capacity canals such as the Stub Ditch, Price Ditch, and Mesa County Ditch were rated at both the inlet and exit sections in the test area.
2. The discharges in the Government Highline Canal and the Grand Valley Canal are so large that the error in the inlet and exit ratings would over-shadow the diversions. To remedy this situation the turnouts from each canal were individually rated.

Land Use Inventory

The quantity of water transpired from vegetation surfaces or evaporated from soil add water surfaces can only be measured using expensive equipment. As an alternative, computational methods can be used to estimate evapotranspiration for each type of vegetation. In order to meet the data requirements of these methods, it is necessary to determine the type and area of each land use. This analysis was performed for the entire Grand Valley (12) with the data subdivided by sections within townships and also by section within townships served by individual canals. The procedure involved carrying aerial photos (1 inch = 1000 feet) into the field and marking the various land uses according to a prescribed index. Then the data was transferred to inked base maps where the acreage of each land use was evaluated.

Seepage Investigations

The seepage from conveyance channels in the three project areas of the study were examined in two parts: (1) lateral seepage in Area I and (2) canal seepage in Areas I and III. This type of study was conducted before and after the linings had been constructed along the lengths of the Stub Ditch, Price Ditch, Government Highline Canal, and Mesa County Ditch. In addition, a before and after measurement was made along the Redlands First Lift Canal, which is located in Area III.

Figure 5: One-Foot Cutthroat Flume Located in an Open Drain in the Test Area

The ponding method for determining seepage loss rates was selected to assure accurate measurements, especially in the two large canals. The degree of error in using inflow and outflow measurements would have tended to mask the magnitude of seepage losses. The ponding method, illustrated in Figure 6, consists of placing an impervious barrier at two or more locations along the canal, filling each resulting isolated section with water, and then taking periodic measurements on falling water elevations, which can then be used to evaluate the seepage rates.

Farm Efficiency Studies

The efficient use of water on the farm would be achieved when the total quantity of water entering the field was just sufficient to meet the demands of the crops, soil surface evaporation, and the quantity of water necessary to leach the residual salts of the evapotranspiration process from the root zone. Factors which decrease the farm water use efficiency in the Grand Valley are numerous and result in excessive deep percolation losses and large field tailwater flows. Since the waste flows result in additional salinity problems, irrigation efficiency is a good indirect examination of the areal magnitudes of deep percolation, drainage interception, consumptive use, and field tailwater. As noted earlier, without expensive and complex instruments, farm efficiency studies become the most feasible method of estimating these variables.

The principal parameters related to evaluating on-farm water use include:

1. Field tailwater which can be measured in the Grand Valley with small Parshall or Cutthroat flumes.
2. Deep percolation and leaching requirements derived from budgeting the root zone flows.
3. Root zone storage changes measured by soil sampling and correlated neutron probe techniques.
4. Evapotranspiration which is computed.
5. Uniformity of applications evaluated from soil moisture samples, along with advance and recession analyses.
6. Precipitation.

Results of the Canal and Lateral Linings

Basin-Wide Benefits of Salinity Control in the Grand Valley

If the economics of salinity control are examined closely, almost any control method is feasible on the basis of the traditional benefit-cost ratio. The extension of this concept to a basin-wide scale yields some interesting points. According to the estimated damages being experienced in the lower basin (10), a conservative value of $100,000 per ppm per year at Lee's Ferry, Arizona is not an unreasonable datum. In the period between 1931 and 1960 and adjusted to 1960 conditions in the basin, the annual flow rate at Lee's Ferry was 10,880,000 acre-feet carrying 8,570,000 tons of total dissolved solids (5). Thus, a ton of salt represents 0.676×10^{-4} ppm and results in seven dollars of annual damage.

If it is assumed that a repayment period of 50 years is taken at an interest rate of 7%, the maximum present cost that should be incurred to re-

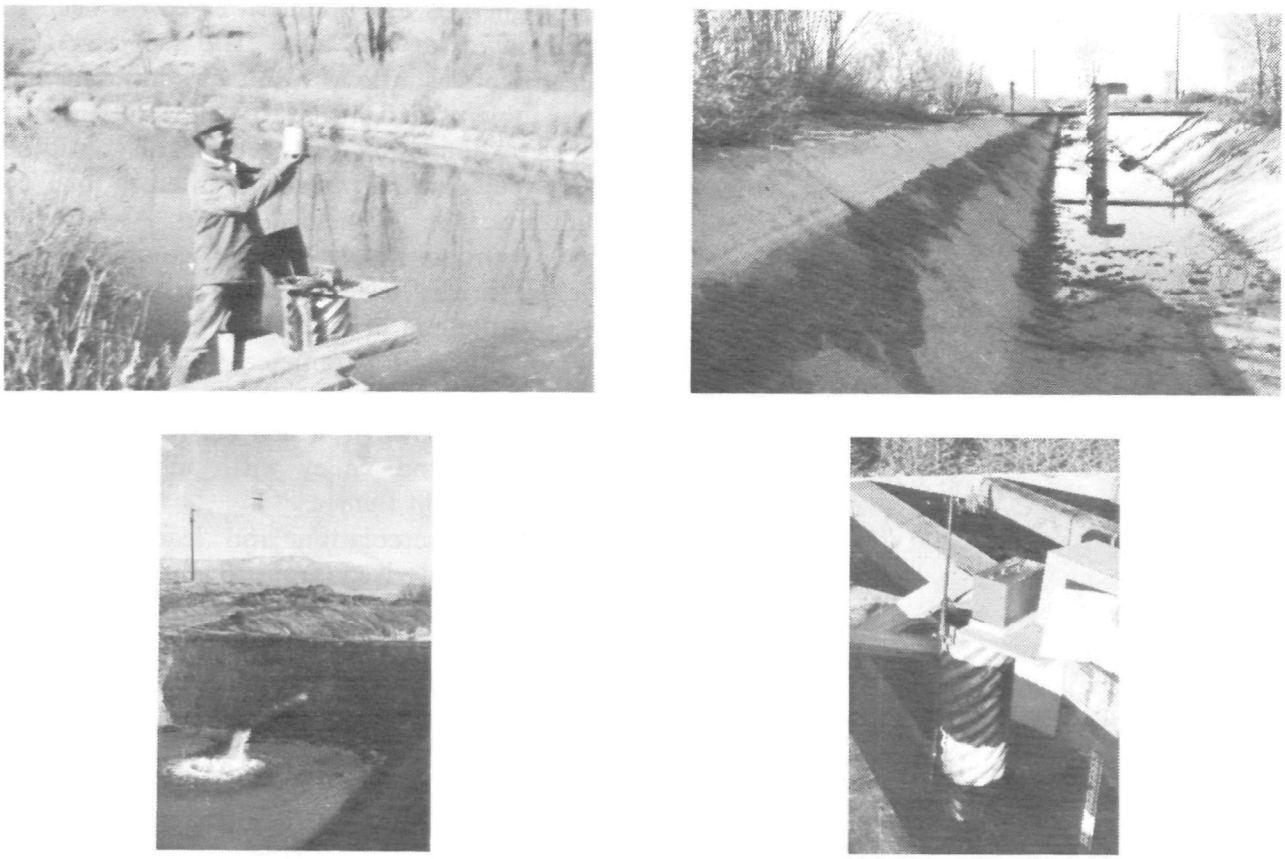

Figure 6: Canal Seepage Measurement Using the Ponding Method

duce one ton of salt from the system is $97. It should be noted that once the money has been spent to control the ton of salt, it is assumed to be a permanent improvement so that the money is only needed at an initial point of time. The total cost of the lining program was $420,000, with $350,000 being spent for actual construction and $70,000 for administration, design, and construction inspection. In terms of the Grand Valley Salinity Control Demonstration Project, a salt reduction of 4300 tons should be made in order to economically justify the project, based upon downstream damages alone. If for comparison, a repayment period of 30 years is taken, the acceptable present cost of each ton of salt reduction is $87 and the break even point for this project would be a reduction of 4800 tons.

Local Benefits of the Canal and Lateral Linings

An adequate evaluation of the operation and maintenance benefits attained from the linings is difficult. Correspondence with the officials of the Grand Valley Water Purification Project, Inc., most of whom are also serving as local irrigation and drainage officials, has delineated certain benefits resulting from the lining program. The moderate gradient channels, when running near capacity from April 1 to October 31, experience comparatively few problems with bank vegetation, mossing, and sedimentation. Records and comments from irrigation companies indicate an average maintenance cost per mile of between $250 and $370 per year, depending of course on the canal size. In the intensive study area, the construction will probably result in a total savings of $2500 annually. Although periodic maintenance is always necessary, there are linings ten or more years old that have as yet required almost no attention. When the canals are lined, the improvements to the delivery system for new turnout structures and measuring devices greatly aid handling, distribution, and charging for water and provide a stimulus to irrigators for more efficient water management.

The local benefits from the linings in many parts of the Grand Valley are primarily indirect

and include factors such as improvements to adjacent lands. In the test area and in a large portion of the valley, the value of land is primarily determined by the expanding urban areas and as such do not greatly depend on agricultural production. Nonetheless, the increased utility of well drained soils is worth far more than the cost of the linings.

Seepage Reduction Due to the Linings

The results of the seepage rate measurement before and after the canal linings (summarized in Table 1) indicate that the linings are not especially effective when the seepage rates are already low. However, based upon the modeling results, the reduction in seepage rates attributable to the canal linings was placed at about 600 acre-feet per year. While this figure may not seem very large at this point, the effect on the salinity loadings to the river is fairly substantial and will be noted in a later section.

Although no effort was made to evaluate seepage rates in the laterals after they were lined in Area I, it is not unrealistic to assume the same values as found for the canal linings. A typical loss rate of 0.1 cfs per mile would represent a rate in a usual lateral of about 0.5 cfd, or about as large as earlier studies indicated. Consequently, the lining of most laterals would result in about a 90% seepage rate reduction.

The effect of the lateral linings constructed as part of this project indicates linings probably result in a seepage reduction of on the order of 200-300 acre-feet annually. This reduction is from lining only five of the estimated 90 miles of laterals in Area I. However, most of the linings were constructed where water tables were low and thus represent high seepage rate areas. On a valley-wide scale, the lining of canals could be expected to reduce seepage losses from 5% to about 1% of the total canal diversions. The seepage losses from the lateral system could be expected to be much greater, probably from 10% to about 2% of the total agricultural diversions.

TABLE 1

Comparison of before and after lining results by ponding tests

Canal	*Seepage rate before lining (cfd)*	*Seepage rate after lining (cfd)*	*Reduction (%)*
Stub Ditch (concrete slip-form lining)	0.15	0.07	53
Price Ditch (concrete slip-form lining)	0.15	0.07	53
Gov't Highline Canal (gunnite lining on downhill bank)	0.25	0.13	48
Mesa County Ditch (gunnite lining)	0.15	0.03	80
Redlands First Lift Canal (concrete slip-form lining)	0.40	0.06	85

Salt Reductions Due to the Linings

In order to control the salt pickup from the Grand Valley, the irrigation return flows through the cobble aquifer and the overlying soils must be reduced. It has been argued that even reducing groundwater flows would not reduce the salt loadings since the reduced water would simply become more concentrated and thus carry the same load. The results of this study indicate that groundwater is retained in the soils and aquifer much longer than is necessary to reach chemical equilibrium with ambient salinity concentrations. However, whether a 50 percent reduction in moisture movement through the soil would result in a 50 percent reduction in salt pickup is not known at the present time. Nevertheless, since the quantity of water reaching the groundwater due to conveyance seepage is small, this assumption can be made with confidence.

The exact region of salt pickup through the soil and aquifer profiles has not been defined in this study. It was originally though that when water came in contact with the Mancos Shale the most significant load of salts was picked up, but later data analysis showed this assumption to be false, so the specific nature of the salt loading in the area is unclear. Nonetheless, these unanswered questions do not significantly affect the reliability of the model which was developed to evaluate on a quantitative scale the magnitudes of the various segments of the hydro-salinity system.

Although the complete water and salt budgets derived during the course of the study will not be presented herein, it is interesting to examine some of the annual figures. During the 1971 water year, the total salt input to the intensive study area was approximately 23,000 tons and the total outflows amounted to about 79,000 tons. Consequently, a net gain of about 56,000 tons occurred, which amounts to almost 12 tons per irrigated acre. Even though this figure is above the valley average (8 tons per acre), it is reasonably certain that salt loading varies from region to region within the valley and the conditions encountered in the test area are probably the most conducive to high salt loading anywhere in the valley.

Of the total salt input in Area I, 14,810 tons (0.86 tons/acre-foot) is computed to be the area contribution to the groundwater flow system, with 12,520 tons resulting from over irrigation (deep percolation), 170 tons from canal seepage, and 2120 tons from lateral seepage. Thus, for each ton of salt added to the groundwater basin (assuming that here is where all additional salt is added), 3.8 tons can be expected to result when the irrigation return flows reach the river. The effects of the canal and lateral linings can now be seen. The canal and lateral linings which reduced seepage into the groundwater basin by about 930 acre-feet during the year reduced the salt contribution from the area by 4700 tons. The canal and lateral linings which were constructed as part of the project, while undertaken for the purpose of investigation and demonstration, are thus economically feasible from a salinity control standpoint with a benefit-cost ratio of 1.09. If the damage figure for each part per million at Lee's Ferry, Arizona is increased to $150,000, the resulting minimum cost per ton of salinity reduction is $138 and the lining in this project would have a benefit-cost ratio of 1.54 based solely on salinity control (50 year repayment period at 7% interest).

Indirect Impact of Canal and Lateral Linings

Although the formal results of canal and lateral lining will establish that the impact on salinity reduction due solely to reducing seepage is small in comparison to the total problem, the importance of canal system improvement should not be underestimated. The greatest impact on the salinity problem from canal and lateral linings is better system management. Almost every arid agricultural area depending upon a year to year fluctuation in the water supply can produce evidence to substantiate the fact that during periods of diminished supply, farm production is often higher as a result of better water management on the farm. The explanation of this observation does not lie in the use by the farmer alone, but also involves the distribution of an equitable water supply to the irrigator. Thus, the irrigation company or district which is faced with water distribution among demands which totally exceed the supply are the primary controllers. This indicates that any presently proposed salinity control alternative to be implemented on a valley-wide scale must involve efficient canal management. In or-

der to improve canal system management, rehabilitation by programs of linings and installation of adequate diversion, measurement, and control structures is inherent.

Study Conclusions

The basis for reducing salt loadings from the Grand Valley is to minimize percolation into the groundwater basin. At the present level of salinity control technology, it is difficult at best to determine what effect a 50% reduction in these flows valley-wide would have. However, the bulk of the deep percolation losses are the result of excessive irrigation applications and, as such, the objective of any salinity control program should include measures to improve the efficiency of on-farm water management.

The first and most important consideration in improving farm water use is sound canal company management practices. Implied in this realization is the requirement of sound water measurement at the farm turnout and again at critical division points among farmers below the turnout. This would necessitate a considerable rehabilitation of both the canal and lateral system, and the implementation of a "call period" to allow canal operators more time for flexible water handling. In addition, it is an important requirement that the canal companies extend their control of the water below the canal turnout structure to include key division points within the lateral system in order to insure equitable allocation of water among users. Other necessary aspects of efficient on-the-farm water management are the incorporation of irrigation scheduling programs and an effective drainage system.

An important conclusion of this study is that no single salinity control measure will effectively alleviate the Grand Valley salinity problem. It is thus adamant that an integrated program involving a planned combination of water delivery rehabilitation, on-the-farm water management, and effective drainage be implemented for efficient salinity control.

Probably the most binding constraint for reducing salinity from the valley is not in the relative feasibility of the technological alternatives, but in the institutional structure of western water laws. In order for water management in the area to improve without devastation of the already burdened agricultural system, new mechanisms for economic incentives for improving the efficiency of water use must be applied. Present water laws are actually a deterrent to better water management because of the resulting loss of a portion of a water right, which is considered very valuable to an irrigated agriculture.

The results of this study indicate that the lining in the test area reduced salt inflows to the Colorado River by up to 4700 tons annually. The bulk of this reduction is attributable to the canal linings, but clearly indicated is the greater importance of lateral linings. The economic benefits to the lower basin user alone exceed the costs of this project. Consequently, it seems justifiable to conclude that conveyance lining in areas such as the Grand Valley where salt loadings reach 8 tons per acre, or more, are feasible. The local benefits accrued from reduced maintenance, improved land value, and other factors add to the feasibility of conveyance linings as a salinity control alternative.

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Management of Irrigation Water in Relation to Degradation of Streams by Return Flow

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ABSTRACT

Alternatives for improving the quality of return flow to avoid the concentration of soluble salts in the return and seepage flows are discussed. The process of concentrating salts is an inevitable consequence of evaporation and transpiration. Possibilities for using automated water management systems with a high degree of water control to deposit salts either in the soluble or insoluble form below the root zone or in the aeration zone above the water table are discussed. The dilemma of keeping excess salts out of return flow and streams or continuing to periodically leach them out of the root zone to maintain a neutral or favorable salt balance cannot now be resolved. Eventual solution of the problem must take into consideration the crop, depth to water table, amount of rainfall, quality of irrigation water, and water management practice.

INTRODUCTION

The specter of rich, western irrigated valleys turning into salty deserts or marshes like the once productive plains of the Tigris and Euphrates Valleys of ancient Mesopotamia has induced us to think that every irrigation project and every field should have a favorable salt balance. Favorable salt balance means that total salt in drainage return flows should be at least equal to or greater than that of the irrigation water applied. Since the water evaporated from soils or transpired by plants is essentially distilled water, the inescapable consequence of this consumptive use is that the salt concentration in the drainage is necessarily higher than that of the irrigation water. Degradation of water quality by increase in salinity is inevitable if there is drainage.

These traditional ideas on the need for a favorable salt balance have been entirely consis-

tent with the very practical need to keep salt in the root zone at permissible levels so that yields will not be reduced. Salts inhibit plant growth largely by reducing water absorption by the roots, although there are some specific ion effects such as the limited tolerance of some species to chloride.

Salts originate from the weathering of primary minerals and of some sedimentary rocks, such as marine shales that may be high in salts. Other sources of salt are the cyclic salts from the sea that come down in rain or as particles, especially along coasts. Salt rarely accumulates in soils from the weathering of rocks to levels of significance to plants, but becomes concentrated in soils by the evaporation of salt carrying waters.

Our traditional approach to improving saline soils or to controlling the accumulation of salts in nonaffected soils is to periodically leach them. In sophisticated terms, this means the calculation of the leaching requirement, which is the amount of water that must be applied in excess of consumptive use to keep the soil solution at the bottom of the root zone at a permissible salt concentration, depending on the kinds of crops to be grown. The salt concentration of the input and drainage waters, and the consumptive use are the parameters needed in making such calculations. Precipitation of insoluble compounds such as lime and gypsum or their solution is ignored in such calculations (U.S. Salinity Lab Staff[20]).

Obviously, the kind of irrigation system and its management is just as important as the kind of cropping and cultural system and irrigation water quality in management of excess salts that no one wants, either in the drainage or in the soil.

Alternatives for Improving the Quality of Return Flow

If irrigation is to continue, then at this time, we appear to be caught on the horns of a dilemma. One horn is the need to keep salts low in the root zone, and thereby degrade the quality of the return flow to rivers by increasing the concentration of salt in the drainage or the percolate to ground water which eventually reaches rivers or is pumped for reuse. The other horn is the need to maintain good quality return flow by having neither leaching to ground water nor runoff. The salts accumulating from consumptive use would have to be stored either in the root zone or in the aerated zone between the bottom of the root zone and the capillary fringe of the water table. The amount of the latter space depends on substrate porosity and the depth of the water table and its fluctuations. Possibilities for salt storage include storing them in part of the surface soil not used by roots (as in trickle irrigation) or the precipitation of lime or gypsum so that they no longer enter into the salt balance. Another possibility is to grow more salt-tolerant crops. Sections of the world that are very arid and have no water for leaching are further along than we in the United States in knowing how to live with salts in the root zone.

Since we are caught on the horns of the dilemma, it seems that some compromise will have to be worked out between degradation of quality of return flow and degradation of soil. The compromise will have to be made on a river-by-river basis or regional basis, with all benefits and detriments known or estimated. On one river some degradation would have little effect; on others, it would add to an already acute problem.

Little is known now about storage of salts in the soil profile in insoluble forms so that they do not enter the leaching requirement equations to maintain a favorable salt balance. Eaton[5] pointed out that irrigation waters high in residual bicarbonate should accumulate lime and sparked a whole new set of investigations on special treatment of high carbonate waters in assessing the sodium hazard. Thorne and Thorne[19] examined 14 paired profiles that had 12 different water sources in Utah as to changes in chemical compounds. Lime content changes varied from an increase of 2½ percent to a decrease of 7½ percent in the surface 6 inches of soil. Lime content decreases were associated with the waters highest in salts as measured by electrical conductivity, calcium plus magnesium, chloride, and sulfate. This behavior was explained by increased solubility of calcium carbonate in salt solutions. By statistical methods they showed that lime content did not change when the water had a conductance of 2 mmhos per cm. Such water has high or very high salinity hazard.

Several studies (Bower and Wilcox[2], Bower et al.[3], and Bower et al.[1]) have dealt with the question of precipitation and dissolution of $CaCO_3$ when soils are irrigated with high bicarbonate water. However, most irrigation waters do not contain residual carbonate as defined by Eaton[5], and so the extent of precipitation of lime, gypsum, and other salts of low solubility in soils irrigated with more common irrigation waters are now unknown. Extensive studies of the phenomena are now underway at the U.S. Salinity Laboratory.

In the management of irrigation water for the final disposition of salt, the amount applied and time of application in relation to consumptive use and the method of irrigation are very important management variables.

Controlled Application of Irrigation Water to Achieve High Application Efficiencies

Based upon arguments presented above, it appears that a salt control achieved either by controlled leaching, by chemical precipitation of salts in the soil profile, or by storage of salts in or below the surface soil is essential if a permanent irrigated agriculture is to be maintained. In any alternative, the need for efficient application and controlled distribution of irrigation water is implied. Recent technological developments to automate existing water control structures on surface irrigation systems and the development of automated solid-set and traveling types of sprinkler irrigation systems have stimulated capital investment on large or corporate farms to achieve a high degree of water control and at the same time reduce irrigation labor requirements. More recently, widespread interest in the solid-set trickle- or drip-irrigation method, although limited in application, offers further promise of achieving an even greater degree of water and nutrient control under certain soil, water and cropping conditions. Regardless of the irrigation method used, application efficiencies and uniformity coefficients > 90 percent are possible if the necessary capital investments are made and the irrigation systems are properly designed and operated to maximize their potential capabilities. In the discussion that follows, the viewpoint is that it is desirable and essential to attain a high application efficiency to avoid excessive deep percolation and runoff losses, thereby using the deep subsoil as a "salt-sink" to reduce the buildup of salt in the return flow and/or ground-water reservoirs.

Surface Irrigation Systems

Dead level irrigation, where applicable, provides an excellent system of water control and is readily adapted to automation. This irrigation practice is being used principally on alluvial soils in the Desert Southwest to reduce irrigation labor requirements and to achieve a higher degree of water control for efficient operation. Water is applied to dead-level irrigated blocks of land ranging from 5 to 10 acres in size. Large streams of water, usually 10 to 20 cfs, are released through standard jackgates installed in open channels or from a buried pipeline equipped with alfalfa valves and risers.

Where jackgates are used, the irrigator need only open one gate and close another to change irrigation sets. This can be done in minutes. Application efficiencies approaching 95 percent are possible by rapidly flooding the basin to irrigate a solid crop like alfalfa or applying water to dead-level furrows formed within the irrigated block. No applied water or rainfall runs off. Water applied to "fast" furrows is turned around at the far end to irrigate "slow" furrows. Thus, the farmer is able to apply nearly the exact amount of water required on a timed basis to satisfy crop needs and leaching requirements, provided the stream size is matched to soil texture and/or intake rate, crop and the size of area irrigated. In the Lower Rio Grande Valley of Texas, additional benefits accrue through maximum utilization of rainfall (about 20 inches annually) for leaching and/or supplemental water for crop growth in an area where the average annual irrigation allotment is about 1 acre-foot per acre.

An example of how a dead-level irrigation system has been automated on the Bruce Church Ranch, Inc., near Poston, Arizona, is illustrated in Figures 1 through 6[11]. The USDA pneumatic diaphragm[10], shown in Figure 1, is used to control the remote release of water from standard alfalfa valves and risers attached to buried pipelines.

Although the captions for each figure describe the function of the various components

Figure 1: Pneumatic Diaphragm installed on 12-inch alfalfa valve and riser to automatically control discharge. When inflated, as shown, flow of water ceases; when deflated, as shown in Figure 2, water is released (Bruce Church, Inc., Poston, Arizona, February 1971)

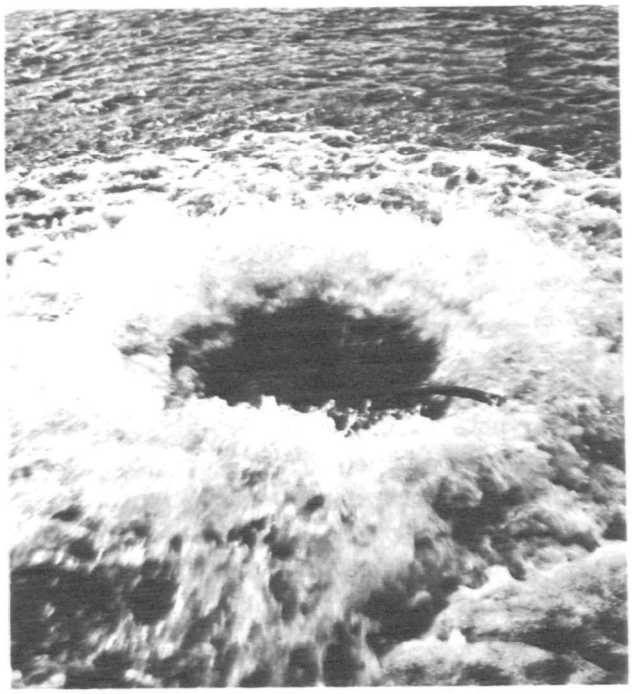

Figure 2: Same as Figure 1 with pneumatic diaphragm deflated to permit discharge of water

Figure 3: Automatic irrigation system shown in operation on 20 acres of wheat, Bruce Church Ranch, Inc., Poston, Arizona, February 1971. Zig-zag border permits distribution of water in both directions from buried distribution pipeline. Each 5-acre field is dead-level and 4, 12-inch valves discharge a combined flow of about 10 cfs. Field at right with valves in "zigs" has received a 4-inch depth of application and at left, 4 valves in "zags" have just opened to water opposite 5-acre field

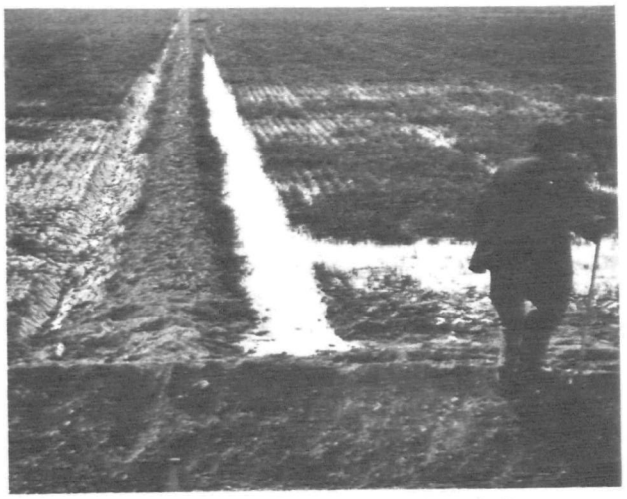

Figure 4: Border dikes surround each 5-acre field. Water flowing in dead-furrow completely surrounds irrigated area permitting rapid flooding from all directions

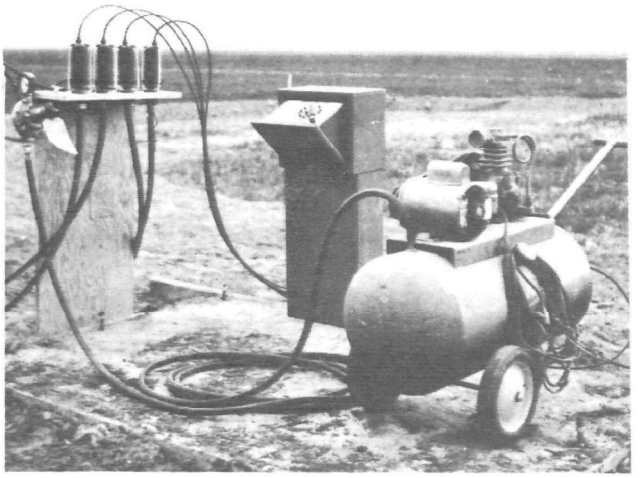

Figure 5: Controls required to operate automatic surface irrigation system consist of pressure regulator (far left), pilot valves with 1/2-inch polyethylene control lines attached, a commercially available electromechanical timer used to irrigate turfgrass, and air compressor (far right) with 1/2 H.P. electric motor

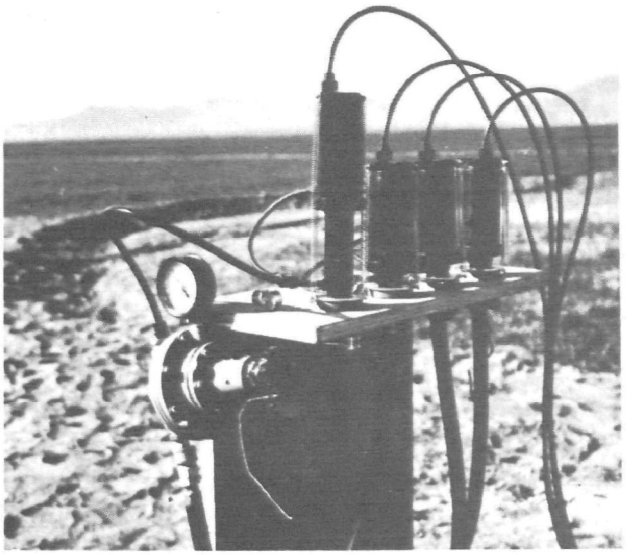

Figure 6: Nearest pilot valve is opened to permit rapid discharge to atmosphere of air in pneumatic closures for release of water from riser and alfalfa valve in set 1. Holes in wall of piston of extended air cylinder allows rapid discharge of air from control line connected to pneumatic closures. When in retracted position, air pressure is fed to pneumatic closures through 5/16-inch tubing to close alfalfa valve and stop the flow of water

and collectively explain how the system works, a few additional remarks are offered to clarify operation procedures. When manually operated, the irrigator opens 3 or 4 12-inch valves in the first irrigation set. He then alternately opens and closes the required number of valves per set until the 40-acre unit has been irrigated. The combined flow from the 3 or 4 valves (usually 10 to 15 cfs) floods a 5- to 10-acre area surrounded by a dike. From 1.5 to 2.0 hours are required to irrigate each set. During the peak water-use period, as many as 14 irrigators are needed to simultaneously apply water to designated fields on this 6,000-acre ranch. With automation, it is anticipated that the labor requirement could be reduced by one-half.

The dead-level system of irrigation described here provides a high degree of water control and leaching capabilities from an engineering point of view. Whether a favorable salt balance can be maintained and at the same time promote the precipitation and the deposition of salts at some point within the soil profile is a matter of speculation. Certainly the degree of water control this system provides is adequate to accomplish such an objective if soil profile conditions, depth to water table, and other chemical and physical factors are favorable.

Level or low gradient border strips or checks offer the same automated capabilities and degree of water control as the dead-level irrigation system. But certain limitations of slope, topography, soil texture, soil depth and development must be recognized.

In 1959 and 1960 a low-gradient border strip irrigation system was constructed at the Newell Field Station, Newell, South Dakota, on Pierre clay with slopes ranging from 0.5 to 5 percent[4]. Based upon the high application efficiencies achieved with low-gradient irrigation systems elsewhere and coupled with the possibilities for automation, it was believed that maximum utilization could be made of rainfall during years when irrigation allotments to the Station were 12 inches or less. A full irrigation allotment of 24 inches was received in 10 of 34 years (1930 to 1964) and, during the same period, 10 allotments were less than 12 inches. One further advantage anticipated was the possibility of adapting automatic controls to alfalfa valves and risers in each border strip or check.

Problems that were difficult or impossible to solve soon appeared. Most of the surface soil that was moved downslope to create the level or nearly level border strips was deposited in the escarpment or berms between each leveled strip. After 12 years, the soil productivity of the "cut" areas on the original steeper slopes has not been fully restored. Where the depth of "cuts" exceeded 12 inches, high salts in some of the exposed subsoil reduced productivity further. Since it is difficult to maintain a perfectly level surface, low spots with standing water following irrigation or rainfall have interfered with trafficability and timeliness of cultural operations. Where grass was planted on the escarpments between border strips, large soil cracks appeared in the shrinking-swelling clays as they dried, resulting in leakage from one border strip to another. Rodent burrows further complicated the problem. A 6-mm. plastic sheet placed in the escarpment with a "berm splitter" prevented leakage but considerably increased the cost of the installation. Surface drainage following periods of heavy rainfall was inadequate on the nearly level border strips, and border dikes at the lower end often had to be opened to remove excess water.

Based upon these experiences, the advantages of low-gradient irrigation systems originally envisioned are far outweighed by the problems created. Where site conditions are similar to those described above, low-gradient bench-leveled border-strip irrigation systems are not recommended.

In contrast, level or low-gradient border strips or checks constructed on Tripp fine sandy loam on the Scottsbluff Experiment Station near Mitchell, Nebraska, have been highly successful on slopes up to 5.0 percent. Topographic conditions are comparable to those of the Newell installation. "Cut" and "fill" problems were avoided by stockpiling the surface soil for reapplication to the cropped area[14]. Subsurface soil was used to form the escarpments or berms between the border strips.

If properly designed and operated, the border irrigation system gives a high degree of water control. Jensen and Howe[16 17] working on the Mitchell site obtained application efficiencies of 80 to 95 percent where alfalfa, corn, field beans, and sugar beets were grown in rotation. Sugar beets restricted surface flow of water late in the season, resulting in one or two irrigations in which water was poorly distributed. They indicated, however, that distribution could have been improved either by applying a greater depth of water or by using a larger stream size with only a small reduction in irrigation efficiency.

Howe and Heermann[13] extended the Mitchell investigations of Jensen and Howe[16 17] by establishing low-gradient border strips on two fine-textured soil sites near Grand Junction, Colorado. Both stream size and slope were varied in developing design criteria. They found that for practical purposes the uniformity coefficient is independent of input and stream size within the range of 0.03 to 0.12 cfs per foot of border width and is independent of slope in the low-gradient range and for steeper slopes with close-growing crops. Both the medium- and fine-textured soils had high initial intake, up to 3 or 4 inches in the first 2 hours. Proper operation of the irrigation system, and not design, was the key factor for efficient irrigation applications. The need for automatic control where frequent changes of irrigation sets are required to achieve efficient irrigation was recognized by Howe and Heermann as an essential ingredient for widespread adaptation of the border irrigation practice. Automation can be easily achieved by adapting the pneumatic diaphragm, Figure 10, to alfalfa valve risers from buried pipelines or from open channels with automated check gates[15].

Automated Furrow Irrigation Systems

Automated furrow irrigation systems with tail-water reuse facilities also are being used to attain the same degree of water control as previously discussed. Haise and Fischbach[9] summarized the progress made in research and development of hardware for the automation of single- and double-pipe irrigation systems.

As implied, the double-pipe automated irrigation system requires two pipelines: One that is buried for conveyance of water and the other on the surface to distribute water. The surface pipe has adjustable gated outlets to direct the flow of water into furrows and, where automated, is attached to a hydrant or valve body equipped with a pneumatic diaphragm shown in Figure 1. The

essential features of this system are shown in Figures 7 and 8. Remote controls used to change irrigation sets are the same as those previously described to automate the level basin irrigation (see Figures 5 and 6).

Fischbach and Somerhalder[6] report that reuse systems are an essential part of any automatic irrigation system if high application efficiencies and uniformity coefficients are to be attained. Measured uniformity coefficients ranged from 86.5 to 95.4 and application efficiencies from 84.4 to 96.8 percent. The same automated irrigation system operated without the reuse or cutback features resulted in an application efficiency of 64.8 percent with 27.1 percent of applied water lost as runoff. Where reuse systems are incorporated with automatic controls, minimum water application depths ranging from 1.5 to 2 inches were possible.

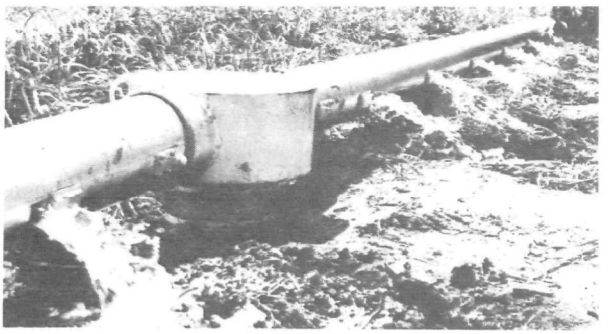

Figure 7: Auto-surface valve (1970 model) with double outlet. A 1/2-inch polyetheylene pipe connected between controller and pneumatic valve controls discharge by regulating the flow of air to inflate or deflate the pneumatic valve — developed by Fischbach[9]

Figure 8: Automatic irrigation system (3200 feet buried pipeline) being used to irrigate field beans near Wiggins, Colorado, in 1966. Inflatable pneumatic valves shown in Figure 1 are placed inside of standard hydrant attached to alfalfa valve riser. Risers are spaced 200 feet apart and sufficient gated pipe is available to irrigate 4 sets in 24 hours. Control wire for telemetry system that actuates 3-way pilot valve was placed in same air line used to pressurize pneumatic valve for remote control operation. Barrell section was used to cover valve when system is moved to the next point of control

Automated double-pipe irrigation systems are now commercially available. With the increased cost of labor and the trend toward larger farm operation, farmer acceptance of automated furrow irrigation systems probably will be accelerated. One word of caution, however: Automated surface irrigation systems are best adapted to soils with a medium to low intake rate but are not recommended where slopes exceed 1.5 percent. At present, the estimated cost of automated furrow irrigation with reuse features is comparable to the self-propelled center-pivot and less than automated solid-set sprinkler irrigation systems.

Automatic pipe-gates installed in a single-pipe irrigation system have the advantage of utilizing a single pipe to transmit and distribute water to furrow-irrigated crops. The experimental pipe-gate, shown in Figure 9, is a normally open valve that utilizes a small penumatic

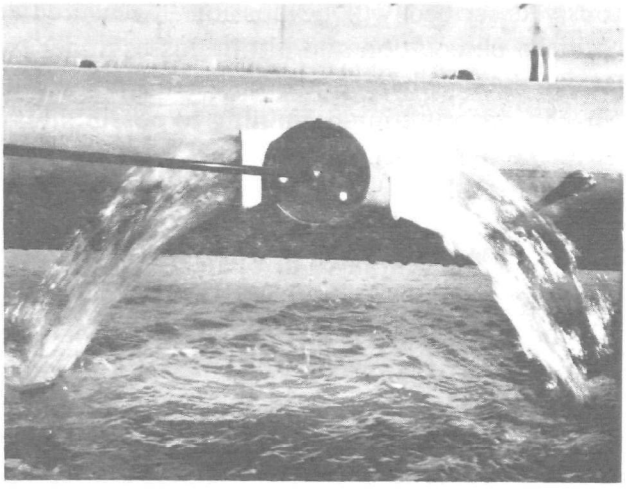

Figure 9: Pneumatic pipe gage in operation. Note that pipe outlets have been added to direct discharge into each of two furrow

diaphragm to provide the closing force. The exploded view of the pipe gate (Figure 10) illustrates its simplicity. The plastic disc, a unique

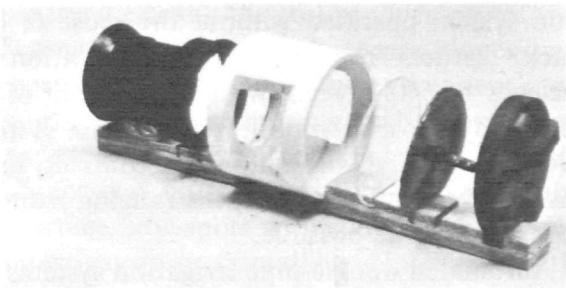

Figure 10: Exploded view of components used to develop normally open pneumatic pipe gate showing, from left to right: pipe locking mechanism, rubber gasket, valve body (white), sealing disc, pneumatic diaphragm and threaded diaphragm support

feature of the pipe-gate, placed between the diaphragm and valve seat, provides an effective water-tight closure. The valve embodies a built-in fail-safe feature whereby loss of control pressure causes all valves of the pipeline to open. When this happens, water is dissipated by reapplying it to all furrows irrigated by the pipeline until the malfunction is located and repaired.

A one-quarter-mile automated single pipeline that incorporates the pipe-gate shown in Figure 7 and a tailwater reuse system will be operated near Waverly, Colorado, in 1972. Application efficiencies comparable to those systems previously described will be possible. Measurement of deep percolation and nitrate losses under two water management practices at this site should provide information pertaining to possibilities of utilizing controlled water applications to reduce percolation losses and salts in return flow.

Humpherys, et al.,[15] describes the use of automated check gates in open conveyance distribution channels where outlets are installed in spreader ditches or distribution bays to water individual furrows or corrugations. A stream cutback feature incorporated in the design of this system provides for improved water control on sloping or graded fields.

Sprinkler Irrigation Systems

Automatic center-pivot, and to a lesser extent, solid-set sprinkler irrigation systems are becoming a familiar sight in eastern Colorado (187,000 acres), in the sand hills of Nebraska, in the Columbia River Basin of Washington, in Idaho and elsewhere in the Western United States. For controlling irrigation applications and the eventual movement of water, salts and/or nitrates within the soil profile, few irrigation methods can equal the performance of a properly designed and operated center-pivot or solid-set system. Heermann and Hein[12] report measured uniformity coefficients of 87 and 90 for two center-pivots in eastern Colorado.

Some operators of center-pivots tend to over-irrigate by continuous operation of the system. Others apply less water than the crop needs, especially where soil intake rates restrict the amounts of water that can be applied per irrigation. Preliminary data obtained by Heermann* on two center-pivots used to irrigate corn near Crook, Colorado, in 1971 indicate that the total water applied was 26 inches including irrigation and rainfall on a coarse-textured site where only 21 inches were needed based upon estimates of ET using the modified Penman equation[18] and measured soil water depletion. Irrigation plus rainfall on another field in the same area totaled 21 inches, but here a slowly permeable layer at the 6-foot depth reduced deep percolation losses. In the latter instance, application efficiency exceeded 95 percent. In spite of hail damage, both fields produced about 125 bushels of shelled corn per acre.

Center-pivot and/or solid-set irrigation systems have a high initial cost (about $250/acre) but provide a high degree of water control with a low labor requirement. For example, one operator and his elderly father irrigated about 1,000 acres of corn with a center-pivot and performed all cultural operations except planting and harvest.

Trickle Irrigation

Perhaps the ultimate in water and nutrient control has been achieved in Israel with the development of the trickle irrigation system. This system is designed to drop water into the soil at designated points along the crop or tree row using nozzles or orifices to control discharge (2-10 liters per hour). A typical installation for a

*Personal communication.

deciduous orchard consists of one or two trickle lines per tree row with nozzles spaced one meter apart on each line. Crops irrigated include citrus, pears, peaches, apples, grapes, bananas, and some high-valve row crops, including tomatoes and melons.

Advantages of the trickle system include (a) an exceptionally high degree of water and nutrient control, (b) maintenance of low amplitudes in the fluctuation of matrix and solute suction by frequent irrigations especially where highly saline irrigation waters are used, (c) maintenance of dry areas between trickle lines to facilitate timeliness of cultural operations, (d) possible savings in water under certain soil, crop and climatic conditions, and (e) marked increases in yields.

Water moves downward and outward into the soil from the point of application forming a leached, onion-shaped zone beneath each nozzle. Goldbert and Shmueli[8] delineate 3 saline zones: An upper zone where the salinity increases as the distance from nozzle and the soil surface decreases; a wide intermediate zone where salinity values are low; and a lower zone where the salinity level increases with depth and with distance from the nozzle. Plant roots are generally concentrated in the intermediate zone where most effective leaching occurs. Concentration of accumulated salts depends upon the salinity of the irrigation water applied, the rate of application, evapotranspiration, hydraulic conductivity, and back diffusion of salts into the leached zone during the offirrigation cycle. Goldberg, et al.[7], later reported on the use of the trickle system for irrigation of grapes using three frequencies of application.

The question of how long trickle irrigation systems can be operated without leaching is pertinent. Most researchers believe that some leaching in arid regions will be required to sustain high yields even though the crop may be planted in the same wetted strip previously cropped. Even so, when considered in terms of immobilizing salts by chemical precipitation and/or deposition, the trickle irrigation method, more than any other irrigation system, offers possibilities for achieving such an objective. The dry area between the trickle irrigated rows might serve as a salt sink. With controlled periodic leaching, these salts might then be moved downward into a zone below that normally wetted by the drip-nozzle, providing that leaching by rainfall is not excessive and water table depths do not fluctuate throughout the layer of accumulated salt.

Outlook

In spite of the desirability of improving water quality in rivers and aquifers by avoiding return and seepage flows that are enhanced in soluble salts, we do not know if a permanent irrigated agriculture can be achieved without having neutral or favorable salt balances in river basins and on individual fields. The process of concentrating salts is an inevitable consequence of evaporation and transpiration. Whether the answer to this concentration will be the growth of crops more tolerant of salinity, or water management systems with sufficient control that the salts can be deposited either in a soluble or insoluble form in part of the root zone or in the aeration zone above the water table, cannot be given now. The alternative is to keep salts out of the root zone by periodic leaching, with some of them reaching ground and surface water. This is what is now being done.

The problem will have to be solved differently in different regions depending on kinds of crops, depth to water table, amount of rainfall, and quality of irrigation water.

Methods of irrigation that can be closely controlled and fully automated, even though expensive, are now available so that the consumptive use requirements can be almost exactly supplied. These systems can also be used to supply the exact amounts of water for leaching requirements when leaching is needed. Such systems include automated basin, sloping border and furrow systems with reuse of runoff water, and center-pivot and solid-set sprinkler systems. Among the latest developments is trickle irrigation, which may be most useful when water is very scarce and there is little alternative to storing the accumulated salt in part of the soil profile out of reach of roots.

Proper scheduling of irrigations and applying the correct amount of water on automated or non-automated irrigation systems remains an age-old problem. Irrigation scheduling procedures developed by Jensen, et al.,[18] offers promise of predicting when a farmer should irrigate

and how much water he should apply. But applying the correct amount of water particularly on sloping lands by surface-irrigation methods in the absence of tail-water reuse facilities still constitutes a major hurdle. Farmers generally irrigate by experience. Seldom do they measure the input to our runoff from individual fields. As a consequence, irrigation systems that can provide a high degree of water control become inefficient if improperly operated.

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Water Quality Aspects of Sprinkler Irrigation

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ABSTRACT

Sprinkler irrigation affords a unique means for managing irrigated agriculture to improve water quality. In order to obtain maximum flexibility for managing water quality the sprinkler system must be designed to produce a UC in the neighborhood of 84 percent, have a capacity in excess of the maximum evapotranspiration demand, and be automated to allow maximum operational flexibility. Both automatic solid-sets and center pivot sprinkler systems provide the flexibility for optimizing the management of irrigating with saline and nutrient rich waters. With good scheduling practices and salt management within the soil profile, the normal water quality hazards associated with irrigation can be greatly reduced. Furthermore, nutrient rich waters can be utilized to augment fertility requirements, thus providing an extra value, in addition to being cleaned up for discharge into receiving water supplies. Sprinkler irrigation affords a means for saline land reclamation as well as an auxiliary system for leaching the salt build-up which may be associated with other forms of irrigation.

Sprinkler irrigation systems can be designed to afford a high degree of uniformity and operational flexibility. Under proper management, such systems have the potential of being operated to minimize the salt build-up and pollution problems normally associated with irrigated agriculture, utilize waters of relatively low quality, and even improve the quality of waters having high organic and nutrient loadings through the "living soil filter" concept.

Sprinkler systems can be designed to efficiently and uniformly apply water to almost any type of soil and topographic condition. Furthermore, areas can be irrigated in their natural state requiring a minimum of disturbance to the soil surface. This is especially important where topsoils are shallow and land leveling or extensive surface preparation operations would damage delicate soil profiles.

System Design Requirements

General information and instructions for designing sprinkler systems can be found in a number of books and publications of which some of the best known are[12,21,27]. However, the following special design considerations are necessary where irrigation systems are to be used for water quality control management purposes.

System Capacity

Where it is desirable to manage the sprinkler system to control the storage and release of salts from the unsaturated soil profile, the system capacity should be 10 to 50 percent greater than

that necessary to meet the maximum evapotranspiration demand.

It may be advisable to have system capacities over double that which would normally be required for irrigation purposes when: a) high salinity waters are apt to cause leaf burn and it may be necessary to stop sprinkling during the hottest and windiest parts of the day, or b) the living soil filter concept is employed to reduce BOD and nutrient loadings of sewage effluent prior to entrance into the groundwater system.

Application Uniformity

In order to obtain a high degree of control over the deep percolation or effluent from the unsaturated profile underlying a sprinkler system high application uniformities are essential. The most widely used and best known of the sprinkler application uniformity coefficients was presented by Christiansen[7] as,

$$UC = 100 \left(1 - \frac{\Sigma d}{mn}\right) \quad \ldots\ldots\ldots\ldots \quad (1)$$

where d is the deviation of individual observations from the mean value m; and n is the number of observations.

The UC value is a single parameter which has proven quite useful for predicting the entire distribution of water throughout the sprinkled area. Tables giving the distribution for various UC values are available.[14 19] With UC = 84 percent the wettest 5 percent of the area will receive over one-third more water than the average application depth (conversely the driest 5 percent of the area will receive less than two-thirds of the average application). This should be a sufficiently high uniformity for most sprinkler systems which are designed for water quality control purposes.

Timing and Application Depth

To exercise maximum control over the quality of deep percolating waters and best utilize sprinkler systems for waste disposal, maximum system operational flexibility is essential. It must be possible to commence irrigation at will and have full control over the depth applied during each irrigation cycle.

Types of Systems

To have full control over the depth and timing of applications without excessive labor requirements automatic sprinkler systems must be employed. Sprinkler systems which are not automatic are useful for waste disposal and the application of less desirable waters on agricultural lands. However, they do not provide the needed flexibility for the management of the quality of effluent from the unsaturated soil profile underlying the sprinkler field.

Manual Systems

Hand move, wheel move, tow move, boom sprinklers, giant sprinklers, mobile solid-set, giant traveling sprinklers, and manual valved solid-set systems all require sufficient labor input to reduce their flexibility in terms of timing and depth of water applied. It is beyond the scope of this paper to describe each system in detail, however, sufficient descriptions and photographs are presented elsewhere.[12 21 27] Most any of these manual systems can be designed to provide a very efficient level of irrigation with a UC = 84 percent or higher. Of course, wind speeds and directions should be taken into consideration and large water droplets or high application rates should be avoided where the soil infiltration rate is low.

Automatic Systems

Solid-set sprinkler systems with automatic valves and center pivot systems are the only fully automatic sprinkler systems with proven reliability. The automatic solid-set system is the most versatile, however, it may be several times more expensive per unit area covered than a center pivot system. Although it is possible to obtain an ordinary automatic solid-set system for less than $500 per acre, a high capacity, high uniformity system could very well cost in the neighborhood of $1,000 per acre. Typical center pivot systems will cost between $150 and $250 per acre, depending upon the mechanical quality and versatility desired. (The above cost figures do not include storage reservoirs, pumping plants and the general water distribution and drainage systems which will be required.)

A paper covering the general criteria for the design, use, and management of solid-set agricultural sprinkler systems is available.[19] While solid-set systems can be designed for any application rate desired, center pivot systems normally produce very high application rates near

the outer end of the moving pipeline. For many soils and topographic conditions, the infiltration capacity of the soil is exceeded creating runoff problems. In order to solve these problems light depths of application at frequent intervals and/or small circles are required. Under such conditions, the versatility of the center pivot in terms of water quality management is greatly reduced.

Soil Moisture

Figure 1 shows the moisture content variation in the unsaturated soil profile or root zone. This

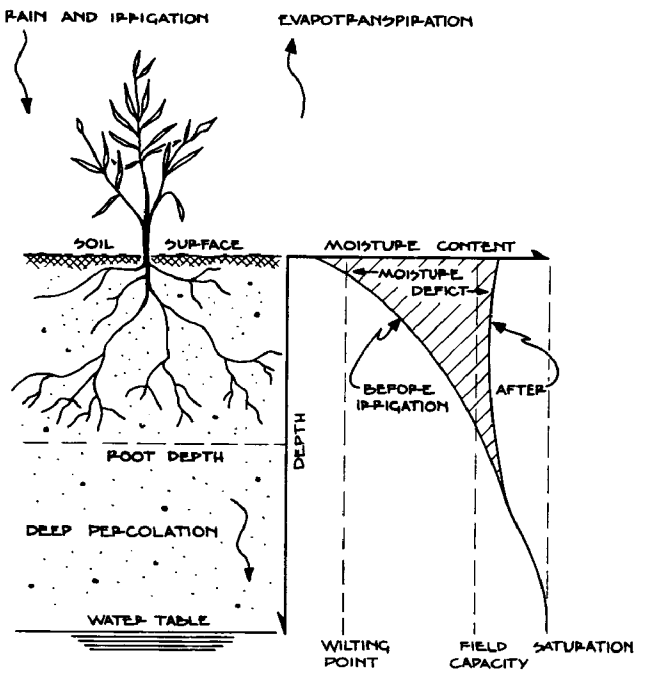

Figure 1: Moisture Content Variation in the Unsaturated Soil Profile-Root Zone

would be reasonably uniform throughout a homogeneous field which is irrigated by a high uniformity sprinkler system.

Moisture Flow

Under sprinkler irrigation, water is uniformily distributed over the soil surface. Therefore, the moisture movement can be depicted as a one-dimensional flow system operating in the downward vertical direction. Under furrow irrigation there is lateral flow between furrows as well as downward flow. With trickle irrigation the flow is three-dimensional radiating from each source point. In high water table subsurface irrigation the flow is one-dimensional but in the upward direction.

Moisture Content

Border or flood irrigation provides a source for one-dimensional downward flow. However, since the surface is inundated, water enters the soil at a maximum rate and the surface layer of soil becomes essentially saturated. Under sprinkler irrigation, the rate at which water enters the soil is controlled by the rate at which it is applied.

It has been found[18] that the soil moisture content in a deep soil profile after long periods of sprinkler irrigation could be depicted by:

$$\theta = J(A)^j + \theta_0 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

in which θ is the soil moisture content by weight, A is the application rate, and J, j, θ_0 are soil parameters which are positive in sign and differ for each soil but are unaffected by consolidation or compaction. From Equation 2 it is apparent that as the application rate increases the soil moisture content increases.

It was found[18] that with very low application rates the soil profile could be watered without increasing the moisture content appreciably above the so called "field capacity". It is expensive and difficult to achieve very low application rates and high uniformity under windy conditions. With automatic solid-set systems, however, it is possible to obtain similar results by frequent cycling of higher application rate systems.

Salt Flow

Since salts move with the water, the salt movement or leaching operation under sprinkler irrigation is vertically downward in the unsaturated soil profile. There are no salt concentration areas left behind and the salt movement within the unsaturated profile can be carefully controlled by varying the depth and timing of water applications. The depth to which the profile is leached depends upon the quantity of water applied. Studies have been conducted which demonstrated that the leaching efficiency is improved by decreasing the application rate.[20]

In many instances reduction of soil water evaporation and, therefore, upward movement of water will result in a more efficient leaching of the top portion of the soil profile. By combining surface mulches, to reduce evaporation and upward water movement, with periodic sprin-

kling, more effective leaching can be attained as compared to the conventional leaching practice of flooding the ground surface.[6]

The changes in the effluent salt concentrations resulting from leaching a uniform soil profile may be similar to those changes represented by Figure 2.[1] The maximum concentration of

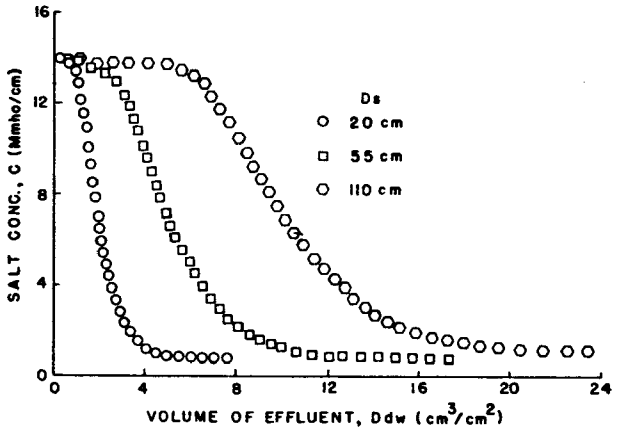

Figure 2: Leachate Concentration Curves for Uniform Sandy Loam Soil Profiles of Various Depths, Ds[1]

the drainage water will be equal to the maximum salt concentration within the soil profile at the beginning of the salt removal process. It will gradually decrease as the volume of the drainage water increases. A stratified soil profile where two different salinity strata exist will yield a leaching curve similar to any of those shown in Figure 3.[1] The peak value of salt con-

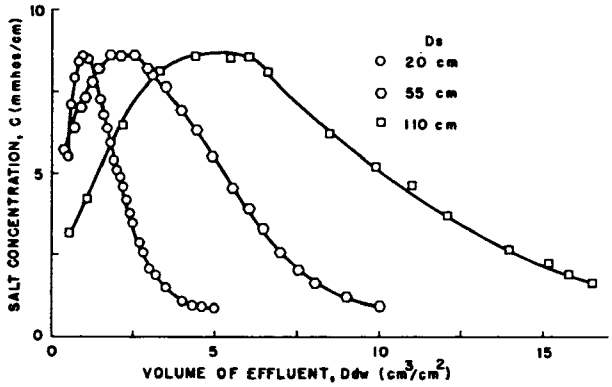

Figure 3: Leachate Concentration Curves Resulting from Sprinkling of Stratified Soil Profiles of Various Depths, Ds, of Salinized Sandy Loam Soil over a Non-Salinized Sand[1]

centration will depend upon the maximum concentration in the profile before water application, its location with respect to the soil depth, and initial water content. This indicates that higher peak values may be obtained for both uniform and stratified soil profiles at lower water contents.

Under sprinkler irrigation the entire surface layer of soil is leached by each irrigation. If just enough water were applied by each irrigation to supply the moisture deficit, salts would build-up in the lower portion of the root zone. With careful management, the salinity and moisture content at various levels in the root zone can be controlled and additional leaching water applied when it becomes desirable to discharge the salts into the water table. Details of the management schemes necessary for such an operation will be discussed later.

Irrigation Scheduling

Scheduling of irrigation can be based on observations of the soil moisture status, estimates of moisture used, or a combination of the two.[27] These methods of scheduling may not necessarily deal with the quality of the water, however, water quality aspects can be built in to the scheduling program.

A recent innovation for irrigation scheduling using climate-crop-soil data, computers to facilitate tedious computations, and field observations by experienced personnel[17] is being met with widespread popularity.[15 16] Scheduling services of this type have the potential of increasing the skills available for managing the water quality aspects under sprinkler irrigation. The general framework and the use of computer scheduling in Idaho and Arizona will be discussed in this conference. The necessary computer program and operational details are available from the USDA Agricultural Research Service.

Managing Saline Waters

Special sprinkler irrigation management techniques must be applied where salinity is of a major concern. Since all water contains some salt which is left behind by the evapotranspiration process, the salinity of percolating waters is greater than the salinity of the irrigation water. Although this is a problem inherent in any irrigation system, the discharge and quality of these saline waters from the unsaturated profile can be controlled by careful management of the irrigation systems.

When high salinity irrigation waters must be utilized, special attention is required for selecting the crops to be grown and the proper soil management practices. Various crops have different tolerances or abilities to produce within a saline environment. It is beyond the scope of this paper to discuss the salt tolerance levels of various crops, however, a brief review of the subject is available which cites much of the literature where specific crop-soil salinity tolerance information may be obtained.[23]

Leaf Burn

Salinity, or presence of soluble salts in concentrations above the recommended levels for plant growth may result in absorption of salts by plant roots and subsequent accumulation in the plant leaves causing leaf burn. Moreover, some plants can absorb nutrients and other ions directly through their leaves. If the foliage of saline sensitive crops is wetted by sprinkler irrigation, it may result in harmful accumulation of toxic ions and characteristic leaf burn. Symptoms of toxicity in leaves of sensitive plants are similar when the toxic ions are absorbed by either roots or foliage[3] but the rate at which they accumulate may differ greatly. The difference in rates of root and foliar absorption is further emphasized by the fact that during the growing season root absorption is continuous while foliar absorption during sprinkling occurs only about one percent of the total time.[10]

In some cases low saline waters that would not have harmful effects if applied directly to the soil may affect plant growth when applied by sprinkler irrigation. The rate at which foliage injury develops varies with species, salt type and concentration, and time and mode of water application.

Direct foliage injury as a result of sprinkling with saline waters is not likely to occur in *vegetables* and *forage crops* if the crops can tolerate similar salt concentration in the root media. However, gradual accumulation of salts which are not removed by an excess of water may in time injure the leaves.[10]

Citrus is quite sensitive to damage by foliar absorption of sodium and chloride. Water containing as little as 70 to 100 ppm sodium or chloride may be harmful if applied by sprinkler irrigation. In orchards sprinkled with waters containing less than 40 ppm of solium or chloride no leaf damage was observed.[13] However, these ions may accumulate in the leaves more rapidly by direct foliar absorption than by root uptake even from soil solutions 10 times more concentrated.[2] Therefore, some fruit crops absorb salt through the leaves 100 times faster than through the roots. *Apricot* and *almond* trees accumulate these ions most rapidly, *orange* and *plum* are intermediate, while *avocado*, a sensitive fruit to foliar concentrations of sodium and chloride, has a remarkably low rate of absorption through its leaves.[10]

Strawberries are very sensitive to soil salinity and furrow irrigation may cause salt accumulation as a result of unequal salt concentrations in the root zone. However, indications are that foliar absorption under sprinkler irrigation should be relatively unimportant since much more chloride would be absorbed from the root media containing equivalent levels of chloride than from the foliage.[9]

Sugar cane plants were not adversely affected by sprinkler irrigation using water containing up to 15 milliequivalent per liter, or about 500 ppm of chloride salts.[4]

Cotton sprinkled with saline water containing an average salt content over 3,000 ppm, at a rate of ¼ inch per hour resulted in leaf burn when the plants were less than 12 inches tall. Higher sodium content of washed cotton leaves occurred when plants were sprinkled during day time than a night. With the same quality of water, night sprinkled and furrow irrigated cotton produced comparable yields. The day sprinkled cotton, however, produced only 68 percent as much of the furrow irrigated short staple cotton and only 43 percent as much of the furrow irrigated long staple cotton.[5]

Earlier foliar injury may be expected in sensitive crops when sprinkled with waters containing $CaCl_2$ or NaCl than when sprinkled with waters containing $NaSO_4$. Sodium may be more rapidly accumulated from NaCl than from $NaSo_4$ solutions because of the difference in solubility. Chloride accumulations may be expected to be equal from waters containing either NaCl or $CaCl_2$.

Saline waters applied to sensitive crops by sprinkler irrigation during the hottest part of the day should be avoided since the foliar uptake of

salts may be twice the amount absorbed during evening irrigations.[10] In general more severe injury may be expected by sprinkling with saline waters in hot, dry climates than in cool, humid regions.

More sodium and chloride may accumulate under intermittent conditions than when sprinkled continuously. Intermittent sprinkling, such as for crop cooling, allows for evaporation with a subsequent increase in concentration of salt from the water film left on the leaves. On warm days with low humidity rapid evaporation results. The first salts to precipitate and be deposited on the leaves are the relatively insouble salts such as $CaCO_3$, and $CaSO_4$. It is theorized[13] that sodium and chloride ions remain in solutions until most of the water has evaporated. Thus, relatively high concentrations of these ions in solution will result, accounting for the fact that only sodium and chloride appear to be absorbed by the plant foliage.

To minimize foliar absorption of salts and, therefore, leaf burn, water should be applied by sprinkler irrigation at low angles below the foliage of tall crops such as trees. Cool and cloudy day or night irrigations should be preferred to maintain the foliage continuously wet during sprinkling, thus minimizing leaf burn hazards.

Soil Profile

Managing sprinkler irrigation systems to control the movement of salt through the soil profile is a practical possibility. Salinity control in the soil profile is an important part of controlling the quality of irrigation return flow, i.e., that part of the water diverted for irrigation which eventually returns to the stream or groundwater body. Details of models for describing the water and salt movement in the root zone are being presented at this conference.[22] These models provide the design and operation criteria for the sprinkler system. These proposed models for managing irrigation are based on the concept of temporarily storing salts in the soil profile and leaching only when necessary to prevent the salt from becoming too concentrated in the root zone. This concept requires a fairly accurate knowledge and control of the timing of irrigations and depth of water applied during any given irrigation. In any given irrigation, the percentage of applied water required for leaching may be as high as 50 percent. This extra water can be obtained by increasing either the rate of application, the duration of irrigation, or a combination of both.

Profile Effluent

The models of the movement of water and salt through the soil profile predict the quantity and quality of water leaving the bottom of the root zone (deep percolation) as a function of time during the irrigation season.[22] In addition, through the mass balance the amount of water and salt existing in the root zone at any time is also known.

With all other conditions the same, varying the interval between irrigations changes the time at which the peak salt load in the profile effluent occurs. Thus, particularly in areas with an extensive man-made drainage system wherein the residence time for the effluent is short, a wide range of possibilities for quality control exists. For control in entire valleys or irrigation districts, possible alternative modes of operation might be: (a) schedule the irrigations involving leaching of salts from the profile on different farms at different times so as to smooth the peaks of salt in the drainage effluent and provide a more nearly constant quality of effluent during the season; or (b) attempt to peak the salt removal from all farms at nearly the same time and divert this high salinity water to an evaporation basin or other suitable salt sink.

Under certain conditions, however, deep leaching may not be needed every year. Again, it should be emphasized that controlling the depth and timing of irrigations is necessary for a successful profile effluent quality control program.

Managing Waste Waters

Irrigation in general and sprinkler irrigation in particular provides an effective method for utilizing and/or improving the quality of waste waters. Through the "living soil filter" the biological oxygen demand (BOD), as well as the concentrations of nitrogen, potassium and phosphorous can be reduced and the suspended solids and bacteria removed from the waste water. Excess irrigation will result in recharge to the groundwater of a portion of the effluent. If properly managed, the water leaving the "living

soil filter" will be equivalent to or higher in quality than that produced by a third stage or tertiary treatment facility.

It has been estimated that over 400 cities in the United States are currently using crop irrigation as a means of disposing of domestic and industrial waste waters.[11] The proceedings of the Municipal Sewage Effluent for Irrigation Symposium presents many nationwide aspects of this subject which attest to the validity of returning domestic liquid wastes to the land.[28]

Nutrient Removal

It has been estimated that the fertility value of domestic effluent in terms of nitrogen, phosphorous and potassium is in the neighborhood of $18.00 per acre foot.[11] However, this figure can vary significantly. In order to effect the removal of nitrogen the waters must be applied to vigorously growing crops. The primary purpose of the crops in the renovation cycle is to remove the nitrogen added to the irrigation water. Once the nutrients are incorporated into the crops it is imperative to remove these crops from the irrigated area and thus remove the incorporated nutrients.

It has been found that phosphorous can be readily removed by soils and crops and the choice of crops can vary with the typical patterns of land use in the area. Although the crops only remove a portion of the phosphorous applied, many soils have a high capacity for absorbing the remaining phosphorous.

The nitrates contained in the effluent are not as readily removed as the phosphorous. The overall design must ensure that these nitrates are adequately removed by crops and/or soil microbes so that the renovated water does not cause undue degredation of the groundwater.

In high exchange capacity soils, potassium is normally exchanged onto the soil complex and is thus removed from the waste water.

BOD

Although a vigorous crop is necessary for the removal of nutrients, the typical soil microflora will greatly reduce the BOD in the waste water as it trickles through the system. Only rarely will the hydrologic environment not renovate waste water to the equivalent of secondary or biological treatment. Terrestrial disposal has been used in lieu of secondary treatment.

Special Considerations

Sprinkler irrigation has certain unique advantages for dealing with waste water disposal. By sprinkling the soil at a low application rate, the soil moisture content can be maintained at a low level, as mentioned earlier, thus maintaining adequate soil aeration for optimum plant growth and microflora activity. Some of the special design features required for effluent disposal through sprinkler irrigation have been pointed out.[8 24 25] In essence, for optimum performance it is important to locate the disposal area on the better quality lands where the water table depth is over 5 feet. Storage facilities and sprinkle field design depend on effluent quality, volume, and climatic conditions. Prior to entering the sprinkler system, domestic sewage should be treated through a secondary treatment facility and chlorinated to reduce potential health hazards.

A number of legal issues are involved in the application of waste waters through sprinkler systems.[24] Under wind conditions the spray from sprinkler systems is apt to drift a considerable distance from the sprinkled area. One of the unanswered legal and health questions to date is the amount of border area required in order to eliminate potential health and environmental hazards from air-borne bacteria, virus and odors.

Sprinkler irrigation has the potential of playing a unique role in the disposal of hot water from large thermal power generating stations. The temperature of the spray reaches the wet bulb temperature regardless of the temperature of the irrigation water.[27] Therefore, it appears possible and practical to sprinkle with very hot water without casuing crop damage.

Leaching with Sprinkler Systems

Since sprinkler irrigation effectively produces a one-dimensional soil moisture flow system as described earlier, it is uniquely adaptable for reclamation and leaching purposes. Furthermore, by utilizing low application rates the removal of salts per unit of water applied can be maximized. The system can be used for the reclamation of new lands as well as for leaching the

salts which may build-up under other forms of irrigation.

Reclamation

In many cases, the reclamation of new lands can most efficiently be achieved by the use of sprinkler irrigation. Under sprinkler irrigation it would not be necessary to remove the existing vegetation and disturb a delicate soil surface during the initial leaching phases. Furthermore, through controlled low application rates the amount of salts removed per unit water applied can be maximized to minimize the water table build-up associated with reclamation. After the surface profile has been partially leached the native vegetation can be replaced by salt tolerant, densely growing crops which may further aid the leaching process. By applying more water than the evapotranspiration demands, crops can be grown which will produce some return while the remaining soil profile is being renovated.

Drip Irrigation

With trickle or drip irrigation systems, water is applied from point sources and redistributed in the soil profile by capillarity and gravity. Drip irrigation offers the possibility of applying water frequently at short intervals to maintain the root zone moisture at an optimum level for maximum production.

By irrigating frequently, the soil water within the root zone may be maintained at high levels to provide an adequate invironment for plant growth even if saline waters are used. With any irrigation water accumulation of salts at the periphery of the wetted portion of the profile is to be expected. Such a condition will develop in time depending upon the quality of the water used for irrigation. Where natural rainfall is not sufficient to move these salts, some auxiliary leaching is required. By periodic applications of water through a sprinkler system the necessary leaching can be achieved. The capacity of an auxiliary sprinkler system used for periodic leaching could be quite small. Under normal conditions it might only be necessary to apply a single deep application of water once every several years.

Subsurface Irrigation

High water table and plastic seep line or emitter type subsurface irrigation systems eventually result in salt build-up in the surface soil. Where natural rainfall is insufficient, periodic leaching with uniform applications of water to the surface is necessary as with drip systems.

Furrow Irrigation

While furrow irrigation does not uniformly apply water to the soil surface, under normal operations, the minor salt build-up in the beds between furrow is leached from time to time as the fields are cultivated and new furrows installed. Of unique importance, however, is the salt build-up in the beds during the seed germination period. Often seeds are planted just above the water line so the upward movement of water from the furrows to the bed leaches the zone in which the seeds are planted. This is necessary since many seeds and seedlings have a low salt tolerance although the crop may have a high salt tolerance once in a vigorous growth stage.

The accurate construction of furrows and planting of seed just above the water line is difficult and sometimes impossible. In order to eliminate this problem, sprinkler irrigation is often utilized for the germination of delicate seeds. Once germinated, the crop can then be furrow irrigated.

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Subirrigation Studies in the High and Rolling Plains of Texas

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ABSTRACT

Results from the first year of a study involving the influence of subirrigation on soil water conditions and ion concentration of soil extracts are presented.

Soil layering resulted in high soil water potentials and retention. With this condition subirrigation can maintain high soil water potentials for plant growth and yet leave water retention capacity for rainfall.

Early in the growing season, breakdown of organic residue and subsequent nitrification resulted in significant increases in nitrate-nitrogen of soil water extracts. Nitrate-nitrogen concentrations were lower in the subirrigated plots than in the furrow- and sprinkler-irrigated plots. Nitrogen was efficiently applied in increments through the subirrigation system.

Calcium and chloride concentrations were lower in subirrigated plots than in sprinkler- or furrow-irrigated plots. Concentrations of phosphate, potassium, sodium and ammonium were not influenced by method of irrigation. The quality of water applied influenced sulfate concentrations and electrical conductivity more than method of irrigation.

INTRODUCTION

Irrigated agriculture is the major consumer of water in the United States. With the increasing pressure on the water resources of the nation for municipal and industrial as well as agricultural needs, there is increasing concern about the influence of irrigated agriculture on the quality of the nation's water resources.

Water used in irrigated agriculture may be stored in the soil, evaporated from the soil, consumed by the crop, or may leave the irrigated area as surface runoff or leachate which percolates through the root zone. Water that runs off and percolates through the root zone may return to the source of the supply. Two major residues in this water which create water quality problems are dissolved mineral salts and plant nutrients. Mineral salts tend to increase in the return flows due to the discharge of additional minerals into the return flow and concentration of the minerals due to abstraction and consumptive use. Law[1] notes in his summary that 20-fold increases in mineral content have been noted on the Colorado and Rio Grande Rivers.

Intensification of crop production has resulted in increased applications of nitrogen fer-

tilizer. In any area where water application is applied in excess of that needed for crop production, the potential of leaching of nitrogen from fertilizers and nitrification exists.

If irrigation water could be more efficiently utilized, less mineral salts would be applied and less water would be available to return salts and plant nutrients to the source through irrigation return flows, and the quality of waters receiving these return flows could be enhanced.

The quality of the waters commonly used in the High Plains and Rolling Plains of Texas is relatively good compared to that in other parts of the U.S. Commonly this water contains less than 1500 ppm total salts with less than 50 percent sodium salts (Table 1). However, in certain parts of the Rolling Plains a potential nitrate-nitrogen pollution problem exists. The nitrate-nitrogen content of 62 water samples collected from the Seymour formation in 1962 varied from 5-41 ppm with 39 exceeding the recommended Department of Health limit of 10 ppm. Nine towns use water from this formation and none have an approved water supply due to the presence of nitrate. Analyses made in 1968 and 1969 indicate that the concentration of nitrate is continuing to increase.

TABLE 1

Analyses of water from typical wells in the High and Rolling Plains of Texas

	High Plains	*Rolling Plains*
pH	7.9	7.5
Electrical Conductance (ECx10^6)	1101	2214
Ion concentration (ppm or mg/l)		
Total salts	627	1360
Calcium	68	92
Magnesium	47	67
Potassium	7	4
Sodium	36	217
Carbonate	0	0
Bicarbonate	309	425
Sulfate	50	262
Chloride	134	244
Nitrate-Nitrogen	2	11
Sodium adsorption ratio (SAR)	.84	4.17
Sodium percentage (SSP)	17.6	47.7

A project was initiated in 1970 to determine if irrigated agriculture may be contributing to the increasing nitrate-nitrogen content of the ground water and to evaluate the influence of irrigation and fertilization techniques on the potential pollution of the underground water supply. Irrigation systems being evaluated include furrow, sprinkler, subirrigation and automated subirrigation. Nitrogen fertilizer sources, various moisture levels, and methods of fertilizer applications are being examined.

This paper deals with a portion of the data obtained from the study concerned primarily with subirrigation.

Methods and Materials

In early work at Lubbock, the major problem hindering the development of subirrigation sys-

tems was the clogging of orifices with sand and closing of punched orifices due to plastic flow. These problems were reduced by the development of molded orifices[4] which were installed in the subirrigation systems used for this study. The orifices have a diameter of .022 in. and are spaced 34 in. apart on the 0.5-in. dia. polyethylene laterals. The laterals are 40 in. apart directly beneath each crop row. The plots are 220 ft long with header lines on each end. Flow rate is controlled by Dole valves. Water entering the system was filtered with 100 or 300 μ cartridge filters. The systems are operated for a short period at least once per month to clean the orifices. These systems have been used for one year. No clogging problems have yet been encountered.

The field treatments at the Rolling Plains site are shown in Table 2. Each plot is equipped with soil water extraction tubes at various depths from 0.5 to 30.0 ft and access tubes to 30.0 ft for making neutron probe measurements at 2 locations in each site. Tensiometers were at various depths from 0.5 to 10.0 ft at 2 locations in each site. Cores for physical and chemical data were taken at 28 locations on the site at the beginning and end of the season. Particle size analyses were made using the Bouyoucos hydrometer method. Moisture retention data were obtained from pressure plates. Soil water samples were procured during the growing season with the extraction system and analyzed with an AutoAnalyzer for calcium (Ca^{++}), sodium (Na^{+}), nitrite-N (NO_2^-), nitrate (NO_3^-), ammonium (NH_4^+), chloride (Cl^-), sulfate ($SO_4^=$), potassium (K^+), and phosphate ($PO_4^{\equiv}$). Since the nitrite-nitrogen in the soil water extracts was present in low concentrations and in only a small number of samples, the analysis for the ion was discontinued. The indicator crop was sweet corn and yield data were obtained at the end of the season.

TABLE 2

Parameters being evaluated at the Rolling Plains site (Knox County, Texas)

Methods of Irrigation	*Moisture Treatments*	*Fertilizer Sources*
Furrow	High moisture level based on stage of growth	NH^3
Sprinkler	High moisture level based on tensiometers	NH^3 with "N-Serve"
Manually operated subirrigation	Moderate moisture level based on tensiometers	Sulfur coated urea
Automated subirrigation	Constant high moisture level based on tensiometers	Nitrogen solution Control

Two plots of a prototype automated subirrigation system were installed at Lubbock to eliminate automation problems prior to installation of an expanded system in Knox County. Each plot was equipped with 4 switching tensiometers in a circuit, whereby, if any two of the tensiometers increased to a preset tension level, a solenoid would open and apply water until the tension decreased on 1 tensiometer. An event recorder recorded the time water was applied. Work with the prototype has resulted in a simpler and less expensive automated system for Knox County. Soil water content and potential measurements were made at selected points

around orifices to determine the flow pattern of the irrigation water.

Results and Discussion

Soil Water Potential and Content (Rolling Plains)

The Knox County site, which had not previously been irrigated, is classified as a Miles loamy fine sand. As can be seen in Fig. 1, the clay content of the surface 12 in. of soil was fairly uniform at 4 to 6 percent, except where some land leveling was necessary for furrow irrigation. Below this the soil contained alternating layers of higher and lower clay content.

This layering effect influenced the soil water potentials at field capacity. The soil water potential remained greater than -10 cb below 2 ft for most of the growing season. The highest potentials occurred in or above the layers of highest clay content in all irrigation systems. The subirrigation system had an additional zone of high potential around the subirrigation pipe (Fig. 2). As would be expected, increased water retention was associated with the high potentials. Pressure plate and bulk density data indicate that the soils retain 12 to 20 percent more water by volume at -10 cb than -33 cb.

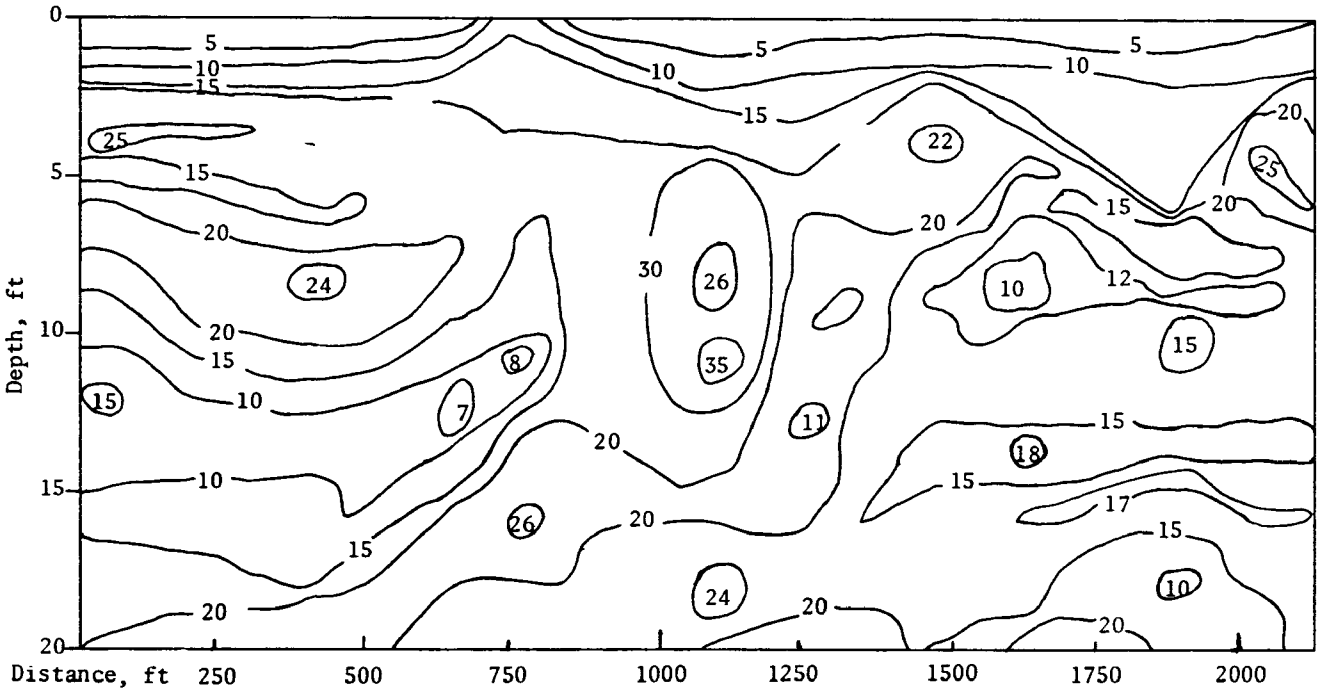

Figure 1: Percent clay between the surface and the water table. (Miles loamy fine sand, Rolling Plains Field Site)

Figure 3 shows the relative soil water contents on a subirrigated and sprinkler-irrigated plot on various dates during the growing season. The soil water content is related to the clay content of the various layers.

Most of the change in water content in the soil profiles between the surface and 10 ft occurred between May 10 and July 8, prior to crop emergence. Changes between July 8 and Sept. 3 were small. For this reason, as will be seen later, the highest concentrations of ions in the soil solution were generally located in the surface 5 to 6 ft and did not shift to lower depths of the soil profile.

Effects of layering in soils have been previously reported by Miller[2] and Miller and Bunger[3]. They point out that before water can move from a finer-textured layer to a coarse-textured layer, the potential must be high enough to allow water to enter the large pores of the coarse layer. Such effects are noted in these soils. The soils they described had only 1 layer while this soil had 3 to 4 porous layers.

This layering effect could be a major factor in maintaining the water quality of irrigation return flows. This soil retains water at potentials of -10 cb and greater. Many crops grow

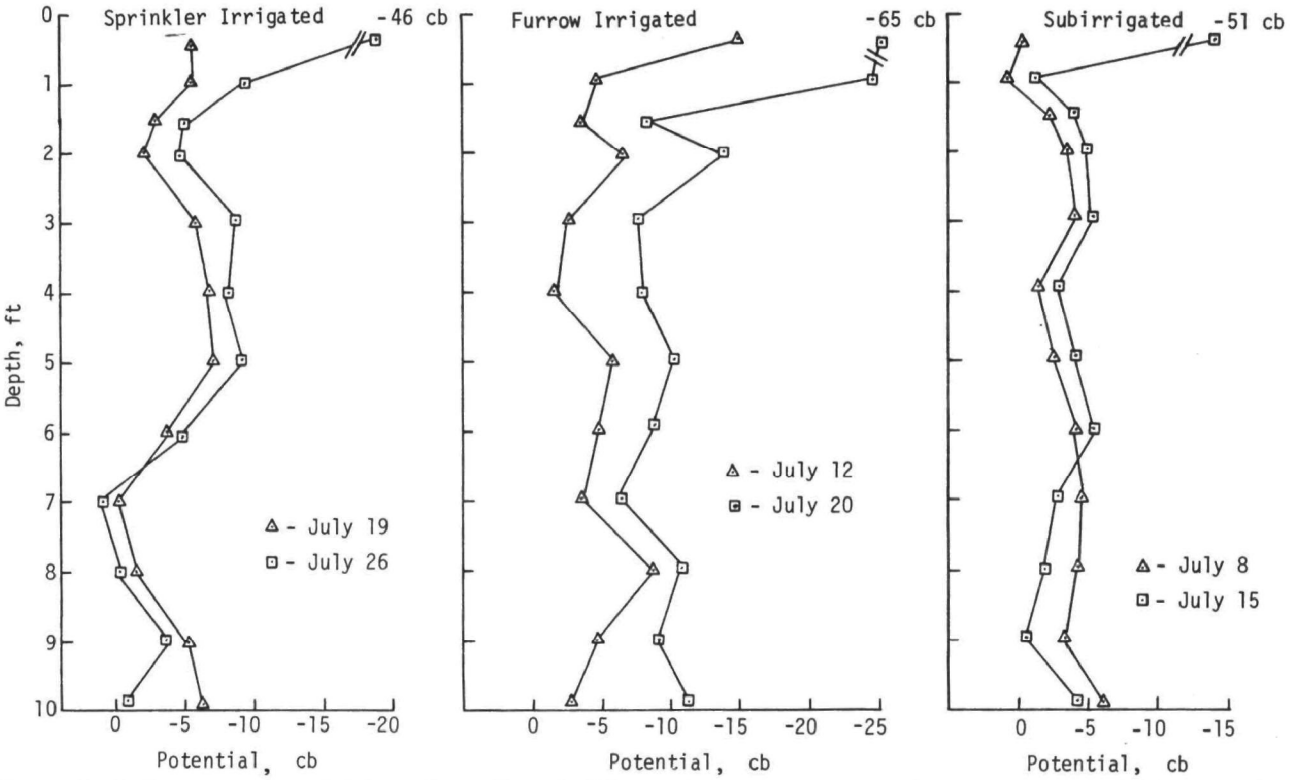

Figure 2: Soil water potential in soil profile of different irrigation systems between water additions. (Miles loamy fine sand, Rolling Plains Field Site)

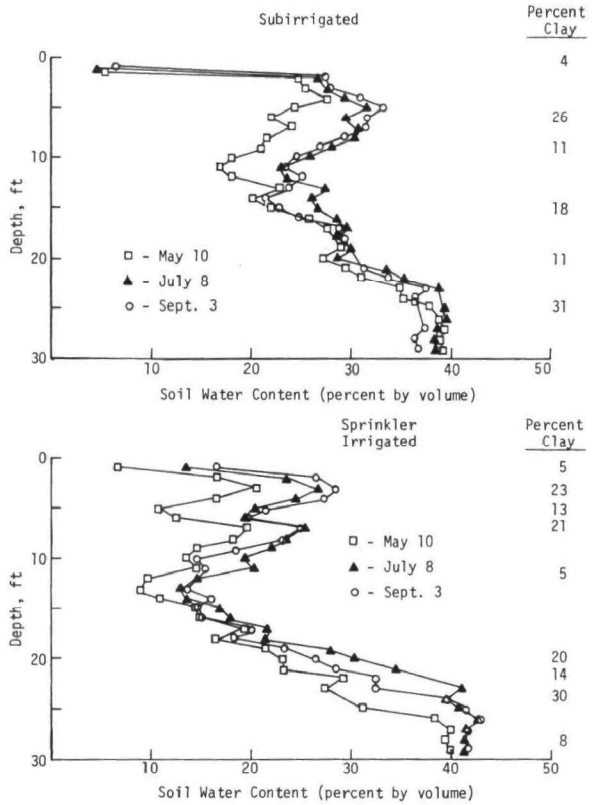

Figure 3: Maximum and minimum clay contents and changes in soil water content of sprinkler and subirrigated plots during the 1971 growing season. (Miles loamy fine sand, Rolling Plains Field Site)

well at lower potentials. Sufficient irrigation water could be added to such crops to adequately supply their needs without utilizing all of the soil's water-retention capacity. Retention capacity would still be available for a large amount of rainfall so that a minimum of leaching would occur with proper management.

Soil Water Potential (High Plains)

The prototype of an automated subirrigation system was installed in an Amarillo fine sandy loam at Lubbock, Texas.

Although the subirrigation system was installed in March, the automation was not completed until July when the sweet corn was at the tassel stage of growth. Four switching tensiometer in each of two plots were located 6 in. to the side of orifices and were set at potentials of -30 cb and -60 cb. The amount of water applied through the system to the 2 plots is shown in Table 3. Between July 12 and July 22 the system was inoperable due to the necessity of making changes in automation and Dole valves.

The -30 cb plot was relatively dry at the time the system was installed. During the six-day period from July 7 and July 12, more than 6 in. of water were added to the profile (Table 3).

TABLE 3

Inches of irrigation water applied automatically to subirrigation plots at Lubbock

Date	*Time*	*Total Hours*	*Water Applied (Inches)*	*Total (Inches)*
	30 cb Plots 2 5 gpm Dole Valves			
July 7-8	7:30 p.m. - 7:30 a.m.	12	1.12	
July 8-9	8:30 p.m. - 9:30 a.m.	13	1.18	
July 9-10	9:30 a.m. - 1:30 a.m.	16	1.49	
July 10	4:00 p.m. - 6:30 p.m.	2½	.19	
July 11	12:30 a.m. - 9:30 a.m.	9	.84	
July 11-12	3:30 p.m. - 11:00 a.m.	19½	1.82	
				6.64
	30 cb Plots 2 2.5 gpm Dole Valves			
July 22	1:00 p.m. - 11:45 a.m.	22¾	1.06	
July 25-26	9:00 p.m. - 7:30 a.m.	10½	.49	
July 29	7:45 p.m. - 8:15 p.m.	½	.02	
July 30	9:00 a.m. - 9:30 a.m.	½	.02	
July 30	8:30 p.m. - 9:00 p.m.	½	.02	
July 30-31	11:45 p.m. - 12:45 a.m.	1	.04	
July 31	9:45 a.m. - 10:15 a.m.	½	.02	
July 31	1:00 p.m. - 4:00 p.m.	3	.14	
July 31	8:30 p.m. - 12:00 p.m.	3½	.16	
Aug. 3-4	11:00 a.m. - 11:30 a.m.	24	1.12	
				3.09
				9.73
	60 cb Plots 2 5 gpm Dole Valves			
July 10	5:30 a.m. - 7:30 a.m.	2	.18	
July 11-12	8:30 p.m. - 11: a.m.	14½	1.35	
				1.53
	60 cb Plots 2 2.5 gpm Dole Valves			
Aug. 3-4	11:00 a.m. - 11:00 a.m.	24	1.12	
				1.12
				2.65

As evapotranspiration potential during this period did not exceed .5 in./day, it appears that a portion of the water added replenished the profile.

To obtain information concerning soil water distribution, tensiometers were installed at 4, 10 and 20 in. from an orifice at 2 locations in each plot at different depths. The system was operated manually for 24 hours during which 1.12 in. of water were applied to each plot. From Figs. 4 (low potential plot) and 5 (high potential plot), it can be seen that the primary area of

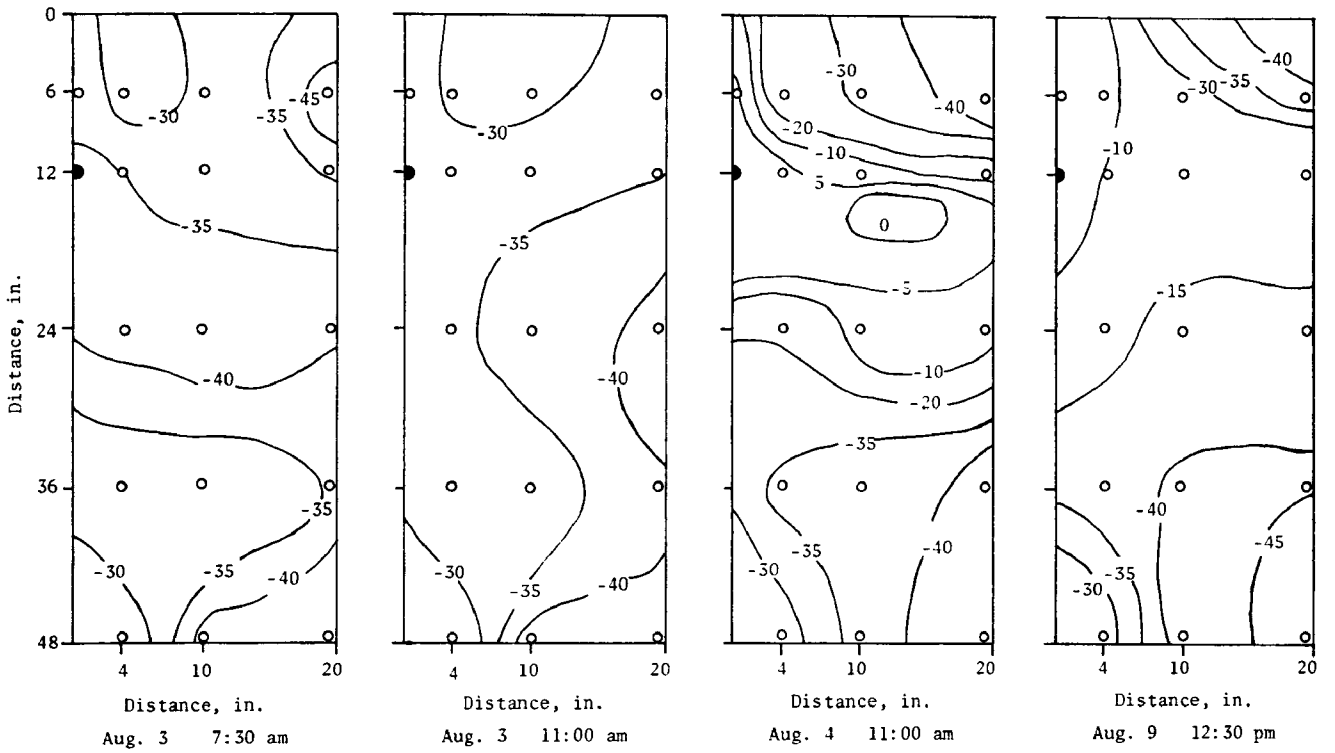

Figure 4: Soil water potential in soil profile of plot with low initial soil water potential during and following irrigation. [Values on graphs in -cb, o - tensiometer locations, ▸ - subirrigation pipe location. (Amarillo fine sandy loam, High Plains Field Site)]

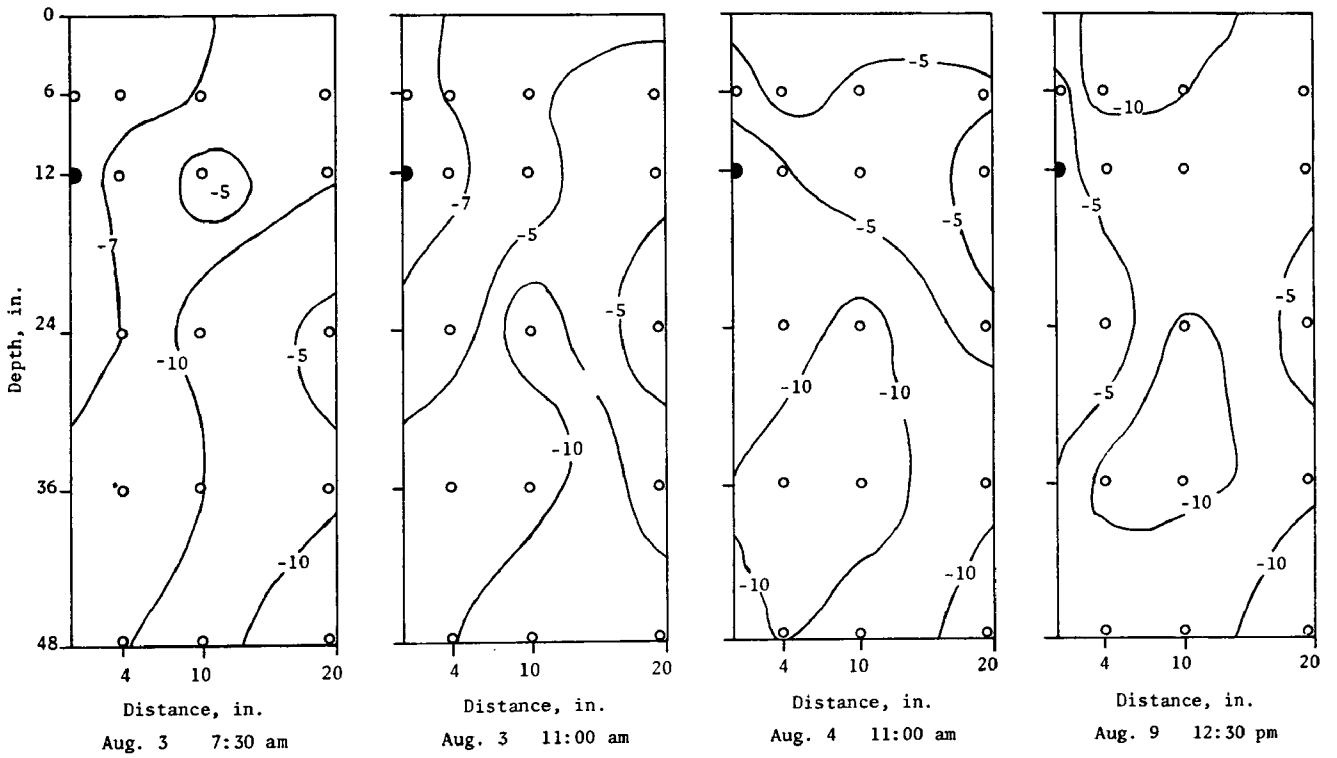

Figure 5: Soil water potential in soil profile of plot with high initial soil water potential during and following irrigation. [Values on graphs in -cb, o - tensiometer locations, ▸ - subirrigation pipe location. (Amarillo fine sandy loam, High Plains Field Site)]

potential change following irrigation occurred below 6 in. and above 36 in. In the low potential plot, the largest increase in potential occurred at 12 in. followed by 24 in. Changes in potential at 6 in. were small while those at 36 and 48 in. were negligible. This indicates that most of the water applied to this plot was stored at 12 and 24 in. and there was still retention capacity in the soil profile for storage of rainfall. The corn in the -60 cb plot showed visual signs of stress and the yield was only 8500 ears per acre.

In the high potential plot, which yielded 17,000 ears of corn per acre, the potential was higher initially and less change in potential occurred after the irrigation water was applied. The crop was healthier and apparently used more of the water so that less decrease in potential occurred. As with the low potential plot, there was little change in potential at 6, 36 and 48 in. This soil is underlain with a sandy layer at the 36-in. depth. It appears that this may be a factor in maintaining a high potential under field conditions. The lack of potential change at 6 in. suggests that little water is lost to evaporation.

The automated subirrigation systems apparently do have some of the advantages hypothesized in the initial project. It is necessary to maintain a low potential in only a portion of the profile to supply crops. This leaves room for soil water storage from rains. Using the limited content and potential data obtained, the authors estimated the water-holding capacity of the soil at Lubbock following irrigations at -30 and -60 cb. This information is presented in Fig. 6.

The necessity to maintain a high potential in only a portion of the profile coupled with the increase in water retention due to soil layering indicates that irrigation return flows can be minimized and quality increased through better water use efficiency in soils of this type.

Ion Concentration of Soil Water Extracts

All of the ion concentration data were procured from the Rolling Plains Site located in Knox County. Breakdown of residue from the previous dryland grain sorghum crop and subsequent nitrification resulted in significant increases in nitrate in the soil solution. Peak concentrations occurred in July. Nitrate-nitrogen in soil water extracts at the beginning of

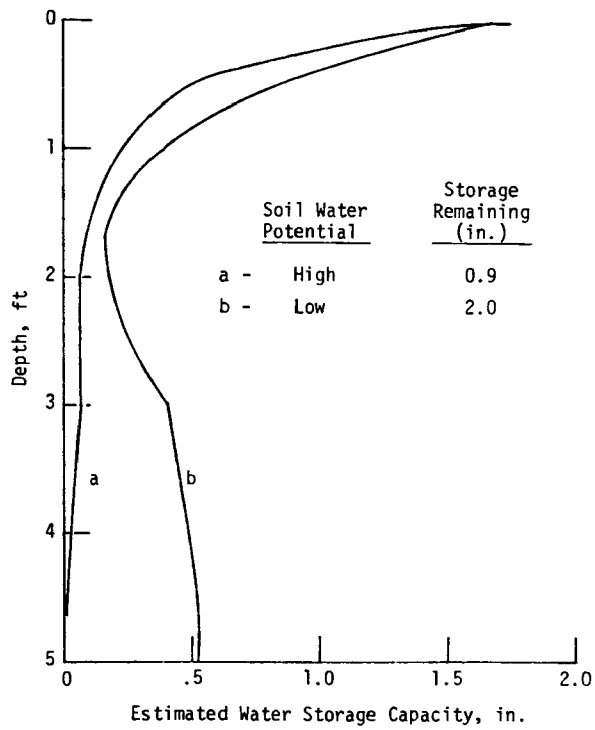

Figure 6: Estimated soil water storage capacity remaining in the top 4 ft of soil following subirrigation at low and high soil water potentials. (Amarillo fine sandy loam, High Plains Field Site)

the season following emergence along with yields of unfertilized plots from each irrigation system are shown in Fig. 7. It can be seen that nitrate-nitrogen concentration in the furrow and sprinkler plots was considerably higher than that of the subirrigated plot. This was true for similarly treated plots between irrigation systems throughout the growing season.

Some difficultly was experienced in obtaining emergence on the subirrigated plots when they were planted on the bed. Up to 8 in. of water were applied to obtain emergence. Some of the plots were replanted in a furrow in order to place the seed closer to the subirrigation pipe to determine if this problem could be eliminated, and emergence was obtained without any problem with 2 in. of water or less.

Significant increases in nitrogen were detected in fertilized subirrigated plots only when fertilizer was applied through the irrigation system. This was probably a consequence of water from the subirrigation system moving the banded nitrogen away from the soil water extraction tubes located in the bed. However, no large concentrations of nitrate were detected at

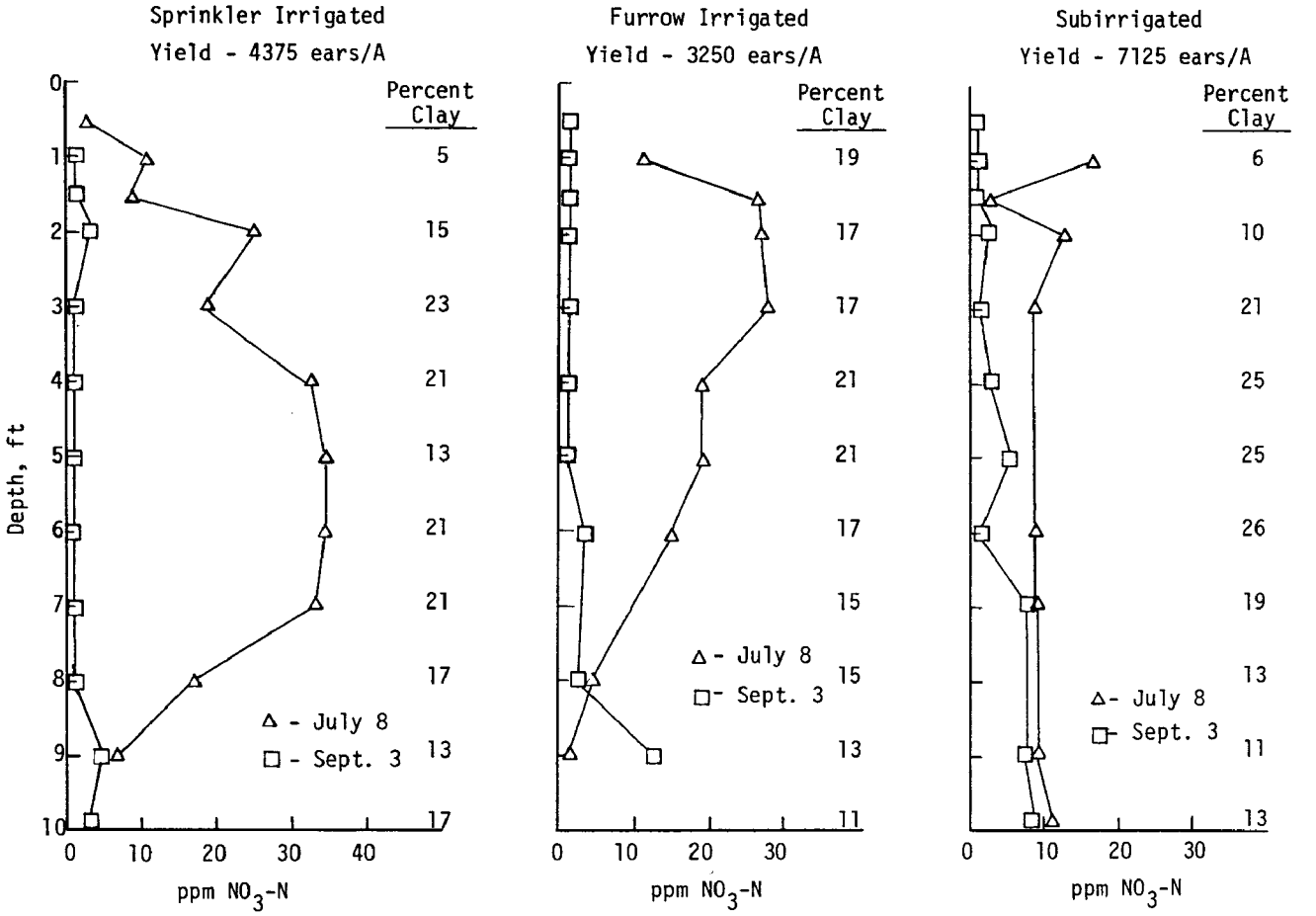

Figure 7: Nitrate-nitrogen concentration of soil water extracts from various depths of unfertilized plots of different irrigation systems. [Concentration in irrigation water 6-8 ppm NO_3-N. (Miles loamy fine sand, Rolling Plains Field Site)]

depths greater than 4 ft under the subirrigation system; therefore, it is doubtful that important amounts of nitrate were leached from the root zone by water applied throughout the subirrigation systems.

Results of fertilization through the subirrigation system are shown in Fig. 8. It can be seen that the injection of the nitrogen solution increased the nitrate-nitrogen content of the soil profile and the subsequent yield. The nitrogen solution used contained 50 percent of its nitrogen as urea and the other 50 percent as ammonium nitrate; however, increases in ammonium ion concentration were not detected.

The highest concentrations of ions were found immediately above the first or second clay layer. This was true not only of nitrate (Fig. 7), but other ions also (Na^+ - Fig. 9). No major differences existed among irrigation systems in the sodium content extracted from the soil profiles. There was a tendency for the concentrations to increase between the beginning and end of the season, but there was no general trend with respect to irrigation system or moisture level. Except for a few points, the sodium concentration of water extracted from the profile was less than that of the irrigation water (84-127 ppm Na^+).

Calcium concentration of extracts from the 1- to 4-ft depths increased between the beginning and end of the season (Fig. 10), especially in the furrow- and sprinkler-irrigated plots. The sprinkler, furrow, and subirrigated plots received 3, 15 and 5 in. of irrigation water, respectively, between the dates shown on Fig. 7. The subirrigation system apparently does not allow as much calcium to accumulate in the 1- to 4-ft zone as do the furrow and sprinkler systems due to its unique flow pattern away from the orifice and the plane of sample extraction, while the other systems move surface concentrations of ions into the soil profile. In this zone, the

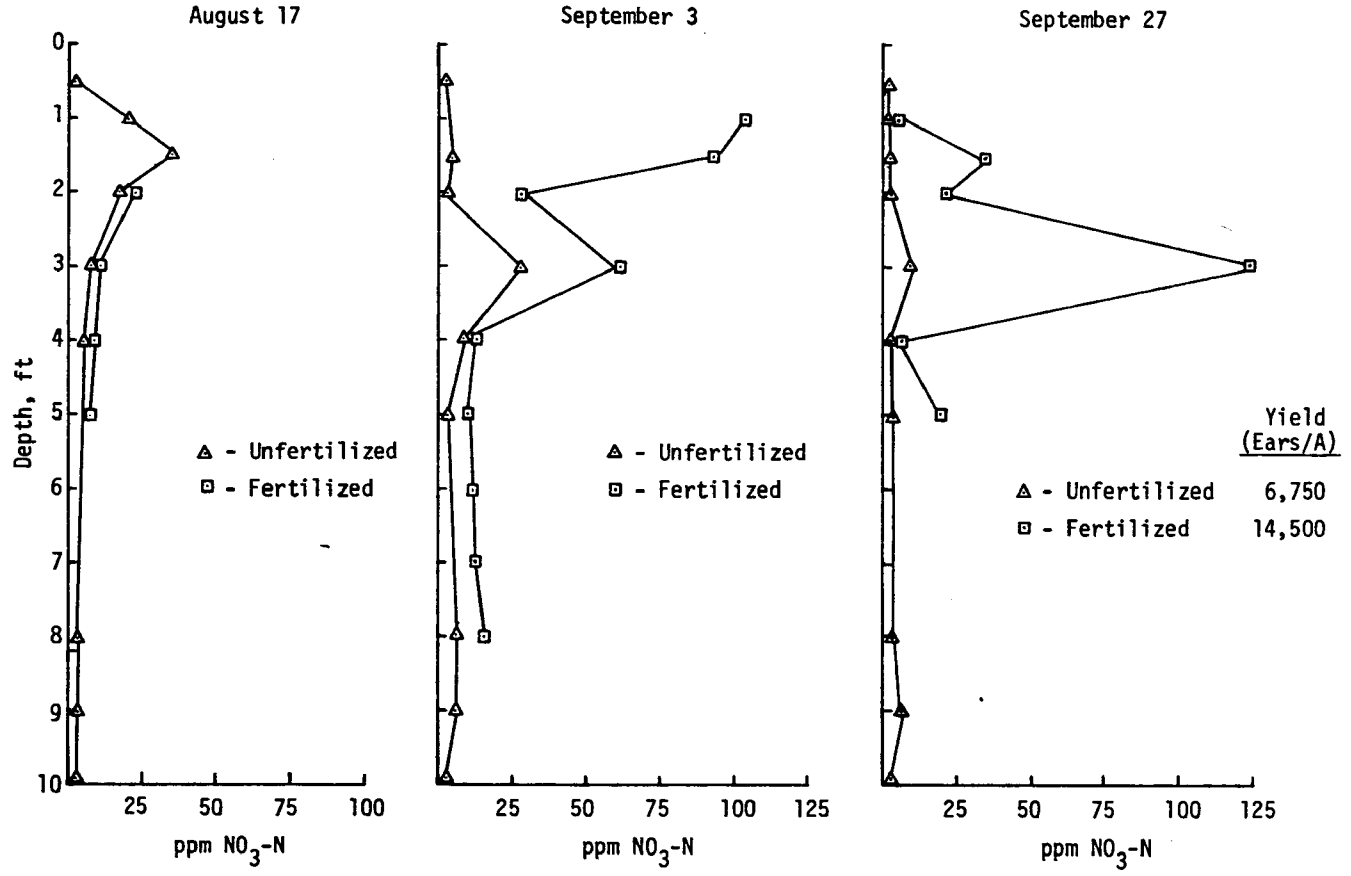

Figure 8: Nitrate-nitrogen concentration of soil water extracts of unfertilized and fertilized subirrigation plots. [Nitrogen solution was injected in the system of the fertilized plots on Sept. 2, Sept. 8 and Sept. 13 at the rate of

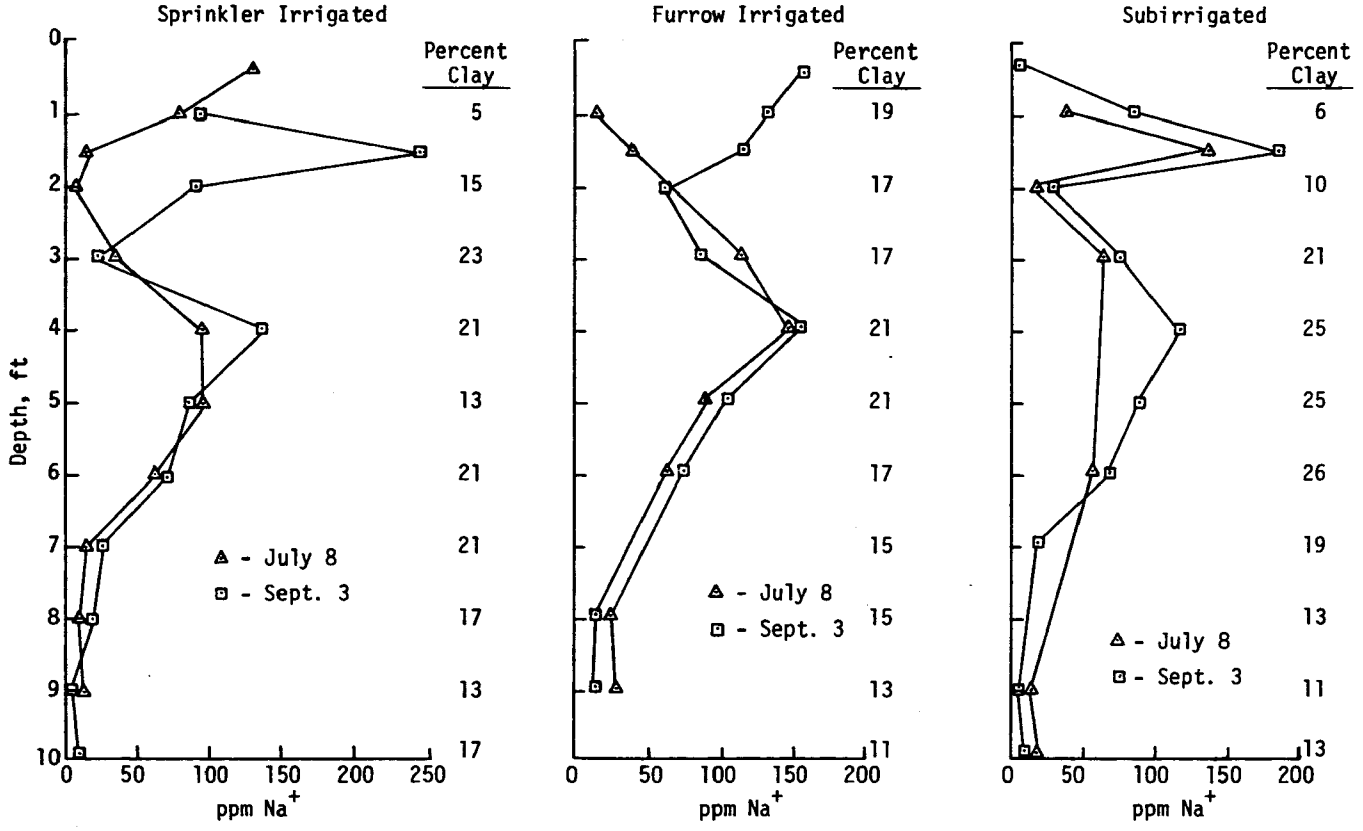

Figure 9: Sodium concentration of soil water extracts of unfertilized plots of different irrigation systems. [Concentration in irrigation water 84-127 ppm Na^+. (Miles loamy fine sand, Rolling Plains Field Site)]

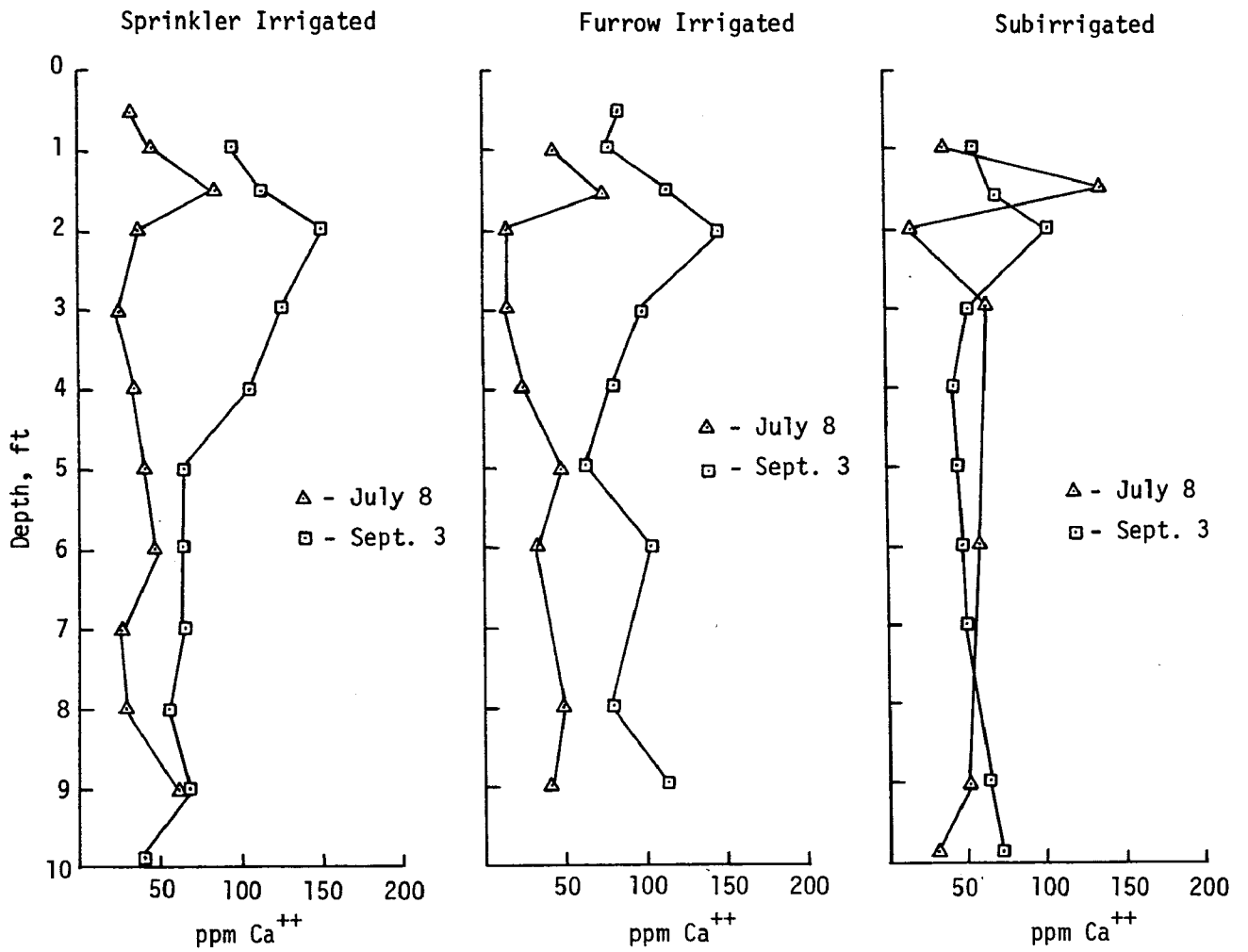

Figure 10: Calcium concentration of soil water extracts of unfertilized plots of different irrigation systems. [Concentration in irrigation water 70-96 ppm Ca^{++}. (Miles loamy fine sand, Rolling Plains Field Site)]

calcium concentration of the sprinkler- and furrow-irrigated plots generally exceeded that of the irrigation water (84-127 ppm Ca^{++}) while the extracts from the subirrigated plots did not. The same trend was found with respect to chloride content of the extracts (Fig. 11). There was

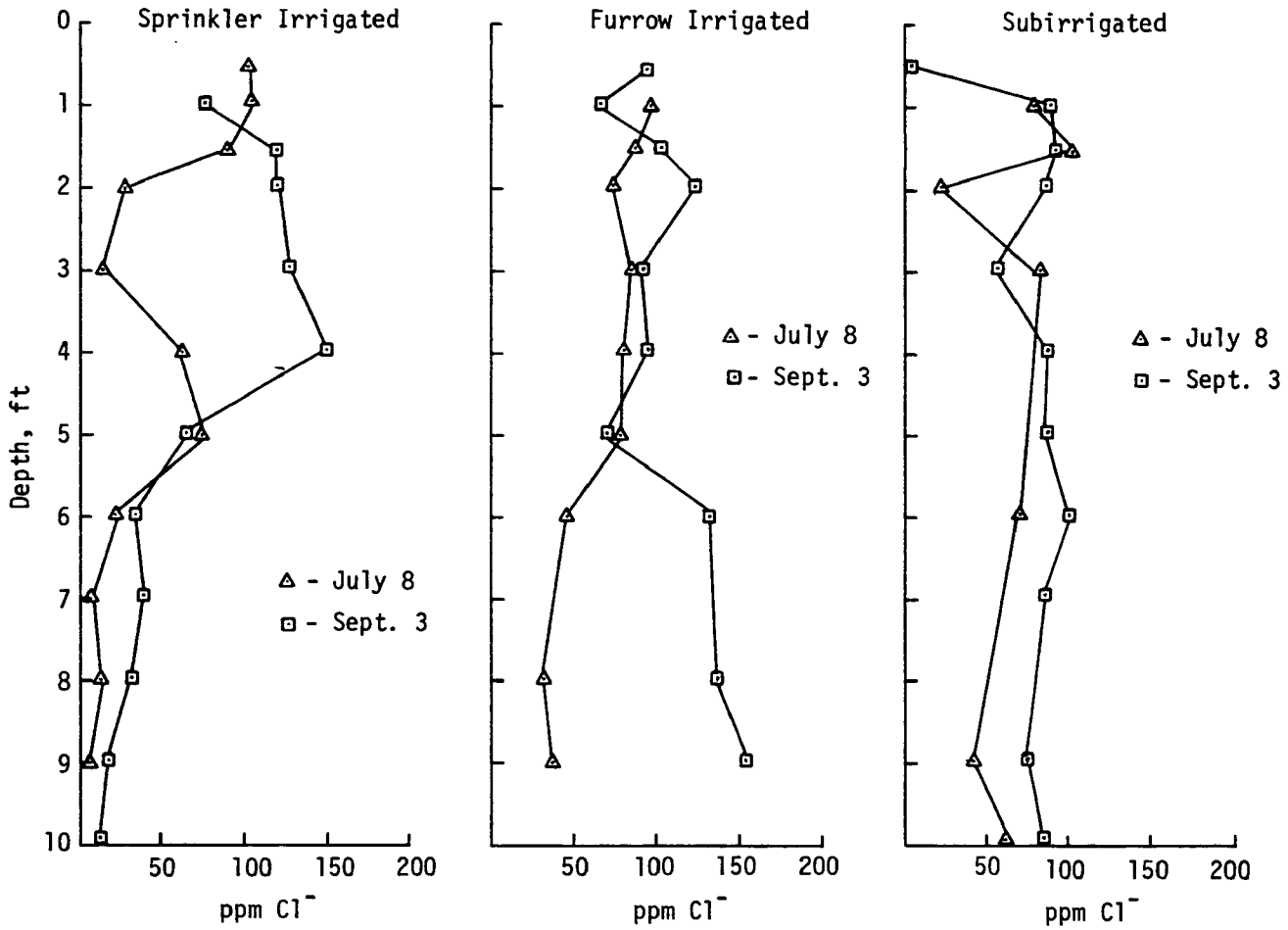

Figure 11: Chloride concentration of soil water extracts of unfertilized plots of different irrigation systems. [Concentration in irrigation water 81-97 ppm Cl^-. (Miles loamy fine sand, Rolling Plains Field Site)]

a significant increase in the 1- to 4-ft zone in the furrow- and sprinkler-irrigated plots with the concentrations exceeding those of the irrigation water (81-97 ppm Cl^-). In some of the furrow plots there were significant increases down to 9 ft. However, this was not a general trend over all plots.

The amount of sulfate in the extracts was influenced by irrigation system and amount and type of water applied (irrigation or rainfall). The sulfate concentrations between July 8 and Sept. 3 tended to increase in the sprinkler- and furrow-irrigated plots (fig. 12). The increase in the subirrigated plots was small, especially if the plots were irrigated prior to the last sampling in addition to receiving rainfall. Subirrigated plot (b), which received 4 in. of irrigation water in addition to the rainfall between Aug. 17 and Sept. 3, did not show any changes in sulfate concentration between the beginning and end of the season. However, subirrigated plot (a), which received 3 in. of rainfall only between Aug. 17 and Sept. 3, showed a substantial increase in the sulfate concentration of the extracts from 1.5 and 2 ft.

Sprinkler-irrigated plot (a) received only rainfall after Aug. 17 and showed a higher concentration of sulfate on the last sampling date in the top 2 ft than sprinkler-irrigated plot (b) which received 9 in. of irrigation water plus rainfall, and showed a substantial decrease in sulfate concentration at 1.5 and 2 ft and a substantial increase at the lower depths.

The furrow-irrigated plots showed a similar trend. Furrow-irrigated plot (b), which received 6 in. of irrigation water between Aug. 17 and

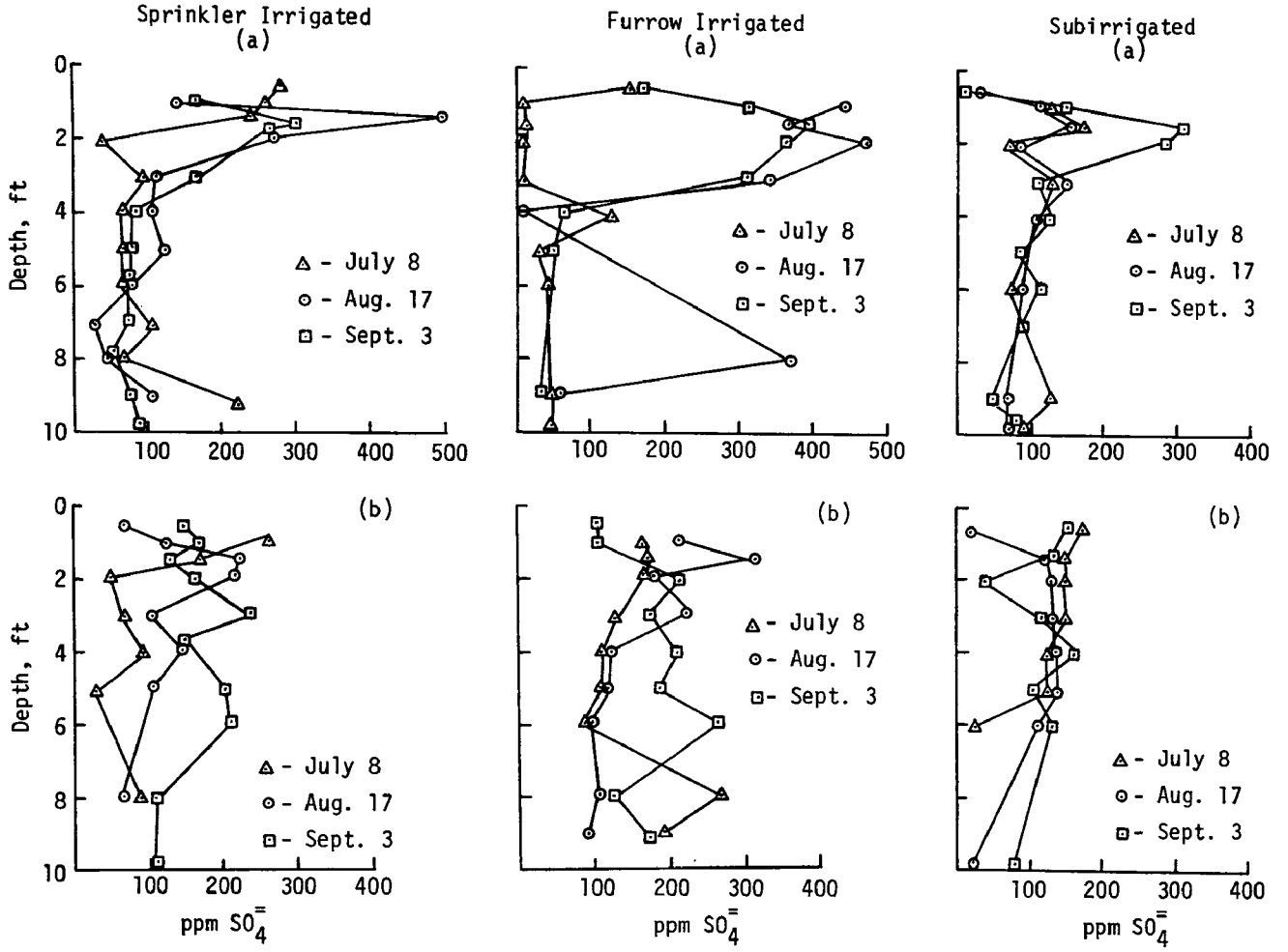

Figure 12: Sulfate concentration of soil water extracts of plots from different irrigation systems which received different amounts of rainfall and irrigation water. [Plots in top graphs received rainfall while plots in bottom graphs received rainfall plus irrigation water between Aug. 17 and Sept. 3. Sulfate concentration in irrigation water 138-172 ppm. (Miles loamy fine sand, Rolling Plains Field Site)]

Sept. 3, showed some decreases at some of the shallower depths with increases at lower depths; while furrow-irrigated plot (a), which received only rainfall, still had high concentrations of sulfate at 0 to 4 ft and showed some decreases at the lower depths.

The sulfate concentration at several depths in the soil profile in the sprinkler and furrow plots exceeded that of the irrigation water, while the sulfate concentration of the extracts from the subirrigated plots exceeded that of the irrigation water at only a few depths.

Electrical conductivity also increased with rainfall (Fig. 13). Those plots which received only rainfall between Aug. 17 and Sept. 3 had higher conductivities than plots which received irrigation water plus rainfall. This is not surprising since rainfall contains few if any soluble ions while the irrigation water contains chlorine, calcium, sulfate and sodium. With this difference in water quality, a difference in the concentration of some ions in the soil solution and a change in conductivity may be expected. As previously mentioned, the sulfate concentrations were higher at the shallow depths following rains than following rainfall and irrigation.

Typical profiles of phosphorus, potassium and ammonium from the subirrigated plot are shown in Fig. 14. As would be expected, there was little change during the growing season due to treatment or irrigation system. Phosphorus concentrations ranged up to 5 ppm on certain dates in some plots, but most of the phosphorus concentrations of most extracts was 1.5 ppm or less with the highest concentrations occurring in the upper 2 ft of the profile. With these low concentrations, phosphorus will never be a problem as a contaminant in the ground water supplies.

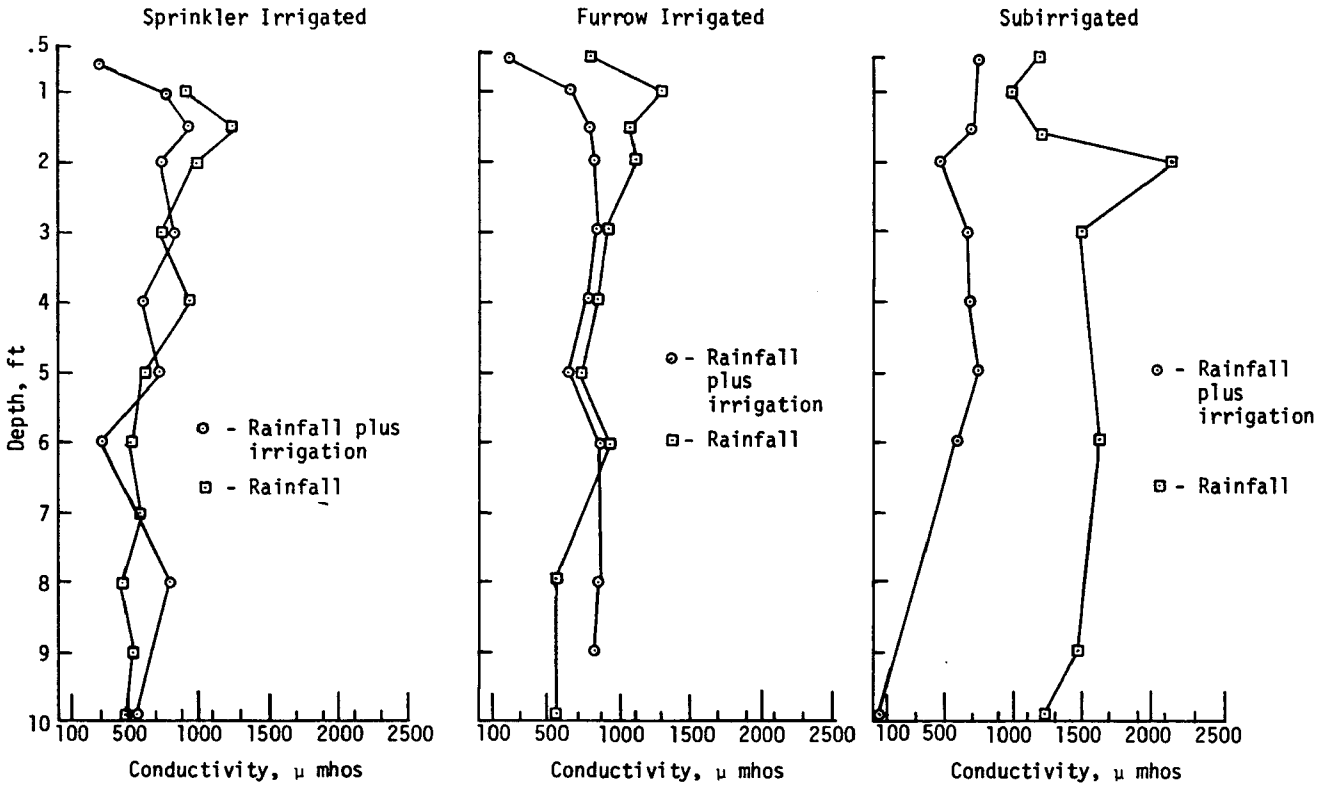

Figure 13: Electrical conductivity of soil water extracts obtained on September 3 from unfertilized plots from the different irrigation systems. [Conductivity in irrigation water 1040-1140 μ mhos. (Miles loamy fine sand, Rolling Plains Field Site)]

No measurable concentration was found in ground water samples procured during the course of the study.

The potassium concentration of the extracts from the upper 3 ft of the soil profile was higher than that of the irrigation water. The source of this potassium was probably the exchange complex of the soil because the concentrations remained reasonably constant throughout the growing season.

Ammonium was found at various times during the season in many of the plots at various depths. There was no pattern as to the amounts present as influenced by treatment or irrigation system. However, the data show that ammonium may move in these soils.

SUMMARY

The layering in the soil profile produced conditions whereby the soil retained more water than would be expected from pressure plate data. This in turn resulted in most of the ions being retained in or immediately above the clay layers in the soil profile. Water samples extracted from subirrigated plots generally contained lower concentrations of nitrate, calcium and chloride. Sulfate concentrations and electrical conductivities were more influenced by rainfall than by the method of irrigation. Phosphorus and potassium concentrations were not influenced by irrigation system or moisture additions.

Soil water potential data indicate that the primary zone of water application from subirrigation systems in the soils in this study is between 6 in. and 36 in. The subirrigation system thus appears to have potential for maintaining the water quality of irrigation return flows for several reasons. Concentrations of certain ions such as chloride and calcium remain low in the root zone due to the fact that less water is applied and the unique flow pattern of the system. Nitrogen can be easily applied to the system in small amounts which will create high nitrate concentrations only in the root zone for plant growth. In layered soils, zones of high potential can be created which will be adequate for plant growth yet zones of low potential will remain in the soil profile for the storage of rainfall.

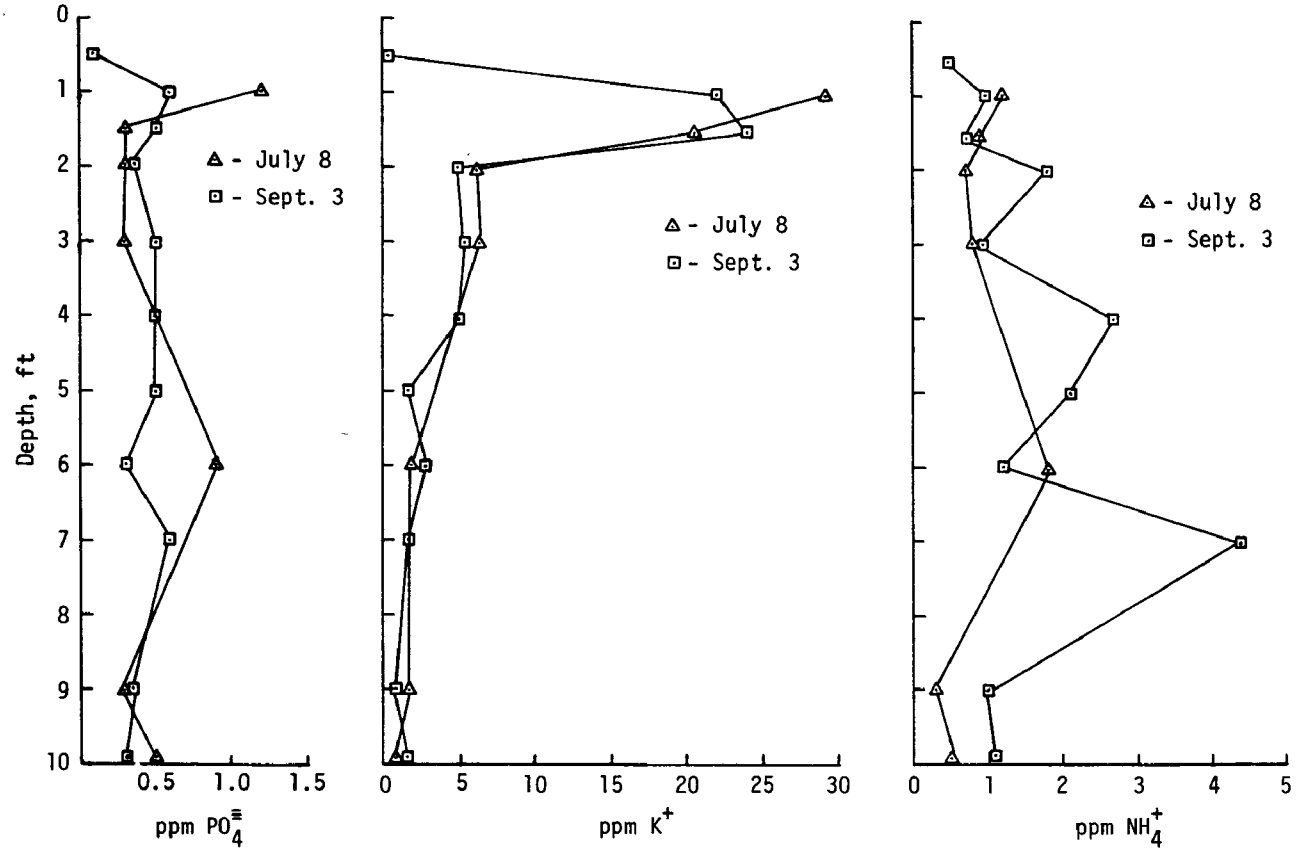

Figure 14: Phosphorus, potassium and ammonium concentrations of subirrigated plots. (Miles loamy fine sand, Rolling Plains Field Site)

In those areas where water of impaired quality is used, it is foreseen that a zone of high salt concentration may accumulate in the periphery of the zone irrigated by the subirrigation pipe. It may be necessary to irrigate during or immediately after rains to prevent these salts from moving into the root zone.

Sweet corn was successfully grown on the subirrigation systems at Lubbock and Munday, Texas in 1971. Some management problems, such as planting too far from the subirrigation pipe, were encountered but solved. The existance of fine-textured layers underlain by coarse-textured layers creates zones of high water retention and low conductivity and the possibility that wider spacings of the laterals could be used which would decrease the cost of the systems.

ACKNOWLEDGEMENT

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Irrigation Return Flow Studies in The Mesilla Valley

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ABSTRACT

Deterioration of the quality of the water in the Rio Grande is a major problem for water users in New Mexico and Texas. From Otowi Bridge near Santa Fe, New Mexico to El Paso, Texas, a distance of 270 miles, the total dissolved solids increases from 221 ppm to 787 ppm, while the percent sodium goes from 25 near Santa Fe to 52 at El Paso. The increase in salinity per mile is more than twice as great in the irrigated areas as in the non-irrigated areas. The greater increase in salinity per mile is due to the return of lower quality drainage water from the irrigated areas to the river. This paper describes a research project designed to determine under field conditions rates of water and salt movement in the soil as affected by frequency and amount of surface water application. The effects of trickle irrigation on return flow quantity and quality are also determined.

INTRODUCTION

The quality of irrigation return flow represents a major problem in the western United States. The water of the Rio Grande in New Mexico has been reported as a classic example of water quality degradation[4 7 12 13]. Table 1 taken from Wilcox[12], shows the variation in composition of the Rio Grande water from Otowi Bridge near Santa Fe to El Paso, Texas.

Table 1 shows a progressive increase in the concentration of total dissolved solids and percent sodium from the upper to the lower sampling stations. Only a small portion of land is irrigated along the river for 42 miles from San Marcial to Caballo Dam. From Leasburg Dam to El Paso, essentially all of the land is irrigated for a distance of 63 miles. The total dissolved solids in the river increased by 66 ppm along the area without irrigation and by 236 ppm along the area with irrigation. The increase per mile is more than twice as great in the irrigated areas as in the non-irrigated area.

The relatively large increase in dissolved solids in the river along the irrigated areas is mainly due to the concentrating effect of irrigation. Plants take up water from the soil solution and transpire it to the atmosphere, but they take up very little salt. Similarly water evaporates

TABLE 1

Variations in composition of Rio Grande water
(weighted means, 1934-1953)

	Station					
	Otowi Bridge	*San Marcial*	*Elephant Butte*	*Caballo Dam*	*Leasburg Dam*	*El Paso*
Miles from El Paso	270	150	130	108	63	0
Dissolved solids ppm	221	449	478	515	551	787
Sodium %	25	41	43	44	44	52
Land Irrigated Acres	80,000	-	-	15,000	70,000	

from the soil surface, but the salts remain behind, causing an increased concentration in the soil solution. With normal irrigation practices a significant portion of the applied irrigation water percolates to the subsoil and groundwater table. This percolating water carries with it salts accumulated in the root zone, thereby preventing excessive salinization of the upper soil profile. Eventually this water affects the quality of underlying aquifers or is picked up by drains and returns to the main stream, resulting in increased salinity of the river. The salt concentration of the drainage water can be as much as two to five times higher than the salt concentration of the irrigation water[10]. Although the volume of drainage water is usually much smaller than the volume of river water, it is obvious from Table 1, that recycling of irrigation return flow has a detrimental effect on the water quality downstream.

The data in Table 1 are for the years 1934-1953. Since 1951 the situation in the Rincon and Mesilla Valleys in southern New Mexico has worsened through the addition of some 1800 wells. Starting in 1951 and continuing through 1957 the Rio Grande project experienced a critical shortage of irrigation water. During this time alone, more than 1700 irrigation wells were drilled to provide supplemental water[13]. The quality of the water from these wells is considerably lower than of the water from the river. Figure 1, taken from Basler and Alary[1], shows the location in the Rincon and Mesilla Valleys of 39

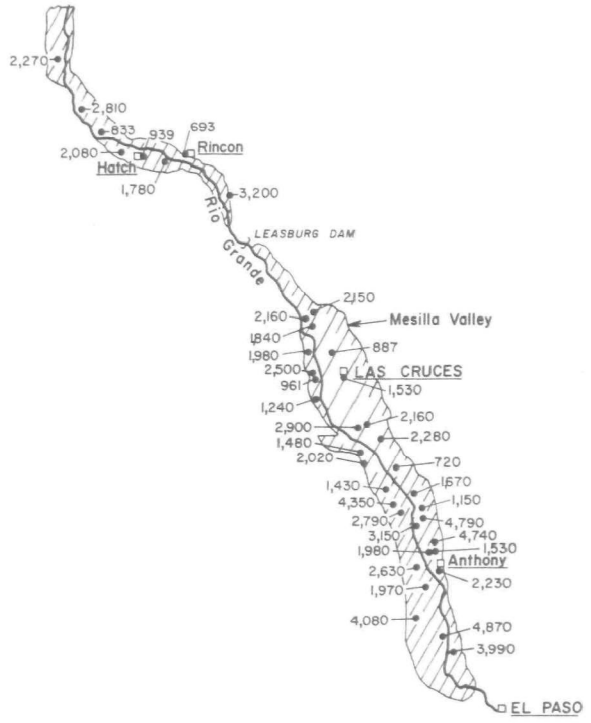

Figure 1: Map Showing the Electrical Conductivity in Micromhos at 25° C of Shallow Groundwater at Selected Sites in the Rincon and Mesilla Valleys, New Mexico

selected shallow wells. Data from these wells, combined in four groups of wells along the river from north to south, are presented in Table 2.

According to the information from the Irrigation District Office in this area, for the years 1951 through 1969, approximately 58 percent of

TABLE 2

Variation in composition of well water in the Rincon-Mesilla Valley, New Mexico (1967)

Group	No. of Wells	Average Conductivity ($EC \times 10^6$)	Percent Sodium
1	10	1891	46
2	10	1849	51
3	10	2268	57
4	9	3417	73

the water used for irrigation in the Rincon-Mesilla Valley came from the district canals, while 42 percent was supplied from wells. Since the groundwater as represented by the 39 wells in Table 2 averages 2320 micromhos/cm, while the weighted mean conductivity of the river water from 1934-1963 at Leasburg dam is 844 micromhos/cm, it would seem that the use of irrigation wells, starting on a major scale in 1951, is adding to the salt problem.

Because it is unlikely that irrigation with well water is a great deal more efficient than irrigation with river water, it may be expected that the use of well water will have an adverse effect on the quality of the return flow. Table 3 compares the weighted mean electrical conductivity of the Rio Grande water at Leasburg dam and at El Paso, 63 miles downstream. Data are presented for the periods 1934-1950 and for 1951-1963. Data for Leasburg dam after 1963 are incomplete. The average discharges at Leasburg dam and at El Paso are also presented. The last column in Table 3 presents the increase in salinity between Leasburg dam and El Paso for every three year period from 1934-1963. Comparing the quality of the river water before 1951 with the quality of the water from 1951 to 1963, it is clear that although the total salinity has increased somewhat, the net increase in salinity between the two measuring stations remained nearly the same. Apparently the increased use of well water after 1951 had, up to 1963, very little effect on the quality of the irrigation return flow. This slow response to changes in irrigation water quality is undoubtedly due to the high buffering capacity of most of the agricultural

TABLE 3

Average discharges and weighted mean conductivities from 1934 to 1963, for Leasburg dam, New Mexico and El Paso, Texas. Data extracted from U. S. Salinity Report No. 113, by L. V. Wilcox, 1968

Period in Years	Average Discharge in 1000 acre feet		Weighted Mean Electrical Conductivity, $EC \times 10^6$		
	Leasburg Dam	El Paso	Leasburg Dam	El Paso	Increase
1934-1936	698	481	972	1351	379
1936-1939	742	534	834	1257	423
1940-1942	1047	842	808	1021	213
1943-1945	828	604	764	1184	420
1946-1948	702	463	846	1254	408
1949-1950	699	469	729	1166	437
1934-1950	791	571	827	1187	360
1951-1953	476	267	851	1209	358
1954-1956	217	73	1304	1505	201
1957-1959	595	306	813	1124	311
1960-1963	569	330	832	1287	455
1951-1963	472	250	881	1237	355

soils in the Mesilla and Rincon Valleys. However, it may be expected that eventually the quality of the irrigation return flow, and thus the quality of the river water at El Paso, will be affected by the increased use of well water.

The high salinity of the water in the Rio Grande below El Paso has already resulted in extensive salt damage to agriculture in the El Paso Valley, particularly in Hudspeth County, below El Paso, where many farmers are discontinuing their operations. Further deterioration of the river water will also have serious affects on agriculture in the Mesilla and Rincon Valleys in New Mexico. In addition, the city of El Paso and the city of Juarez, located across the river from El Paso in Mexico, will in future years become more and more dependent on water from the Rio Grande for their municipal and industrial needs. These cities therefore have a strong interest in maintaining the quality of the river water.

So far, no studies have been made to predict quality changes in the Rio Grande basin as a result of agricultural practices or municipal and

industrial developments within the basin. For sound long term planning of the very limited water resources in the Middle Rio Grande basin, it is necessary to estimate long term water quality changes resulting from changes in the use of water. In the past much work has been done on developing models for predicting the quality changes of water percolating through soil profiles[3 8 9]. Such models are of great value for predicting the quality of subsurface return flow and for determining the effects of agricultural practices on return flow quality. However, few of these models have been adequately tested under actual field conditions.

In cooperation with the Environmental Protection Agency a field plot experiment was initiated by the New Mexico State University Experiment Station to study the quality of irrigation return flow. One of the main objectives of this study is to determine under field conditions with varying degrees of management rates of water and salt movement, under conventional surface irrigation as practiced in the valley. Similar determinations will be made on plots irrigated with trickle systems. Trickle irrigation has been used successfully for irrigation of a wide variety of crops in Israel, Australia and New Zealand and is presently being used on an increasing scale in this country. Little is known, however, regarding the salt build up in the soil profile around trickle lines or the quality of the return flow under trickle irrigation.

Project Description

The project is located at the Plant Science Farm of New Mexico State University near Las Cruces, New Mexico. The farm is located about eight miles south and west of Las Cruces (Figure 1). The experimental area is located near the farm headquarters and is bordered on the east by the 10 to 12 feet deep Del Rio Drain, which serves a large section of land in the Elephant Butte Irrigation District. In this area the Del Rio Drain runs parallel to and approximately one mile east of the Rio Grande. The soil at the site is not uniform, but differs in this respect little from typical soils in the valley, which too are highly variable. It consists in general of 35 cm of clay loam over 20 to 30 cm of clay, over a variable amount of silty loam. The latter changes rather abruptly into medium sand. The depth to the sand varies on this 2 acre field from 65 to 120 cm below the soil surface. Root penetration into the medium to fine sand layer appears to be almost negligible.

In Figure 2 the field plot layout of the experiment is presented. The experimental set up consists of thirty 24 × 24 feet plots and six 20 × 60 feet plots. The 24 × 24 feet plots are irrigated by surface irrigation and the 20 × 60 feet plots by trickle or drip irrigation. Each plot has its own water outlet, which is connected through a 2 or 4 inch underground pipeline to a 8 inch well just outside the plot area. The surface irrigated plots are separated from the surrounding soil by polyethylene plastic to a depth of 2.5 feet below the soil surface. Wooden boards of 1 × 12 inches, extending 8 inches above the soil surface and covered with polyethylene plastic, prevent surface runoff from the plots.

Surface Irrigation

Of the thirty surface plots, three are set aside to determine the hydraulic characteristics of the soil of this study. Triplicate tensiometers have been installed near the center of each of these three plots at depths of 30, 60, 90, 120, 150 and 180 cm below the soil surface. In addition, two neutron access tubes have been installed close to the tensiometers. Following the procedures described by Van Bavel et. al.[11] and Nielsen et. al.[5] the hydraulic characteristics of the soil are determined as a function of water content.

The main treatment affects on the 24 × 24 square feet plots are frequency of irrigation and amount of irrigation water applied. The time between irrigations varies according to soil type, stage of plant development and climatic conditions. In this investigation the plots will be irrigated on the basis of the amount of "available" water in the soil profile, where "available" water is defined as the amount of water retained between 1/3 and 15 bars suction. Treatments include the scheduling of an irrigation when 25, 50 or 75 percent of the available water has been depleted from the root zone.

The amount of water applied to replace the water depleted within the root zone is affected by the efficiency of water application. In this investigation surface runoff is prevented with borders around each plot and side seepage is minimized by polyethylene plastic sheets to a

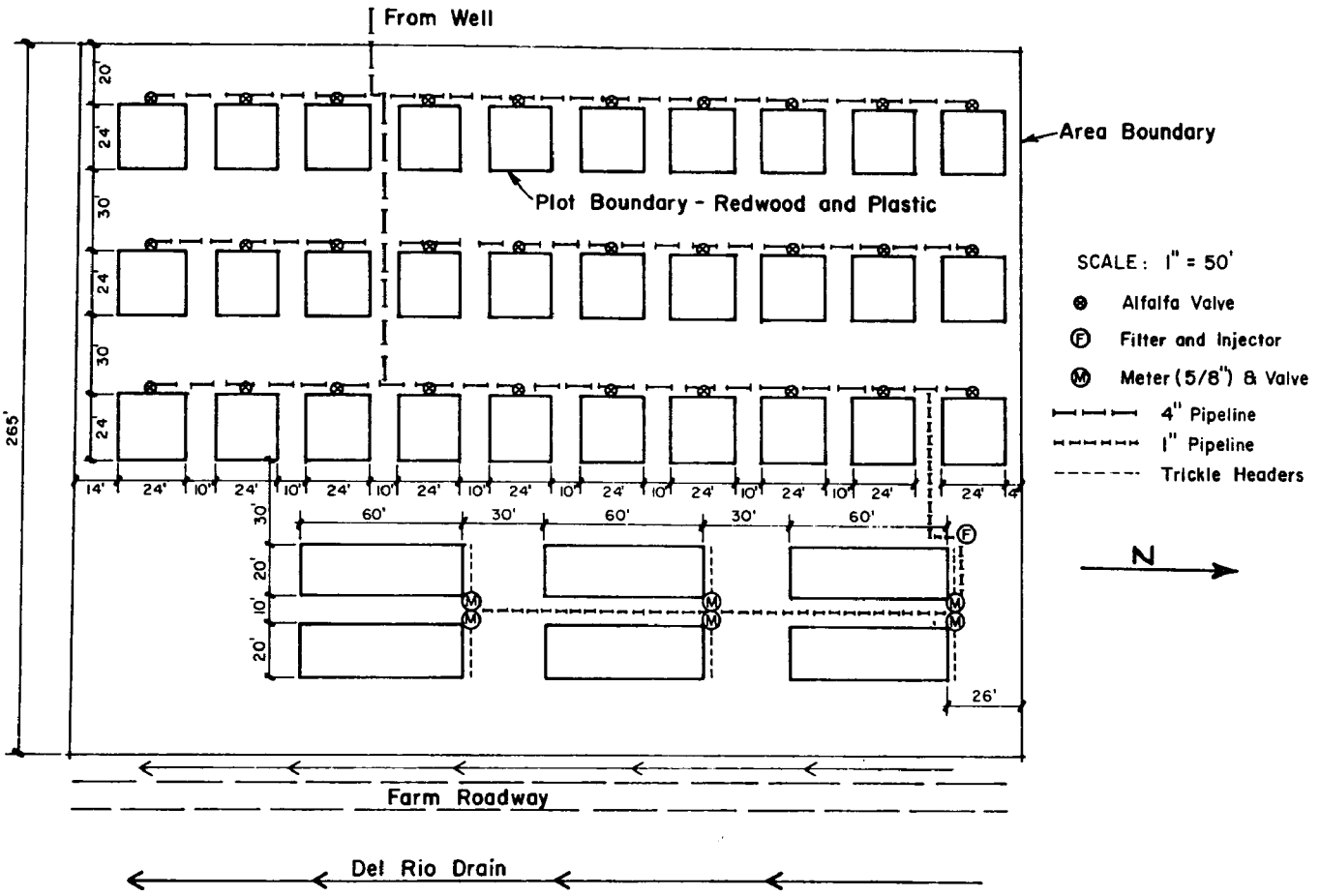

Figure 2: Field Plot Layout of Irrigation Return Flow Project at Plant Science Farm, New Mexico State University, Las Cruces, New Mexico

depth of 2.5 feet below the ground level. Thus the field water application efficiency is a function of the amount of water lost by deep percolation only. Three field water application efficiencies have been selected for this experiment, e.g. 50, 75, and 100 percent, respectively. With 50% efficiency half of the applied water is lost by deep percolation, while supposedly none is lost with 100% efficiency.

The main treatment effects consist of combinations of three frequencies of irrigation with three field water application efficiencies, resulting in a total of 9 treatments. Each treatment is block randomized with three replications per treatment, resulting in 27 plots for this part of the experiment. To determine the water loss by deep percolation, measurements are made of the water content and the pressure gradient below the root zone of each plot. From the pressure gradient and knowledge of the hydraulic conductivity and the water content below the root zone, the net flux in or out of the soil profile is calculated, using Darcy's equation. The quality of the water percolating below the root zone is determined by collecting samples from suction cups located below the root zone. Although changes in the chemical composition of percolating water are rather slow it is expected that three years of filed data will show the effects of frequency of irrigation and of water application efficiency on the quality of percolating water. Cotton will be grown on the 24 × 24 feet plots for the duration of the experiment.

Trickle Irrigation

The effects of trickle irrigation on the amount and quality of percolating water will be studied on six 20 × 60 feet square plots. Three of these plots are irrigated to maintain the soil-water tension at 6 inches below soil surface at or below 0.2 bars. On the other three plots the soil-water tension at 6 inches is kept at 0.6 bars or

less. Irrigations are automated with an adjustable timing control to keep the soil-water tensions at 6 inches at the desired levels.

The amount of percolating water is again determined from the pressure gradients below the root zone as measured with tensiometers at two depths, and the hydraulic conductivity of the soil. Samples of the percolating water are taken through suction cups placed below the root zone of the crop. The electrical conductivity of the well water used for irrigation all plots is 1455 micromhos/cm. Thus a significant salt buildup can be expected away from the trickle lines. However, the time required for the salt buildup to occur is unknown. A one year study with trickle irrigation of corn at New Mexico State University showed no significant increase in salt concentration in soil samples taken in between the rows, as well as in the rows. To more adequately investigate this phenomenon, qualitative measurement are to be made of this increase in soil salinity around the trickle lines, using recently developed salinity sensors[6]. From 9 to 12 salinity sensors are installed around each of several trickle lines. This will allow continuous monitoring of salt accumulation at various grid points. The crop to be grown on the trickle plots is cotton during the first year of the experiment, to be followed with lettuce, onion and possibly corn.

In conjunction with the field experiment a record is being kept of the quality of the water in the Del Rio Drain adjacent to the plot area. Two sampling stations have been established on the drain for measuring the discharge and the quality of the water at weekly intervals. The first station is located adjacent to the plot area, while the second station is 2.2 miles upstream. The quality of the irrigation water used in the area bordering the two mile section of the drain is also monitored by periodically sampling the surface and well water used for irrigation in this area.

Expected Result

The real interest in this research project is in the quality and quantity of irrigation return flow, as affected by trickle and surface irrigation. Trickle systems have great potential for high water-use efficiency. The systems can readily be automated and may be programmed to operate without excessive percolation losses inherent with border and furrow irrigation. At present, the overall irrigation efficiency in the Rio Grande Valley is around 40 to 50 percent. Thus as much as 50 percent of the water used for irrigation may be lost to the subsoil by deep percolation. Part of this water is used again by pumping from wells, and part of it is returned to the river as drainage return flow. However, the quality of this water has degraded considerably during its movements through the soil. It is expected that with trickle irrigation the quantity of irrigation return flow can be greatly reduced. What the effects will be on the quality of the return flow is uncertain. This project should yield valuable information on the quality of the return flow and on the changes in soil salinity resulting from trickle irrigation. The project will also be helpful in establishing management procedures for trickle irrigation for the soil, water and climatic conditions of the Middle Rio Grande Valley.

The surface irrigation treatments should yield information on the amount and the quality of water leaching from the surface plots. The experiment may prove that possibly less water may be used for maintaining a favorable salt balance than what at present is thought to be necessary for leaching of excess salts, based on steady state flow rates. A reduction in leaching water will reduce the volume of drainage return flow and thus have a favorable effect on the quality of the river water downstream.

Water quality standards in New Mexico allow agriculture to return to the mainstream dissolved solids present in the irrigation water. However, in view of the increasing concern with the quality of water in New Mexico, it can be expected that a closer look will be taken at the practices of the largest water user in the state, than is done at present.

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Irrigation Scheduling in Idaho

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ABSTRACT

Scheduling the timing and amount of irrigation water applied has changed very little during the last two decades. Professional irrigation scheduling services are rapidly expanding and many of the companies are using a computer program developed by the USDA. This program uses meteorological, soil and crop data to predict irrigation dates and amounts. Service companies modify the program to fit their needs. Periodic field inspections are provided by trained technicians as part of scheduling service. This paper briefly describes the development of the computer program and the current status of its application in Idaho.

Introduction

In Idaho, as in most irrigated areas in the West, irrigation scheduling had changed very little during the last two decades. In the meantime, there have been significant advancements in irrigation science and technology. Growers stand to gain direct economic returns from better irrigation scheduling by increased yields and in some cases, lower irrigation costs. Irrigation districts whose operating costs are borne by the farm owners and managers regularly encounter unnecessary direct and indirect operating costs that can be attributed to poor irrigation practices.

Irrigation scheduling involves several important components (1) timing, (2) the amount of water applied, (3) the flexibility of the system, and (4) the ability of farm management to respond to irrigation needs. But why has there been little improvement in irrigation scheduling? Probably the most obvious reason why the amount of irrigation water has not been controlled more precisely is that water measurement is not common on most of the older irrigated areas. Water measurement on each field is not a simple task with surface irrigation. The amount of water delivered to the farm can be measured with relative ease, but losses as seepage in the distribution system, deep percolation near the upper ends of the field, and surface runoff are generally not known to the farm manager. Also, the farm manager is not interested in measuring the amount of water applied if there is no obvious direct economic benefit. He is not interested in expending additional funds, time, and often being inconvenienced measuring water just to collect data. Low cost water, obsolete irrigation systems and high labor costs are also important factors that have contributed to lack of change in irrigation scheduling practices.

Large quantities of data are available that show significant reductions in crop yield or quality if irrigations are delayed, but few data show the economic losses that occur as a result of excessive water applications. The natural tendency under these circumstances is to apply

excessive amounts of water to be sure that soil water is not limiting. Another very significant factor is that the cost of irrigation water in most gravity projects is very low. Indirect costs caused by excessive irrigations such as yield reductions, soil erosion, and additional nitrogen requirements are not easily recognized or quantified. Crop and soil damages encountered on lower lying areas some times are a result of excessive use on the upper areas, but these losses are not borne by the upper-area irrigators.

Another significant factor has contributed to slow change in irrigation practices. Until recently research and technical service agencies have not recognized or thoroughly evaluated the scheduling problems faced by managers of irrigated farms. They have not adequately evaluated the acceptability of the usual scheduling procedures that have been promoted for many years. In addition, the farm manager often is not aware that yield reductions are caused by delaying an irrigation even though excessive amounts of water may be applied at the next irrigation. The lack of change in irrigation scheduling technology also strongly implies that the mechanism for providing current irrigation scheduling information to the farm manager has not been satisfactory. Irrigation water scheduling proposals must be economical. Expensive or excessive soil water monitoring or irrigation scheduling techniques that do not pay for themselves in terms of direct and indirect benefits are questionable unless subsidized. We also must not forget that there is no substitute for proven irrigation experience; any irrigation scheduling technique only supplements, but does not replace experience.

Professional Irrigation Management Services

Irrigation scientists and technologists know how to optimize crop production by manipulating irrigation practices, but these specialists are not making the irrigation decisions on every farm. The farm manager is faced with many problems involving soils, crops, plant nutrition, and climatic considerations, and cannot become an expert in all of these areas. Instead of following the traditional approach of training every farm manager to become a specialist in irrigation water management and collect his own data to make scheduling decisions, we decided to develop some basic tools that would eventually provide professional irrigation water management services to the farm manager if he so desired. This approach required a technique for bringing together scientific irrigation principles into a single package that could be applied to every field. Also, procedures were needed for the farm manager and an experienced professional to maintain field-by-field communications. The system had to be economical, practical and dependable, and had to use research and climatological data that were available, or could be obtained easily. The system also had to be dynamic, responsive to the changing needs of the farm manager, and backed up by field inspections by experienced and trained personnel.

One alternative was to promote irrigation water management services using existing tools, but this had been tried to a limited extent in other areas and in general was not being adopted very rapidly. A number of tools and instruments, such as tensiometers, soil moisture blocks, evaporation pans, and soil sampling augers and tubes have been available commercially to farm managers and farm management service groups for many years. We decided to develop a different approach, an approach which would be very palatable to the farm manager and at the same time provide the type of data that he needed and wanted. Pursuit of this objective resulted in the USDA-ARS-SWC Irrigation Scheduling Computer Program.

Development of Computerized Irrigation Scheduling Technology

A systematic approach based on climate-crop-soil interactions was needed to provide estimates of the current soil water status by fields to the farm manager along with predictions of future changes and irrigation requirements. With the recent advances in meteorological science and computer technology the adaptation of computers to irrigation water scheduling appeared to be an attractive approach to modernizing irrigation scheduling.

Development of the USDA-ARS-SWC Computer Program

The USDA Computer Program was developed cooperatively with farm managers and service groups to incorporate their reactions during the formulation of the program. It was devel-

oped as a tool for providing managers of irrigated farms with scientific estimates of irrigation needs for each field. The computer program utilized simple mathematical models and basic equations initially so that limited input data could be used. The various components of the program can be replaced as more accurate relationships are developed through research and applied technology. Briefly, meteorological, soil and crop data are used to predict future irrigation dates and amounts. The principles and procedures have been described in a number of recent publications and are not included in this paper[4 5 6 7 8].

The basic components of the irrigation scheduling program and service were evaluated in southern Idaho in 1966 and 1967. The complete computer program and management services were evaluated in cooperation with farm managers and the Idaho Extension Service in 1968 and 1969. About 50 fields were scheduled in Idaho during these two years and a similar number were scheduled in Arizona by the Salt River Project[3]. Several service groups and companies gained experience using this concept of providing irrigation management services in 1970 and 1971.

The U.S. Bureau of Reclamation, in its fourth year of a pilot irrigation water management study, modified the computer program to provide either general irrigation forecasts for several major crops, soil types, and dates of planting within an irrigation district, or field-by-field scheduling. The general service was made available to 54 farm operators in southern Idaho in 1970. The field-by-field scheduling and monitoring service was provided for 68 fields on 15 farms within the same area! The present USBR general program predicts irrigation dates for major crops and soils, but the printout to each farm is selected from a combination of six crops, four soils, and three planting dates. This procedure was evaluated on 76 farms totalling 14,000 acres in 1971. With this procedure, the farmer must verify the predictions and keep his own records. The field-by-field method, involving field inspections by trained professional or technical staff members, was evaluated on 14 farms totaling 5,000 acres in 1971. The USBR will be providing the general scheduling service to about 24,000 acres and field-by-field scheduling services to about 30 farms and 150 fields totaling about 9,000 acres in 1972. The Bureau's full time staff will consist of two engineers, and an agronomist in 1972. The A & B Irrigation District at Ruper, Idaho and the Falls Irrigation District near American Falls, Idaho, will each provide an agricultural technician[2].

A commerical irrigation management service corporation was formed by potato growers in southern Idaho in 1971. This company will be operating in four general regions in Idaho in 1972. A college trained agriculturalist will supervise field monitoring and inspections in each region. This company anticipates providing irrigation scheduling services to about 40,000 acres in 1972.

About three years ago another commercial service company began an irrigation management service in southern Idaho using tensiometers to indicate the soil water status. One or more tensiometers per station are installed in the grower's field. Each station represents from 10 to 20 acres. These instruments are read about twice a week early in the season and every other day during the peak water use period. The service company installs, maintains, and reads the tensiometers. It then interprets the data and makes irrigation recommendations to the farm manager accordingly. This company serviced approximately 10,000 acres in 1971 and hopes to expand its service to 15,000-20,000 acres in 1972.

Another company began providing irrigation and plant nutrition services in cooperation with a sugar company in southern Idaho in 1971. This service company conducts soil and tissue analyses for plant nutrients and provides general irrigation scheduling and field-by-field inspections in a cooperative study to determine if sugarbeet yields and quality can be increased. This study involved 52 test fields in 1971. Field inspections by this company frequently revealed another primary irrigation problem. In addition to the timing of an irrigation, nonuniform distribution of water within a field that is surface irrigated can greatly affect production.

Development of a Communications System

Under the field-by-field scheduling service, a better system for obtaining up-to-date feedback data involving the date and approximate

amount of water applied is still needed. Where center-pivot sprinkler systems are used, service companies probably will install their own rain gages to measure rain and applied irrigation water. These gages are designed to minimize evaporation so that they can be read on a weekly basis.

Expected Improvements and Expanded Services

As quantatitive data are developed relating plant growth to other parameters in addition to soil water these can be incorporated into the scheduling program. Improved mathematical models that predict plant growth based on microclimate, plant characteristics, plant densities, soil water, and nutrients will be added to the program when they have been fully developed and tested. Simple calibration techniques probably will be needed to relate the calculations to the specific site conditions. Improvements in techniques for estimating evaporation from the soil surface will be added. These improvements, when combined with effective leaf resistance to water vapor diffusion which varies as plant cover develops, will improve the estimates when a partial plant canopy exists.

Yield-soil-water-climate functions for all stages of plant growth are needed to predict the relative adverse effects of delaying irrigations or excessive irrigations, and to optimize the timing of limited irrigations. Eventually, procedures will be developed to predict the distribution of water throughout the length of the field by taking into account the size of stream, the rate of advance through the field and the duration of the set.

Most of the service companies now using this computer program are operating in areas where salinity is not a significant problem, or where excessive water is being applied. Under these conditions there is no salinity hazard and no resulting build-up of salts in the soil. If the amount of water applied is known or can be measured and the quality of water taken into account, then soil salinity changes can also be predicted. If the amount of water applied is not measured, we recommend that companies providing irrigation management services monitor the salt concentration in soils where salinity problems are suspected. If salts increase to adverse levels then additional irrigations or larger irrigations can be scheduled to leach the salts.

CONCLUSIONS

Irrigation scheduling practices have not changed appreciably in most western U.S. irrigated areas during the last two decades. Low water costs, unacceptable new scheduling techniques, and the fact that adverse direct and indirect effects of excessive water use are not readily apparent are major factors that have delayed improvements in irrigation scheduling. Scheduling irrigations for each field by using meteorological, soil, and crop data coupled with field inspection appears to be an economical and acceptable irrigation management service in the USA. A professional irrigation management service requires technical competence and a modern communication network. Reliable meteorological data are also needed. Collection of these data requires technical competence and periodic calibrations of the instruments. The USDA-ARS-SWC irrigation scheduling program using meteorological techniques and soil-crop data, is enabling Idaho private firms and service agencies to provide improved management services while gaining experience and while the program is being refined.

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Irrigation Scheduling in the Salt River Project

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ABSTRACT

The problem of scheduling irrigation within the Salt River Project area is approached via two methods which determine soil moisture levels and the evapotranspiration rates for different crops and soils. These methods are:

A. Repetitive field checks by trained specialists.

B. A computerized program described by Jensen which uses either the Jensen-Haise or the modified Penman equations for potential evapotranspiration. This program schedules predictions using climatological data, estimated E_t for specified crops, and the last irrigation date.

These two methods are based upon study and experimentation. They are explained and evaluated in this report to illustrate the feasibility of the two concepts.

INTRODUCTION

The Salt River Project's Agriculture Section was formed in the summer of 1965. It was created in response to the need for a technical unit which could work with individual farmers to advise them as to the optimum use of irrigation water for any particular crop growing in any particular soil type. In other words, these men are charged with advising when to irrigate and how much water to apply during each irrigation.

The need for this service is derived from the fact that the Salt River Valley in central Arizona is located in an arid zone which receives only an average of 7.7 inches of rainfall each year. During many years there is even less rainfall and, yet, the Valley, by means of a reservoir storage system, supplemented by groundwater pumping, supports over 238,000 Project-member acres. In 1971 alone, more than 730,000 acre feet of water was applied to Project lands. The long-term average annual reservoir storage is only 978,800 acre feet. On two different occasions, storage has almost been depleted. In any particular year, water use may exceed actual runoff. This comparison between annual application and historic storage shows the need for efficient water use.

From its beginning in 1965 with two employees serving 14,000 acres, the Agriculture Section has grown to eight full-time specialists working with 116 cooperators farming 65,000 acres. The varieties of crops include alfalfa, citrus, corn, cotton, pasture grasses, small grains, sugar beets and vegetables.

The service rendered has also grown. In addition to regular field visits and inspection, an experimental computer program has been added with hopes of eventually providing irrigation information to more cooperators on more acres, faster and more efficiently.

When requested, plant tissue and/or soil samples are taken for analysis to provide nutrient information. The soils information is used to help determine the best initial fertility program. The plant tissue results are utilized to indicate any needed changes in fertilization as the crop grows to maturity.

Other services rendered include irrigation system efficiency evaluations and soil profile checks for root development and moisture penetration.

The Agriculture Section's services are available without charge to any Project-farming enterprise which requests them. To date, the program has been received enthusiastically.

Field Approach to Irrigation Scheduling

The method used by specialists in the field is to check the soil moisture within the effective root zone of a crop, using an Oakfield-type soil probe. Samples are taken at one-foot increments and checked by feel to determine the moisture content. This can be estimated quite accurately with experience. After checking, the specialist estimates the soil's moisture depletion and predicts the time interval (number of days) before the next irrigation is necessary.

The knowledge of available moisture in different soil types, the nature of the growing condition of plants and roots, and the knowledge of actual root distribution of plants at any particular irrigation time is the primary skill all field specialists must have. The technical experience and capabilities gained by thorough study of the Salt River Project area has made the program work more efficiently.

Weekly or biweekly inspection visits are well received. The farmer usually accompanies the specialist during these field checks. This offers him an opportunity to see how the soil moisture determination is made and promotes confidence in the specialist's prediction. These joint field visits also encourage the exchange of ideas and discussion of other field problems. Through the specialist, the farmer learns what is being done by neighbors and other valley farms in the way of fertilization, cultural, irrigation and other operational activities.

This team-approach provides the opportunity for better management decisions. However, the final decision must be the farmer's since the risk is his.

Computer Approach to Irrigation Scheduling

Significant advances have been made in the science of irrigation-timing in recent years; yet, for many reasons, it remains an art practiced successfully only through years of experience.[1]

Deviation from accepted methods of irrigation, such as by calendar or fixed rotation, to another method developed by scientists, may not immediately be acceptable to many farmers. Getting used to such a development takes time and a close working relationship between the technician and the farmer.

The basic components of computerized irrigation management service were evaluated in 1966 and 1967 in southern Idaho. The computer program approach has been further evaluated in 1968-1969 on about 50 fields in Idaho and on similar numbers of fields in Arizona by the Salt River Project. (Franzoy and Tankersley—1970). Formulas for short-term predictions of evapotranspirations based on climatological data were developed by Jensen-Haise[2] and Penman.[3] These were programmed and computerized for experimental use by the Salt River Project. Adjustments, new ideas, and revision of the program were involved during the course of trial runs without any change in the concept of the basic ideas developed by Jensen. During 1970, a number of service groups and companies gained experience in the use of the general concept of irrigation scheduling.[4]

The Jensen program was rewritten by Tankersley* and, during 1968, 1969, 1970 and 1971, was tested on 2,162 acres located on 19 farms in the Salt River Valley. The primary goal of this program was to evaluate the applicability of the Jensen theory by using short-term estimates of potential evapotranspiration (E_{tp}), and local climatological data to predict the actual consumptive use or evapotranspiration (E_t) of a crop,

*E. L. Tankersley, Engineer, Association Engineering, Salt River Project.

with the use of an individual crop coefficient, K_c. In addition to the Jensen-Haise estimates of potential evapotranspiration, a set of modified Penman equations for predicting the potential evapotranspiration (E_{tp}) of individual crops has been used to determine which set of equations best fits local conditions.

For study purposes, the Project area was divided into 5 different regions. (Figure 1). When the program was initiated, 19 representative fields were selected and assigned a code number.

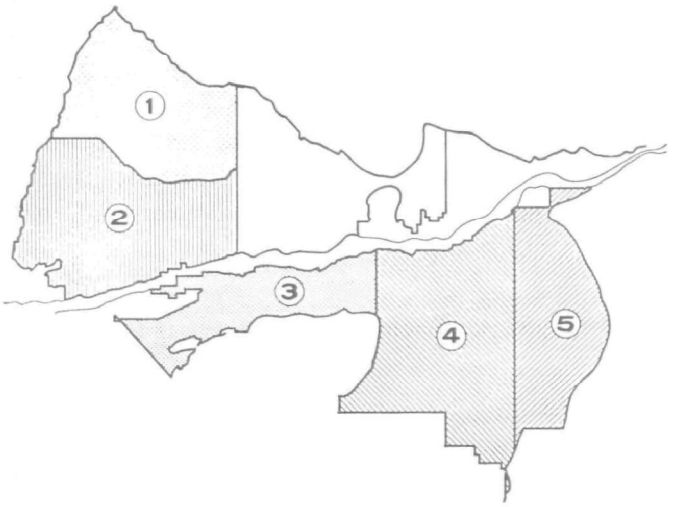


Figure 1: Geographic Regions Included in The Irrigation Timing Study

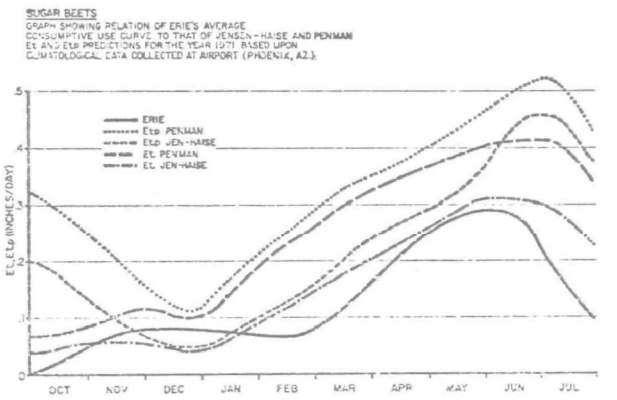
Representative crops such as cotton, sugar beets, barley, wheat, citrus, and maize, were selected as initial crops in the study. The variety of crops will be increased as the program is perfected for operational use and realistic estimates of E_t are obtained.

Studies of consumptive use, both daily and yearly, have been conducted by Erie in Arizona.[5] Erie's data, derived from repeated gravimetric determinations of soil moisture depletion, was used as a basis for checking the computer prediction of potential evapotranspiration (E_{tp}) and actual evapotranspiration (E_t) for the various crops. The predictions have also been checked by field estimates throughout the study period.

Based on the Jensen-Haise and Penman formulas, the computer predicts an E_{tp} which represents the upper limit or maximum evapotranspiration that can occur under given climatic conditions for a particular crop. Then, using the crop coefficient curves originated by Jensen, an E_t for a particular crop can be estimated. Because Jensen's curves were developed from data collected in several areas, some adjustments were made to make the curves fit local valley conditions. Presently, E_t predictions on all crops are satisfactory.

Data received on cotton and sugar beets, comparing the Jensen-Haise method, modified Penman method and the actual average gravimetric analysis of Erie are illustrated in Figures 2, 3, 4 and 5. As shown in these comparative grphas, E_t calculated by using the Jensen-Haise and Penman methods, varies with climatological changes. This is acceptable in view of the actual changes that occur in consumptive use. Also the Jensen-Haise method of prediction shows closer agreement to Erie's 8-year average results on cotton than the Penman equation. Penman's data showed slightly higher E_t's most of the time; therefore, preference was given to the use of the Jensen-Haise method in the Salt River Project.

In the process of implementing the computer program, two types of data were used; meteorological data and field data.



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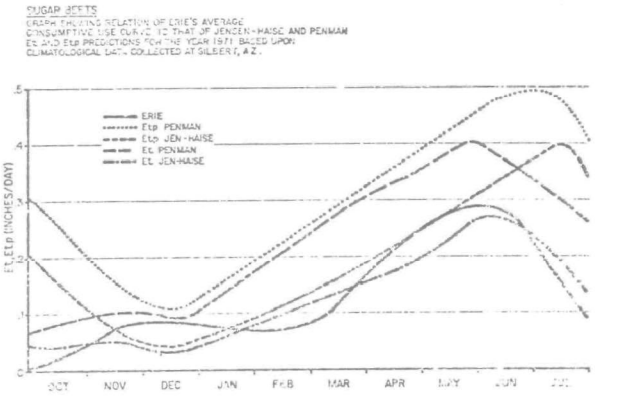

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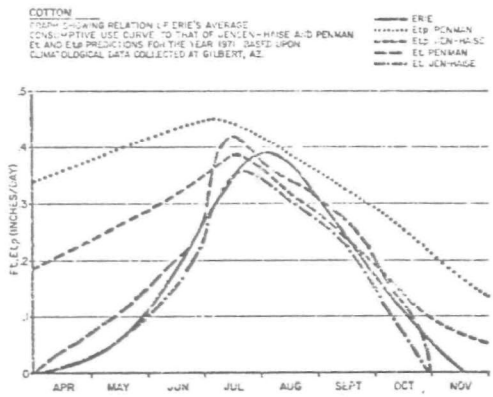

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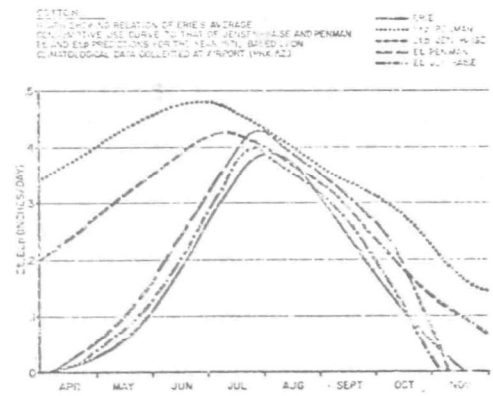

Figure 5.

1. Meteorological data consists of the following:
   A. Daily average temperature.
   B. Solar radiation.
   C. Dew point temperature.
   D. Wind speed for each day.
   E. Saturated vapor pressure.
   F. Vapor pressure at dew point.)

(D, E & F are computed from air and dew point temperatures.)

Data was collected by the National Weather Service which is located at Sky Harbor International Airport, Phoenix. Some additional temperature and precipitation data was supplied by a number of farmers who telephoned reports to the Project every morning. These farmers were provided with thermometers and rain gauges by the Project to ensure more accurate local climatological data.

2. Field data was collected by the field specialists for each of the 19 program fields.
   A. Date of the last irrigation.
   B. Optimum depletion of water from the current root zone.
   C. Planting date.
   D. Harvesting date.
   E. Rainfall.
   F. Estimated irrigation efficiency.

To correlate the estimation of potential evapotranspiration (based on meteorological and field data) to actual consumptive use of a certain crop, Jensen's set of crop coefficient curves were used.

Using this input data, the computer prints out a report containing: 1) E_{tp} by region; 2) E_t for each crop each day; 3) estimated number of days before next irrigation; 4) amount of water to apply at that particular time; and 5) estimation of the next seven day's E_t. Figure 6 explains the field numbering code used and sample printouts are shown in Figures 7, 8, 9, and 10. This report utilizes the best moisture-depletion estimate for the print-out period based upon the type of soil and extent of root development.

Evaluation of the Two Methods (Field and Computerized)

Scheduling irrigations with a computer is an excellent supplement to, but not a replacement for, regular field visits. Frequent monitoring of moisture disappearance and replenishment through field observations by experienced personnel is an essential process for detecting variations in actual evapotranspiration and in maintaining accurate predictions.[1]

When the program can be relied upon to predict E_t accurately, the computer printout can be an aid to the field specialist or technician. Before going out to the field, he can refer to the printout to see how the moisture level for a particular field and crop should have been depleted and how much loss in E_t occurs per day. Fluctuations in E_t can occur daily with variation in the climatological conditions. This review will help the specialist decide more accurately how many days remain until optimum soil depletion occurs. Another added advantage of computer use is that it will enable the specialist to work more efficiently with a greater number of fields. This can be accomplished since trips to the field can be scheduled as the computer-printed forecast data indicates that soil moisture is nearing depletion in the root zone.

Regarding operational purposes, a general picture of the irrigation requirement of the

The following is the code identifying the fields and crops used in the consumptive use and irrigation scheduling study:

A B C D E F G

A - The first digit represents a number assigned the specialist.

B C D - The second through fourth digits are selected at random and represent the field number.

E - The fifth digit represents the region in which the field is located.

1 Peoria
2 Tolleson
3 Laveen
4 Chandler
5 Gilbert

F G - The sixth and seventh digits represent the crop grown on the field. Each series of tens will represent a given group of crops. For example, all cotton will be represented by Tens, all grains by the twenties, etc.

GENERAL CROP CODE

10	Cotton	50	Citrus
20	Small Grain & Forage	60	Sugar Beets
30	Hay Crops	70	Vegetables
40	Oil Crops	80	Green Manure Crops

SPECIFIC CROP CODE

10	Delta Pine Cotton	50	Grapefruit
11	Acala Cotton	51	Lemons
12	Pima Cotton	52	Oranges
20	Wheat	53	Tangerines
21	Barley	60	Sugar Beets
22	Grain Sorghum	70	Potatoes
23	Corn	71	Lettuce
24	Oats	72	Carrots
30	Alfalfa	73	Onions
40	Safflower	74	Sweet Corn

Figure 6: Field Number Code

whole area can be predetermined on a unit-time basis (weekly, for example). This can be a real aid in sequencing water deliveries within the irrigation delivery system.

Discussion

The past four years of study indicate that local experience in characterizing the different crops under variable growing conditions is very essential. Differences in climatic factors, soil capabilities, growth characteristics of crops, farming habits of growers, agricultural operations, fertilization and determination of timely irrigation require the experience and skills of trained men making regular field checks to correlate field conditions and use them in a computerized prediction approach.

During the course of the study, it was discovered that the growth period to maturity varies considerably in response to changing climatological conditions. Also the methods for estimating the correct adjustment for crop coefficient curves to meet local conditions and crops needs careful study. Wrong adjustments for days to effective cover on crop coefficient curves will produce erroneous E_t values; either low or high.

For all of the crops grown in the Salt River Project area, the Jensen-Haise predictive equa-

REGION = TOLLESON

FIELD NO.	*CROP*	*LAST IRRIG*	*RAIN SINCE LAST IRRIG (IN.)*	*ESTIMATED CONSUMPTIVE USE NEXT 7 DAYS (IN.)*	*ESTIMATED DEPLETION SINCE LAST IRRIG (IN.)*	*OPTIMUM DEPLETION (IN.)*	*APPROX. DAYS BEFORE IRRIG*	*APPROX AMT TO APPLY (IN.)*
5996260	SUGARBEETS	12/28/71	0.0	0.34	2.20	2.50	6	3.39
6621260	SUGARBEETS	1/26/72	0.0	0.34	0.41	2.50	-	0.64
6112260	SUGARBEETS	12/28/71	0.0	0.34	2.20	2.50	6	3.67

Figure 7: Irrigation Timing Report for 2/3/72

REGION = TOLLESON

FIELD NO.	*CROP*		1/27	1/28	1/29	1/30	1/31	2/ 1	2/ 2	2/ 3	2/ 4	2/ 5	2/ 6	2/ 7	2/ 8	2/ 9
5996260	SUGARBEETS	AKC =	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
		ET =	0.06	0.06	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05
6621260	SUGARBEETS	AKC =	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
		ET =	0.06	0.06	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05
6112260	SUGARBEETS	AKC =	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
		ET =	0.06	0.06	0.06	0.07	0.06	0.04	0.06	0.05	0.05	0.05	0.05	0.05	0.05	0.05

Figure 8: Table of Daily Crop Coefficients and Consumptive use Values for 1/27/72 thru 2/9/72

REGION = TOLLESON

CROP	TOTAL CONSUMPTIVE USE FOR PAST WEEK (IN.)	CONSUMPTIVE USE FOR 2/ 3	2/ 4	2/ 5	2/ 6	2/ 7	2/ 8	2/ 9
SUGARBEETS	0.46	0.06	0.06	0.06	0.06	0.06	0.06	0.06
WHEAT	0.09	0.01	0.01	0.01	0.01	0.01	0.01	0.01

Figure 9: Consumptive use Table for 1/27/72 thru 2/9/72

REGION = TOLLESON

DATE	AVG. TEMP.	SOLAR RAD.	AVG. WIND	SAT. VAPOR, PRESS.	VAPOR PRESS. AT DEW PT.	NET RAD.	HEAT FLUX	EVAPO-TRANS. POTENTIAL (JENSEN-HAISE)	EVAPO-TRANS. POTENTIAL (PENMAN)
1/27/72	49.0	331.	3.8	14.0	5.4	148.7	-11.7	0.07	0.13
1/28/72	47.0	311.	4.7	13.6	4.0	139.8	-16.7	0.06	0.15
1/29/72	47.0	326.	6.3	13.6	4.0	145.8	- 6.7	0.06	0.17
1/30/72	51.0	314.	5.9	15.1	3.1	136.3	16.7	0.07	0.17
1/31/72	45.5	348.	6.8	13.0	1.4	138.8	-14.2	0.06	0.20
2/ 1/72	44.0	264.	7.1	11.9	2.7	130.2	-19.2	0.05	0.17
2/ 2/72	46.0	368.	6.2	13.4	-0.1	119.8	- 4.2	0.07	0.20
2/ 3/72	42.0	320.	6.3	11.5	3.4	154.0	-15.8	0.05	0.16
2/ 4/72	42.0	320.	6.3	11.5	3.4	155.6	-10.0	0.05	0.16
2/ 5/72	42.0	320.	6.3	11.5	3.4	157.2	- 6.7	0.05	0.16
2/ 7/72	42.0	320.	6.3	11.5	3.4	158.7	- 0.0	0.05	0.15
2/ 7/72	42.0	320.	6.3	11.5	3.4	160.1	- 0.0	0.05	0.15
2/ 8/72	42.0	320.	6.3	11.5	3.4	161.6	- 0.0	0.05	0.15
2/ 9/72	42.0	320.	6.3	11.5	3.4	163.0	- 0.0	0.05	0.16

Figure 10: Prediction of E_{tp} based on Weather Calculations for 1/27/72 thru 2/9/72

tions have given better estimates of E_t than the modified Penman method. The latter's predictions were slightly high for all seasons. An added advantage in using the Jensen-Haise method is that less input information is required.

CONCLUSION

As a result of the knowledge gained from study and experience, accuracy in predicting irrigation dates and the personal rapport developed from working together as a team, the Project's Agriculture Specialists have gained the confidence of most of the farmers in the Valley. These farmers have come to rely on the technical advice in irrigation and water management and the suggestions on soil and plant fertility provided by the specialists.

A forecasting program built around Jensen's concept for predicting evapotranspiration has been initiated as the second phase of implementing a practical agricultural water management program in the Salt River Project area.

The combination of field checks and computerized information is intended to maximize the efficient use of water by confining water application to just that amount needed to satisfy consumptive use and leaching requirements. This will offer the farmer the opportunity to produce crops less expensively through better and more efficient management of water.

Another benefit of the agricultural water management program is the potential for improvement in operational services, ie., actual water delivery because the forecasting program can indicate water delivery demands as much as two weeks in advance of actual need. This can be important when scheduling water through a system of canals which serves 132,000 agricultural acres and 106,000 urban acres.

In addition, preliminary studies to correlate soil moisture to soil temperature, using remote sensory techniques, are being conducted by NASA and other agencies. In the future, if remote sensing becomes a practicability in irrigation scheduling, present computer programming may be adapted to use this additional source of data to correlate soil moisture to irrigation scheduling, based upon plant crop requirements.

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Irrigation Scheduling Studies for Water Quality Improvement

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ABSTRACT

Irrigation scheduling has resulted in improved crop yields for the few areas in the West that have been studied to date. Irrigation scheduling studies are underway in Grand Valley as a salinity control measure. By minimizing deep percolation losses resulting from irrigation, the amount of salt pickup by the moisture movement through the soil profile and over Mancos Shale beds will also be reduced, thereby reducing the salt load in the Colorado River.

The hydro-salinity model previously developed for the Grand Valley Salinity Control Demonstration Project will be used for evaluating the effectiveness of irrigation scheduling for salinity control. A proposed study is described for developing more sophisticated models regarding moisture movement through the soil profile and the associated chemical quality changes. The development of such a model would significantly enhance the predictive ability for evaluating proposed salinity control measures.

INTRODUCTION

The most significant improvements in controlling irrigation return flow quality will potentially come from improved on-the-farm water management. Irrigation practices on the farm are the primary source of present return flow quality problems.

In order to maintain an irrigated agriculture, a salt balance must be maintained in the root zone. This requires that salts applied to the land by irrigation water must be leached through the root zone. Thus, the leaching requirement represents the minimum quantity of deep percolation losses which must be allowed to sustain irrigated agriculture. Therefore, if high irrigation application efficiencies were to be achieved, there would still be some deep percolation losses.

Many studies have shown that in most irrigated areas the amount of water applied and the timing of this water application are quite random. For example, oftimes when the farmer finds that his field is dry, he will irrigate, but the irrigation application may be more than is really needed by the crop. Thus a two-fold problem occurs where the plant has already been stressed because of the field being too dry, which means that the yield has already been reduced. The second problem is due to more water being applied than was really necessary. In extreme cases, this might even lead to a problem of reduced aeration of the soil.

One of the more interesting areas of water management control presently being explored is that of optimum irrigation scheduling. The purpose of irrigation scheduling is to advise a farmer when to irrigate and how much water should be used. Primarily, a farmer relies on visual indications of crop response to decide when to irrigate, or he may have to irrigate on a fixed water rotation system. Irrigation scheduling is geared towards taking soil moisture measurements, along with computing potential consumptive use for the crops being grown, to determine when to irrigate and the quantity of water to be applied.

The reason that irrigation scheduling has become successful is because the measurements are being made as a service to farmers. This has saved the farmer the effort of going out and making these same measurements himself at a time when he is concerned with many farm operations. Because of the busy schedule of the farmer, and the difficulty he might have in the initial interpretation of the data, the problem of irrigation scheduling has met with little success in the past. The efforts in Idaho and Arizona look extremely promising and the farmers are claiming a significant benefit from irrigation scheduling. Yields have been increased due to the fact that water was applied when needed rather than after the crops were stressed. Another benefit to the farmer from this program is that he can anticipate the dates when irrigation is to be accomplished. This allows him to schedule irrigation along with the other duties that must be performed on the farm and relieves him of the responsibility of deciding exactly when is the best time to irrigate.

The limited amount of irrigation scheduling which has taken place to date has not been concerned with controlling the quality of irrigation return flows. Thus, there is a real need for such a demonstration project. Also, it should be recognized that irrigation scheduling has many positive economic benefits to farmers. At the same time, this particular control measure overcomes certain institutional constraints regarding improved water use efficiency on the farm.

Irrigation scheduling is a positive economic incentive for improving water management because of increased crop production. This technique for improving irrigation practices has the advantage of partially overcoming the negative aspects of western water laws. Although the irrigation scheduling reported to date does not cite any reduction in total water use, this reduction will take place as more experience is gained by the farmer regarding soil moisture management in the root zone of his croplands. Even so, the farmer may still wish to divert his full water right. Again, if the farmer could receive an economic return by being allowed to transfer the saved water, then the improvements in irrigation water use efficiency could be brought about at a much faster pace.

Planned Studies

For the last three years, the Agricultural Engineering Department of Colorado State University has been conducting studies aimed at reducing the salinity of the Colorado River. The primary objective is to demonstrate that an improvement in mineral quality of the Colorado River can be achieved by controlling the inflow of highly mineralized water from aquifers underlying the irrigated farm lands in Grand Valley. The initial grant, which was recently completed, evaluates the effectiveness of canal and lateral lining in reducing seepage losses, thereby lowering the piezometric head which causes displacement of highly saline groundwater into the Colorado River. At the present time, these studies are being extended to include an evaluation of the effectiveness of two other salinity control measures, namely irrigation scheduling and tile drainage, which will also lower the piezometric head of the groundwater aquifers.

Secondary objectives are to demonstrate that irrigation scheduling can be effective in achieving greater water use efficiency on the farm along with increased crop yields, while tile drainage will be shown to be effective in reclaiming lands now experiencing low agricultural productivity due to high groundwater tables resulting from canal and lateral seepage losses, as well as deep percolation losses, on higher lands. For those lands incorporating tile drainage, irrigation scheduling will also be practiced in order to minimize the drainage problem.

Water entering the near-surface aquifers in Grand Valley displaces highly mineralized

waters from these aquifers into the Colorado River. In any area where the water is in prolonged contact with soil, the concentration of mineral salts tends toward a chemical equilibrium with the soil. In Grand Valley, as in many other areas, high equilibrium salinity concentrations are known to exist in the near surface aquifer. The key to achieving a reduction in salt loading is to lower the groundwater levels, which will result in less displacement of water from the aquifer into the Colorado River. This can be accomplished by reducing seepage losses through canal and lateral lining, which is presently being demonstrated, or by reducing deep percolation losses by improved on-the-farm water management. Present studies advocate irrigation scheduling as a salinity control measure which will achieve improved farm water management. Also, a combination of irrigation scheduling and tile drainage will be demonstrated in the lower-lying high water table agricultural lands.

The primary local benefit will be increased crop yields. Other water quality benefits to the local area will be derived from the lowering of the groundwater table, which will increase the productivity of local agriculture in areas presently having a very high water table, as well as reduce non-beneficial evaporative losses of water through phreatophytic vegetation. Also, the value of lands presently suffering from high groundwater tables will be increased. Additional local benefits will be obtained by elimination of nuisance problems such as sewer infiltration, basement flooding, and localized swamps which lead to public health problems associated with the production of mosquitoes.

The principal study area in Grand Valley, which has been used for demonstrating the effectiveness of canal and lateral lining in reducing the salt load entering the Colorado River, is also being used to demonstrate the effectiveness of irrigation scheduling and tile drainage as salinity control measures. The advantage in continuing to utilize this study area is that the hydrology is already known. In addition, there has been considerable expenditure of funds in both equipment and personnel for instrumenting this particular demonstration area. The wealth of available information provides a strong basis for evaluating the effects of either irrigation scheduling or tile drainage as salinity control measures in comparison with lining the irrigation conveyance and distribution system.

At least two fields will be selected for studying tile drainage. These fields will be located approximately 1 mile north of the Colorado River. In this area, the soils are very tight and high groundwater levels already exist. As a result, many of the lands near the river have suffered economic damage due to low agricultural productivity. Many of these same lands were among the most productive in the valley at the turn of the century. Also, in this region some drainage problems occur as a result of a leak in the cobble aquifer with consequent upward moisture movement. Due to these difficulties, designing a tile drainage system can be very costly.

In order to effectively demonstrate the advantages of tile drainage to a local farmer, it becomes essential that heavy consideration be placed upon costs. Therefore, the plan of attack will be to thoroughly investigate a number of likely fields, say four, which would benefit from tile drainage. A one-year pre-evaluation of these fields will be undertaken to provide detailed information for designing a tile drainage system. These investigations will have the benefit of minimizing the construction cost of installing tile drainage for each field.

Due to high groundwater levels and tight soils in the region for which tile drainage will be demonstrated, the reclamation of these lands will require very careful farm water management. Therefore, the fields which will be selected for installing tile drainage will also become a part of the irrigation scheduling studies.

Four farms have previously been investigated in the principal study area as a part of the irrigation efficiency evaluations. Two of these farms have been studied more intensively than the other two. These four farms will be incorporated into the evaluation of irrigation scheduling as a salinity control measure. These farms, along with the fields being investigated for tile drainage, will serve as the base for collecting detailed information on salinity control benefits. During the second year of study, the irrigation scheduling program will be greatly expanded to include large blocks of land in the principal study area.

All of the irrigation scheduling to date, which has been quite limited, has been concerned primarily with the timing of water delivery. This demonstration project is concerned with minimizing the quantity of water used, as well as timing, along with minimizing deep percolation losses because of the consequent high rates of salt pickup in Grand Valley. As a consequence, the effort required to evaluate irrigation scheduling as a salinity control measure is considerably greater than previous irrigation scheduling efforts.

Water Quality Evaluation

A hydro-salinity model, which is discussed in a later paper, has been developed for the demonstration area in Grand Valley. This model will allow an evaluation of any proposed salinity control measure. However, this model describes the present physical conditions, which results in one severe limitation. The model assumes that a 50% reduction in ground water flows would result in a corresponding 50% reduction in salt pickup. If deep percolation losses were significantly reduced, the reduction in salt loading reaching the Colorado River could be determined if field measurements were collected over a sufficiently long time period.

The hydro-salinity flow system depicted in Figure 1 can be divided into an examination of the water and salt flows even though the salt flow is located within the water transport network. There is, however, one portion of the salinity system, which is the salt pickup from soils and subsurface contacts, that has been determined by independent analysis for incorporation in the model.

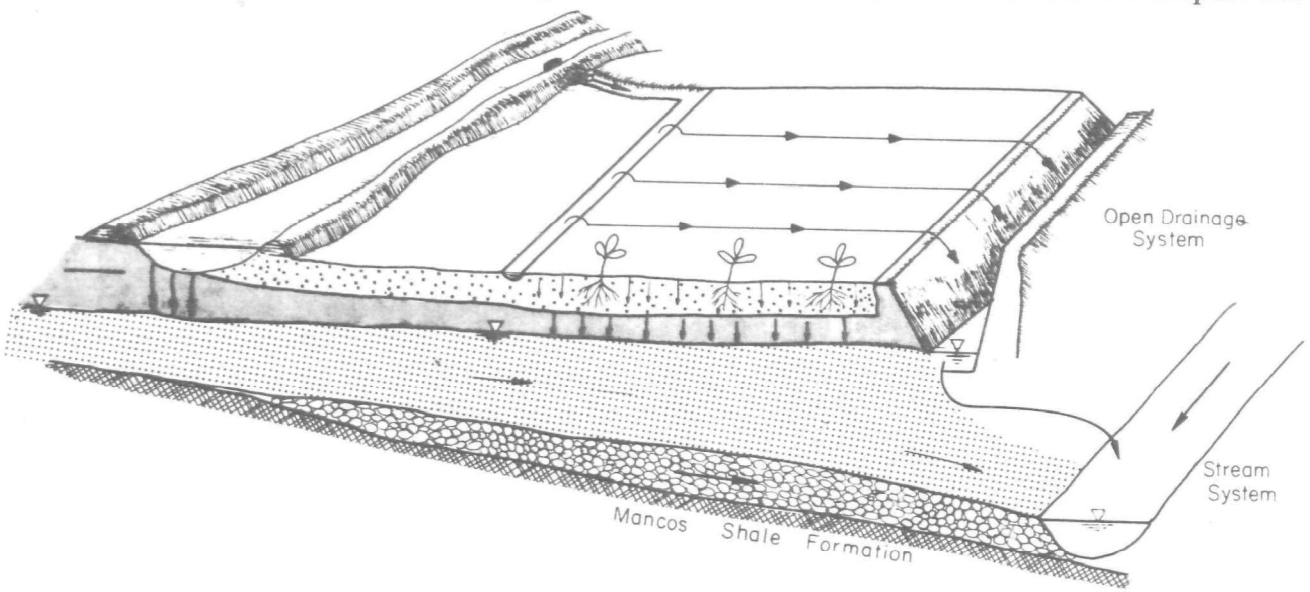

Figure 1: Schematic Representation of Flow System in The Grand Valley Demonstration Area

The computation of the water budgets is the first essential in hydro-salinity modeling because salt flows and water quality in general are dependent on the magnitude and distribution of water in the hydrologic system. In all but the most limited cases, water budgeting requires some adjustment to formulated data to compensate for instrumentation limitations, data accuracy, and interaction among variables. A comparison of mass balance and direct calculation methods is made on ground water flows as a basis for model refinement. It seems justified to conclude that this procedure gives an additional degree of confidence to the results.

The first step in computing the budgets is to evaluate the distribution of the water before it reaches the root zone. Water is initially diverted from the two rivers into the various canals from which a small percentage is lost from seepage, some is spilled into washes or drains to regulate capacity, and the bulk is diverted into the field lateral system. In the lateral network, some of these flows are lost by seepage and the rest is applied to the cropland. In the Grand Valley irrigation systems, a large proportion of the field applications eventually wind up on the drainage system as field tailwater, with the

remaining portions being placed in the root zone, along with precipitation, for crop use.

Once in the root zone, opportunity exists for consumptive use by crops. Under favorable conditions, the water utilized from the root zone will approximate the crops' potential demand. The potential evapotranspiration from cropland surfaces in the Grand Valley has been computed using the modified Blaney-Criddle method. The excess water in the root zone that cannot be stored percolates through the soil profile until reaching the ground water table. Since the water table is not always at the bottom boundary of the root zone, a region of flow between this boundary and the water table should be considered. For purposes of this study, this region (soil profile) has been assumed completely saturated and has been ignored initially. This limitation can only be overcome by considering unsaturated flow and the associated chemical changes resulting from ion exchange, precipitation, etc.

The ground water additions are comprised of canal and lateral seepage and deep percolation from excessive irrigation. Occasionally, the amount of precipitation is sufficient to account for some inflows to the ground water system. A certain proportion of ground water is either intercepted by the drainage system or transpired by phreatophytes. In this model, it has been assumed that phreatophytes use water at their potential rate and use all precipitation that falls on the phreatophyte acreages. Because of the fluctuating nature of the ground water additions, the storage within the ground water basin also varies significantly throughout the year. In budget computations, a negative storage change simply indicates that more flows are leaving the subsurface basin than are entering. The remaining water is forced to flow towards the river by the hydraulic gradients acting on the water from elevation differences in the local topography. These flows are referred to in the model as the total ground water outflows and are then used to evaluate the performance of the entire model.

Although the salinity flow system generally follows the water flows, there are three additional somewhat complicating factors that must be considered. The first of these is the ion exchange process which occurs in the root zone. Since the scope of this project did not allow for such an extensive examination, this factor has been ignored. It should be emphasized that this information is very important to understanding salinity problems in agricultural areas. The The second aspect which must be considered is the quantity of salts actually imparted to the water from the soils themselves. The distribution of this "salt pickup" quantity is not known and was assumed to occur only in the ground water basin. This conclusion is obviously false, but does not interfere with the scope of this modeling effort. Again, the knowledge of where the salt is being added is of the utmost importance to salinity control planning. (For example, if it was known that little salt is actually added in the root zone, then the interception of deep percolation by a system of field tile drainage is a feasible salinity control alternative.) The third and final component of the independent variables affecting salt movements is related to the salt changes that occur as a result of storage changes within the ground water basin. When a large influx of water is added via deep percolation or conveyance seepage, this water has not as yet picked up much salt due to the short time it has been in contact with the soils. As a result, the large storage increases in the spring and early summer result in only small salt flow to the ground water basin. On the other hand, when the large storage decreases occur in the late fall and early winter, a relatively large salt depletion occurs from the system. This particular parameter regarding the salinity flow has been handled in the model.

Proposed Evaluation Improvements

The greatest single technological need at the present time for the subject area of irrigation return flow quality is the development of prediction techniques which will describe the quantity and quality of subsurface return flow. The real critical problem is defining the variability in subsurface return flows for large areas, such as an irrigated valley or a large portion of the valley (e.g., Grand Valley).

In studying large areas, a balance must be reached between the sophistication of the model and the cost of collecting field data. There are still a number of limitations in our ability to make accurate field measurements.

These models must be capable of predicting changes in the quantity and quality of subsurface return flows under a variety of water management alternatives. To fully evaluate chemical quality changes, the models should be capable of handling precipitation and exchange reactions which take place as the moisture moves through the soil profile. These transformations alter the ionic balance of the chemical constituents in solution and are very important in describing the quality of irrigation return flow.

The development of such a model for Grand Valley would answer the question: "If deep percolation and seepage losses are reduced by a particular amount, what is the corresponding reduction in salt loading in the Colorado River?" To begin with, detailed studies must be undertaken to delineate the relationships between moisture movement and chemical quality. Then, the results can be applied to a much larger area, such as the demonstration area in Grand Valley. A proposal for accomplishing the initial detailed studies is described below.

The initial studies would be undertaken in an intensive study area located in the Grand Valley west of Grand Junction, Colorado. An area of approximately 40 acres will be leased for the study. It is contemplated that the area will be near the Government Highline Canal from which the water supply will be obtained. This intensive study area will be divided into about 100 plots each 100 feet square (10,000 sq. ft.) as shown in Figure 2. Both timing and amount of water application will be varied.

The amount and chemical quality of irrigation water will be monitored to determine the system input. Rainfall and temperature data will also be collected. Solar radiation, wind, and humidity data will be obtained from the Grand Junction weather station, which is located only a few miles from the intensive study area.

Drains will be installed across both the upper sides of the plot area. They will be used to intercept any natural discharge water which might otherwise get into the plot area. This natural drainage water will be monitored for chemical quality and quantity.

Each plot will have an individual drain across each of the lower sides of the plot. Details of

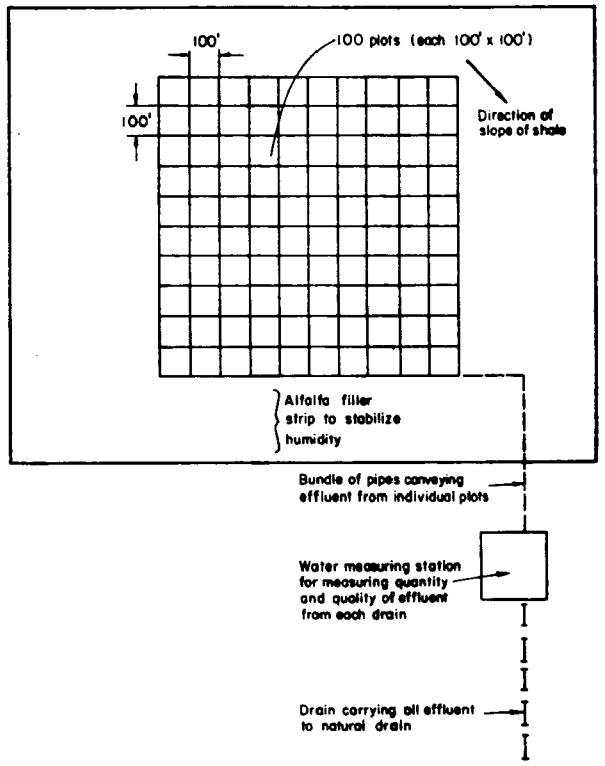

Figure 2: Layout of Intensive Study Area

these drains are shown in Figure 3. The site will be selected so that shale is approximately 10 feet below the surface: A trench will be excavated into the shale. In this trench will be laid a sheet of polyethylene film which will extend vertically a distance of about 5 feet. The purpose of this film is to stop unsaturated flow across the drains. Small plastic drain pipes will be laid in the trench and covered with a gravel filter.

Soil samples will be collected throughout the root zone and below the root zone to shale. The first purpose of the sampling will be to determine the type of ions present at all levels in the soil profile and to determine their concentration. This will provide a reference point for comparing future measurements. Another purpose of this sampling will be to determine soil fertility. From the analysis of the soil samples, the amount and types of fertilizers needed to bring the soil up to optimum balanced fertility levels will be determined.

Four different crops will be used in the tests, namely alfalfa, barley, corn, and pasture. Each will be irrigated with a variety of irrigation treatments. In addition, two levels of nitrogen fertilizer will be applied to the corn. This will demonstrate the effect of irrigation

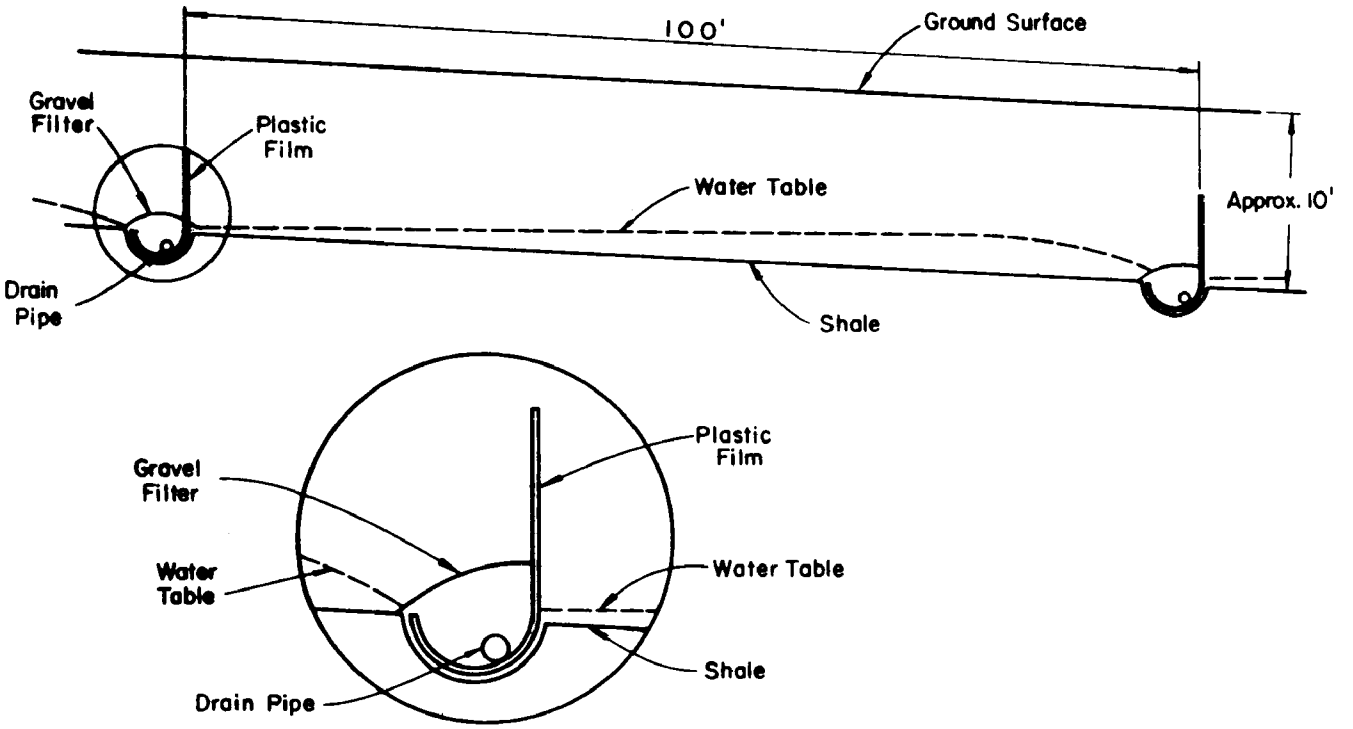

Figure 3: Plot Corss-section with Drain Details

practices on nitrogen efficiency and will also provide useful information on the movement of nitrogen fertilizer into drainage effluent. It is anticipated that for some of the treatments where excessive water is applied, an excessive application of nitrogen will almost eliminate the yield reduction by making up for the amount of nitrogen which is leached out of the soil profile. It is hoped that this demonstration will show that there is also an additional yield reduction because of excessive irrigation water application and that the cost of the added nitrogen fertilizer will provide incentive for more efficent farm irrigation water management.

Soil moisture levels in each plot will be carefully monitored using soil moisture resistance blocks. In addition, neutron probes will be used to check moisture levels throughout the soil profile.

Soil solutions will be extracted from various levels of the profile and analyzed to determine the types of ions present and their concentration. These data, together with the information on the amount and type of water leaving the drains as well as changes noted in soil samples, make it possible to determine where the salt pickup is taking place in the soil profile under the various treatments.

In most field research projects, the moisture and salt movement in the soil profile is monitored, which allows a prediction of the amount of moisture and salts reaching the ground water table. This project will have an advantage in that the outflow will be monitored as well as the inflow and movement through the soil. Thus, the model which will be used to describe the movement of moisture and salts through the soil profile can be verified.

The construction of the drainage system for each plot affords an excellent opportunity to obtain undisturbed soil samples that can be used in the laboratory to determine the relation between saturation and capillary pressure during both imbibition and drainage. The development of these of these relations, along with field measurements of either moisture content or capillary pressure, allow the moisture movement to be described. Relations between saturation and capillary pressure have been developed for numerous soils.

The primary advantage of undertaking this study is the development of a prediction model describing moisture movement and associated chemical quality, thereby allowing more accurate predictions of the effects of proposed salinity control measures. Additional benefits resulting from this study would be a knowledge of fertilizer use efficiency and the development of crop production and crop damage functions for economic evaluations.

The Role of Modeling in Irrigation Return Flow Studies

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ABSTRACT

Modeling can play a critical role in finding alternatives to present water management and cultural practices to improve and control salinity levels in irrigation return flows. The use of systems analysis techniques, sensitivity analysis, and optimization procedures can greatly enhance the usefulness of modeling. A generalized conceptual model is presented to demonstrate the application of systems analysis to irrigation return flow systems. Several applications of systems modeling are suggested with on-the-farm water management cited as having the greatest potential for salinity improvement. The importance of prediction modeling in resource planning and in bringing about institutional changes needed to ensure the success of salinity control measures is established. Systems models for irrigation return flow quality can be integrated into multipurpose river basin models.

INTRODUCTION

Irrigation return flows are the result of a multitude of natural flow phenomena and humanly controlled management practices or malpractices. Water diverted for irrigation seeks the lowest gravity potential possible either on the surface or underground. The irrigator uses this characteristic to his advantage to distribute and manage water for the irrigation of crops. Likewise, he uses the same driving force for removal of drainage water and flushing salts from the soil profile to maintain a satisfactory salt balance in the root zone.

The movement of water and salts in soils is influenced additionally by soil properties such as texture, bulk density, water content, hydraulic conductivity, and exchangeable ions. These parameters may vary considerably from one location to another within an irrigated area further complicating the flow behavior. The loss of water from the surface by evaporation

and from the root zone by transpiration not only interrupts the flow behavior but also concentrates salts in the remaining soil water. The characterization and prediction of the quality of irrigation return flow waters are considerably more difficult than quantity, although the two are closely related. Both are dependent upon a large number of variables which may be interrelated to some degree.

To visualize this complex system and the multitude of interactions which take place within it at some instant in time is taxing even to the analytical mind of the scientist. Not only must he understand the basic laws of physics, but he must be cognizant of the hydraulic and physical-chemical behavior of water and salts moving through the soil. Accurate prediction of the effect of some imposed management practice would indeed seem impossible.

Perhaps the best solution to this dilemma is to consider the overall system to be composed of several discrete subsystems which can be individually identified and examined. Such subsystems can be simulated by physical models or mathematical models to elucidate their behavioral responses to management practices and other input variables. These simulation models allow examination of the processes occurring in the system and their effect on the quality of the drainage waters before capital outlay for construction or implementation of management practices. With this prior knowledge of the expected response of the system, more judicious planning can be made.

The Utah State University Foundation report[3] has recommended that:

> A comprehensive, reliable model should be developed of salt movement through soil profiles in relation to changes in quantity and composition of solutes, soil characteristics and irrigation, and other management practices. Parameters must be identified that will permit rapid evaluation of field situations and predictions of the quality and quantity of return flow water under a variety of conditions.
>
> Systems methodologies for data collection and analysis should be developed for use in assessing the balance between water and salts applied to an area and the quantities leaving as return flow.

The need for such models has been recognized by others and developments have been made in this regard[1]. The availability of high-speed electronic computers has permitted researchers to examine in detail the complex interrelationships of these systems models.

This paper is meant to be an introduction to the models and terminology of prediction modeling as applied to irrigation return flow studies. Other papers in these Proceedings will be addressed to specific problems and problem areas of irrigation return flows.

Simulation Models

The use of simulation models to examine water resource problems has greatly increased the productivity of researchers in this field. Freedom from real time and physical constraints allows the researcher opportunity to examine in depth the behavior of a particular system and the processes acting therein in a minimum of time. Simulation models may be of various forms. Those relating to irrigation have been physical models and mathematical models. Physical models are generally scale models which contain the pertinent characteristics of the object being simulated. Examples of physical models are packed soil columns and sand tanks which may be used to investigate ion exchange processes and drainage phenomena respectively. Surface conveyance structures are studied as models also. For instance, the conveyance and control structures of the California State Water Project were evaluated with scale models. Operational and design faults were identified and corrected before construction began, thus avoiding costly reconstruction.

Electric analog techniques can be used to simulate certain physical processes. The close analogy between flow of water in soils and flow of electricity in circuits provides an excellent means of simulating a process occurring in nature. The electric analog models use resistance and capacitor networks to simulate drainage patterns and flow behavior. Their chief advantage is their dynamic nature in that a measurement can be made at any point of the system at any time and the measured value will be up to date. The major disadvantage is that to solve a large problem a large resistance-capacitor network must be used. The size of problem and size of networks are directly related 1:1.

Mathematical models are representations of physical and/or chemical processes in the form of mathematical equations. The behavior of these processes is known to follow the basic laws of physics and chemistry which can be expressed mathematically. Since these processes may be dependent on time, space, temperature and/or concentration gradients the mathematical equations are likely to be complex and difficult to solve. The usual procedure is to make certain simplifying assumptions which will allow easier solution of the equations. Use of these assumptions requires some judgment since some error may be introduced by the simplification procedure. The end product is a mathematical expression which can similate the process in question with limits of error which can be tolerated.

Mathematical models may be separated into two broad categories based on the nature of the process being modeled. A "stochastic process" is generally defined as the dynamic part of probability theory in which a collection of random variables is studied from the point of view of their interdependence and limiting behavior. A stochastic process is one which develops in time in a manner controlled by probabilistic laws. Some examples of stochastic processes are Brownian motion, radioactive decay, growth of a bacterial colony, and a summer rain shower. Studies of reservior management, rainfall-runoff relationships, and stream flood stage predictions rely on stochastic methods of analysis. Models of the above processes are referred to as stochastic models.

The second category is that of deterministic models. These models do not contain probability mechanisms and are developed using known physical laws and principles to derive the governing equations. Deterministic models are theoretically valid only if they include all the variables significantly affecting the output. Since deterministic models simulate the individual processes taking place within the system, this approach leads to a clear definition of each process and its contribution to the system as a whole. In deterministic theory, the correct prediction will simply state the value of the observable result that will be obtained. The accuracy of the prediction depends on how well the model represents the components of the physical system. Modeling of the components in irrigation systems has generally been deterministic in nature. Conveyance, infiltration, consumptive use, ion exchange, and drainage are some of the components which have been modeled in this manner.

Recently, the concept of systems analysis has been applied to water resource planning with great success. The basic tenet of systems analysis is that the system being modeled can be broken down into subsystems which can be more easily handled and that the subsystems can be related to one another in a systematic manner. A subsystem in turn can be further broken down to consider the individual processes taking place within. Each individual process can be modeled mathematically and related to other processes taking place simultaneously.

Consider for example the general process model presented conceptually in Figure 1. The model would have associated with it "i" input variables, "j" internal variables, "n" model parameters, and "k" output variables. Each individual process occurring within the system has these characteristics. More specifically, if one considers the process of ion exchange in a soil profile the input variables might include concentration and ion composition of the inflowing waters; internal variables might include ion exchange rates and pH relationships; model parameters might include cation exchange capacity and porosity; and the output variables might include concentration and ion composition of the effluent waters. The process model then simulates ion exchange based on the variables and parameters known to affect the process.

Other several process models are closely related and dependent upon one another and can be collected into a group called a submodel. Figure 2 shows such a submodel for the soil system which presents conceptually the process models included as well as their interdependence. The output of one process model is the input to another process model. The submodel has the characteristics of input, internal, and output variables and model parameters just as the process models, however they are somewhat more complex since they include the information necessary for all the process models

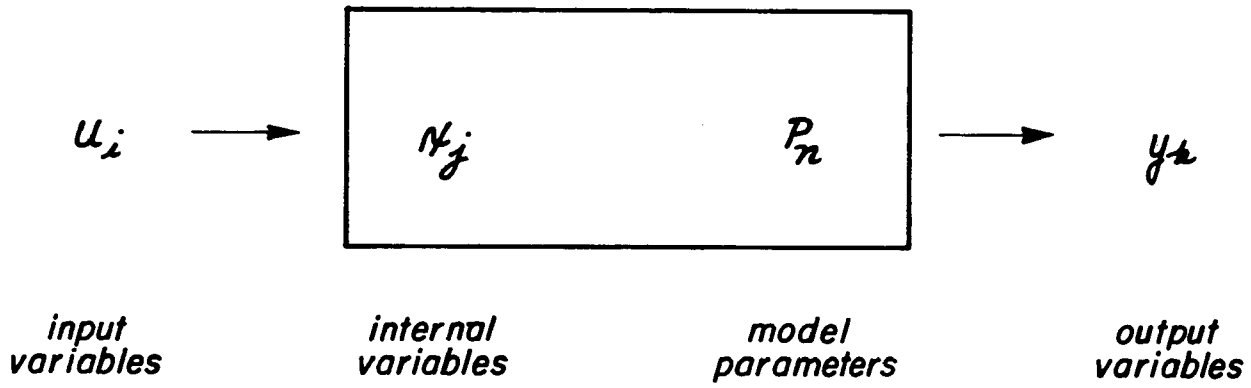

Figure 1: Conceptual Diagram of a Process Model

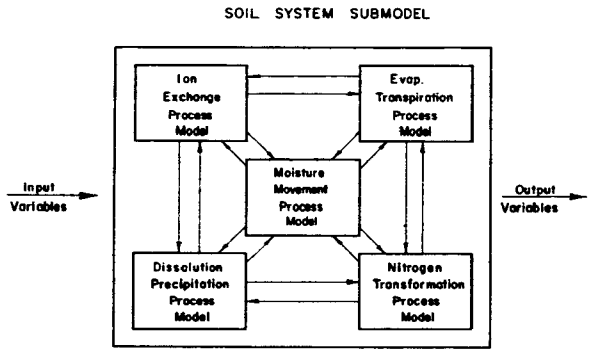

Figure 2: Conceptual Diagram of a Soil Subsystem Submodel Comprised of Process Models

contained in the submodel. The soil system submodel should contain all the process models needed to define the soil system and to simulate the processes that are of interest.

Similarly, several submodels which are closely related can be collected to form a systems models. Figure 3 shows such a collection for an irrigation systems model. The submodels are interdependent in that they share input—output variables. The irrigation systems model contains all the characteristics of the submodels as well as the individual process models, since each of the submodels was developed from process models. The response of the irrigation systems model to some input variable is the net integrated response of all the process models contained by the systems model to that input information.

The real power of systems analysis in the simulation procedure is the capability to model a complex situation by systematically considering the individual processes which are active within the system in such a manner that the response of the system reflects the effect of the individual processes. In addition, since each process model or system submodel is complete within itself, they can be used to simulate that process or subsystem independently of the remainder of the system.

The irrigation systems model presented here could be considered complete within itself or as a part of a much larger systems model for a river basin or water resource management system. The management of water resources requires consideration of many variables which can be handled more easily and accurately by a systems analysis approach.

Use of a concept termed sensitivity analysis allows the processes occurring within a system significantly enhance the quality of the drainage

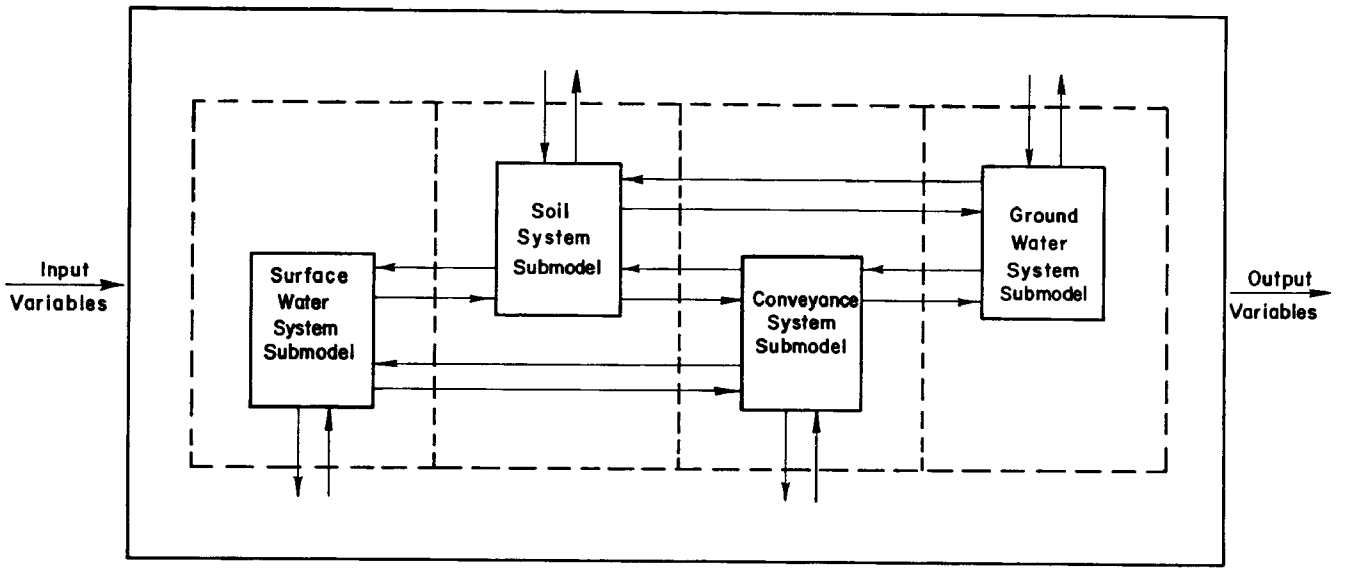

Figure 3: Conceptual Diagram of an Irrigation Systems Model Comprised of Submodels

to be evaluated as to their relative impact on the total behavior of the system. Thus, the sensitivity of the system to a change in some part of it can be analyzed. This concept can be used also to evaluate the effect of some input variable on the response of some process occurring within the system or on the total response of the system. Sensitivity analysis is a tool available to determine the sensitive portions of the system and thereby call the attention of the researcher to the areas needing closer evaluation.

Optimization techniques have been developed which can be used to determine the "best" or "optimal" solution to a simulation model based on certain imposed constraints. In simple terms, if several possible changes in a system can cause nearly the same result, optimization procedures can choose the most advantageous change. Optimization procedures are usually used in reference to some goal or constraint such as reduced salinity level or maximum economic benefit. In the more general river basin models, the constraints may be power generation, flood control, recreational use, irrigation supply, or quality control. In areas where conjunctive use of water takes place, these procedures can be used for efficient management of water resources.

Application To Irrigation Return Flow Studies

The irrigation return flow system can be subdivided into three major subsystems: (a) water distribution, (b) farm water management, and (c) drainage and water removal. The water distribution subsystem consists of the conveyance structures from the point of diversion to the turnouts on individual farms. The farm water management subsystem begins at this point and terminates at the point where surface return water leaves the field and where percolation water leaves the plant root zone. The drainage and water removal subsystem completes the system by conveying drainage waters and surface return waters to the receiving streams.

Water Distribution Subsystem

The planning of adequate reservoir storage for an irrigation project requires an estimate of the irrigation demand that will be placed on the reservoir, as well as other functions for which it will serve, i.e., flood control, power generation, etc. The design, construction, and performance of irrigation conveyance structures can be evaluated with simulation methods in order to produce the maximum benefit for the resource investment required for installation. In situations where canal lining can be shown to

water, as well as conserve water, these benefits should be taken into account when considering the economic benefits and costs of a project during planning stages.

Since changes in quality may be subtle in intensively farmed areas where a wide variety of management practices are in use, prediction models should be sufficiently sophisticated to be capable of evaluating the different processes occurring within the system in order to establish cause and effect relationships.

With such detail in the models, the processes which contribute significantly to water quality degradation can be identified and management schemes can be generated to alleviate or control the degradation. Prediction models are needed which will provide for rapid and accurate examination of novel management schemes to reduce salinity in irrigation return flows. The greatest single advantage of prediction modeling is the capability of examining alternatives to our present management practices without actually implementing them in the field. This permits rapid screening of potential control measures as to their expected response in the system.

Farm Water Management

On-the-farm water management has been cited as perhaps the area of greatest potential for improving salinity levels in return flow waters.[2] Since changes in current management practices may not be reflected as immediate changes in the quality of the return water, expected long term improvements and benefits must be assessed by prediction techniques. Knowledge of the manner in which water behaves in soils has permitted development of prediction techniques for water movement in soil. These techniques can then be used to estimate the amount and timing of irrigation applications resulting in increased water-use efficiencies. Such increases in efficiency can lead to better management of salinity in return flows since excessive leaching can be avoided.

Models which include optimization procedures can predict the best management schemes for reducing salinity levels and improving yields as well as simulating water and salinity flow in the system. Optimization procedures allow the system to be simulated with constraints on salinity levels while maximizing crop yields. Potential management schemes can thus be generated and evaluated by this techniques.

The usefulness of recently developed methods of application of irrigation water in reducing or controlling salinity in drainage water should be evaluated before they are recommended for widespread use. The high cost of installation of subsurface and trickle irrigation systems may make their use restrictive unless comparable benefits can be shown to accrue as a result of their installation. Simulation modeling can be used to evaluate their usefulness both in reducing salinity in the drainage waters and in improving yields as a result of better water management and increased efficiencies.

Likewise, the effects of irrigation scheduling on both yield increases and drainage water quality can be assessed. Scheduling can be used to maximize yields and at the same time used to avoid overirrigation with the resultant excessive leaching of the soil profile. This is of particular interest in areas where the soils are high in residual salts or where there are underlying saline deposits.

In regions where the soils are not high in residual salts or underlain by saline deposits, the primary causes of salinity changes are due to consumptive use and salt precipitation and dissolution reactions. To anticipate the degree of change, models have been developed to simulate consumptive use, precipitation-dissolution reactions, ion exchange reactions, nitrogen transformations, and water movement. These models are used to predict the quality of drainage water eluting from the soil profile as well as the distribution of salts within the soil profile. Individual ions and/or total dissolved solids can be considered.

In areas where the quality of applied irrigation water is marginal with respect to specific ions, models which simulate the quality changes resulting from ion exchange reactions and precipitation-dissolution reactions in the soil can be of considerable aid in managing such waters. With simulation models of the physical-chemical behavior of water and salts in soil, the probable effects of irrigation with the marginal waters can be determined before their use. This is especially helpful in managing high sodium and/or high bicarbonate waters where precipi-

tation of $CaCO_3$ may give rise to increased sodium "hazard."

Drainage and Water Removal

Drainage studies have long been conducted using simulation techniques, however, only recently have quality aspects been considered from the standpoint of minimizing salinity in the return flow water. Sand tanks, electric analog systems, and mathematical simulation have been used to examine the theory of drainage. Based on the technology developed here, prediction models can be used to evaluate the salinity level of drainage water which results from consumptive use, ion exchange, salt pickup, and mixing phenomena which occur as a result of irrigation practices. In areas where poor drainage has resulted in high salt levels in the soil profile, planning for subsurface drains can be enhanced by use of prediction techniques which not only handle the hydraulics but also the quality aspects of the proposed drainage system.

Some areas contain naturally saline mineral formations underlying the soil profile which contribute readily to salt pickup in drainage water. Simulation models with optimization techniques can be used in planning interceptor drains which would prevent applied irrigation water from flushing salines out of the marine deposits. Depth, spacing and size of the drains can be evaluated as to their effectiveness in the control of salinity problems using simulation modeling before construction begins. This assures greater success of the proposed reclamation project.

The length of time required for a unit volume of water and salt to move through the soil profile and saturated aquifer to a drain is referred to as "travel time." In assessing the effects of irrigation management practices on the quality of the stream receiving return flows, an estimate of the travel time is needed and can be obtained by prediction modeling. Thus, one can predict how soon after changing a management practice that changes will occur in the quality of the drainage waters.

Application To River Basin Management

Irrigation return flows are often a major portion of the stream flow in some western streams, thus their management may greatly affect the river basin system in which they are located. In river basins such as the Colorado where salinity levels are of prime importance in the development of new areas and maintenance of present project areas, simulation is a useful tool in managing the total water resource system. The benefits of salinity control measures implemented in a given area may accrue to some downstream users. If an equitable sharing of the expense of upstream improvements in control measures is to be found, then some mechanism for identifying the benefits accruing to both areas must be developed. Simulation models can be used to assess these quality improvements and arrive at an adequate estimate of benefits accrued to each area.

In management of a river basin, irrigation may be only one of several resource uses which are considered in water resource planning. The relative importance of quality degradation caused by irrigation return flows may dictate a shift in water resource uses to comply with salinity standards. To date, most planning of this nature has relied upon seat-of-the-pants estimates of the salinity contribution that can be attributed to agriculture. Simulation can be used to ascertain that which is caused by agriculture and that which is caused by natural processes and other sources.

In some states water laws and water duties are structured such that they may be the chief deterrent to establishing salinity control measures in that area. If institutional changes must be brought about to ensure success of salinity control measures, simulation models can be very helpful in generating possible alternatives to present practices. Subjecting these potential alternatives to economic analysis by optimization procedures can result in better insight of the probable success of the proposed changes. Changes in water laws are not likely to take place unless the quality benefits of doing so are considerable. Prediction models used for this purpose must necessarily be comprehensive and reliable in projecting the benefits of suggested changes.

SUMMARY

An introduction to the terminology and application of systems analysis and prediction modeling as used in irrigation return flow studies has been presented to acquaint the reader

with the tools used by researchers to solve complex water resource problems.

Systems analysis has greatly increased the usefulness of prediction modeling in water resource studies. Application of these methods to irrigation return flow problems offers a more rapid and economical evaluation of proposed salinity control measures than is possible by field studies. Field studies and demonstrations should not be abandoned in lieu of prediction modeling, but rather they should be used to verify potential control measures generated by the prediction models. The irrigator will probably not be using prediction modeling himself, however, the information developed by such models can be useful in solving salinity control problems resulting from management and cultural practices. Prediction modeling is a tool to be used in evaluating alternatives to present practices in an efficient and economical manner.

Prediction modeling can be used not only to evaluate salinity control measures for water delivery, farm water management, and drainage and water removal subsystems, but also to assess the economic benefits accrued by both local and downstream users as a result of these measures.

For management of river systems involving conjunctive use of water resources, prediction modeling can play an important role in planning the system to maximize benefits. In situations where institutional changes are needed to assure success of salinity control measures, prediction modeling can provide insight into the longterm benefits that can be expected.

The greatest single advantage of prediction modeling is the capability of evaluating alternatives to present cultural and management practices before they are instituted in the field.

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Modeling Subsurface Return Flows

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The current concern of the public over the environment has lead to enactment of legislation and the setting of research goals for the maintenance or improvement of water quality. Not only are scientists and engineers asked to develop practices to improve water quality, but also to assess the impact on the environment for water projects being planned for the future. In the past, judgement based on experience and measured parameters have been used by competent scientists and engineers to estimate the effects of water projects on ecology. However, these judgements are subject to error and can possibly be based on a more quantitative basis.

Among the more complex problems is the prediction of the effects of irrigated agriculture on water quality. Methods are needed to predict: 1) the short and long term salt concentrations, including nitrogen salts, in drainage effluent from agricultural areas, 2) the chemical composition of water moving down into groundwater aquifers from irrigation projects, and 3) the impact on water quality in an area under study for irrigation. A provising approach is the development of conceptual models of the dynamic soil-water system. Such models can be used for predicting management practices which minimize pollution under economic constraints.

It is not the purpose of the paper to present a detailed account of any particular model, but rather to report on the "state of the technology." Detailed discussions have been reported elsewhere[1, 5, 15].

Simulation Models for Predicting Solute Changes for One-Dimensional Flow Through Soils

Over the past decade, the author and colleagues have addressed themselves to the development of models for predicting the quality of percolating water. The foundation of these models was the development of computerized numerical solutions predicting from initial nonequilibrium conditions, the equilibrium solute composition for soil-water systems at different moisture contents[2]. The numerical solutions involved more than one chemical reaction (ion exchange Ca^{++} and Mg^{++}, and solubility of a salt, $CaSO_4 \cdot 2H_2O$) and were based on thermodynamics, ion exchange equations, and Debye-Huckel theory. This early work was verified at moisture contents much higher than those encountered under irrigated agriculture, but was later shown applicable to soil systems in the field moisture range[4].

Using the above procedures and a finite difference method, a model was developed to predict the changes in solute composition in an effluent from a saturated soil during one-dimensional flow. Since the chemical reactions consid-

ered were limited, the above model was not applicable to real field situations but the model did demonstrate that such models were feasible.

In essence the procedure was simple. Water was considered to move along a path normal to finite soil segments and the chemical changes were calculated for each aliquot of water as it passed through successive soil segments. Due to the complexity of the soil system these calculations could only be reasonably performed by a digital computer. Modification and extension of the basic procedure and extension to systems of interest in the biosphere have been performed. To date these improvements can be classed in two groups, one dealing with moisture movement and ones dealing with chemical changes.

Water Movement

At the offset the simplest method which was of interest and applicable to certain soil systems was considered, i.e., piston displacement of water. This procedure has been shown to be of value when considering the movement of constituents in water which interact with the soil material during saturated flow[3,6]. Obviously, there are soil systems of interest in which moisture changes occur and in which the solutes only slightly interact with the soil material. When the primary concern is in solutes which are relatively inactive with soil material and when moisture contents are fluctuating, the dispersive effect of soil material becomes a first order interaction. To account for these dispersion effects, Tanji, et al[14], and Terkeltoub[16] have considered machine mixing, i.e., a portion of the soil water to be held by the soil matrix and mixed with successive increments of water entering the matrix.

The most commonly encountered situation under irrigation agriculture is a zone of unsaturated zone below the water table. Within the unsaturated zone moisture movement and content is a function of soil properties and water added or removed. A model of the unsaturated zone above a water table or a region of constant moisture has been prepared[5]. This model basically utilizes the finite difference scheme developed by Hanks and Bowers[9]. In addition, a moisture sink term to allow for moisture loss by evapotranspiration has been included. As with the models of Tanji[14] and Terkeltoub[16] machine mixing is utilized.

Chemical Changes

The chemical constituents and reactions considered to date have been governed by two factors: 1) effect of the constituent or reaction on other solute species present and 2) the importance of the constituent on problems of interest. To date, only neutral to alkali soils have been considered. This limitation of soil alkalinity is related to 2) above. Early models[3,15] considered exchangeable Na^+, Ca^{+2}, and Mg^{+2}; soluble salts of the exchangeable cations; ion pairs of $CaSO_4$ and gypsum.

Additional SO_4^{-2} ion pairs of Mg^{+2} and Na^+ have been considered[11], as well as $CaCO_3$[5,8,10] and boron[12]. To facilitate the application to field problems, methods have been developed to calculate the exchangeable cations mentioned above[5]. This last method substantially reduces the laboratory analysis required to perform calculations. In addition, methods have been prepared for predicting the electrical conductance in the system[10]. All of the above interactions have been accounted for by taking advantage of the fact that the chemical reaction rates are greater than the rate of water movement. Thus equilibrium relations can be used to integrate the dynamic case.

With some constituents of interest, the rates of reaction are slow in comparison with water movement. Such is the case with microbiological transformations of nitrogen. In such cases the reaction rate, which may be a function of several soil-water factors, e.g., moisture content and concentration of constituents, must be determined. Thus the distribution of constituents including the moisture must be found as a function of time. By incorporating unsaturated flow equations, and the aforementioned soil reactions which may be considered as successive equilibria, a procedure was developed to calculate time dependent rate equations. In turn, it becomes possible to calculate the integral changes throughout the soil-water system for the nitrogen constituents being considered. To date, the microbiological transformation treated in the above manner consider the constituents NO_3^-, NH_4^+, urea, and organic-N[5].

Applications

To date applications of one-dimensional models to field situations on a research basis have

included predicting and thus verifying the quality of percolating water[14], predicting the quantity of gypsum and leaching water required for reclamation[7, 16], predicting the salinity in the root zone[10] and predicting the nitrogen entering groundwater[5].

It has been shown that it is feasible to consider 1) moisture additions (irrigation and rainfall) and movement; 2) evapotranspiration; 3) nitrogen transformations including hydrolysis of urea-N, immobilization-mineralization of ammonia-N or organic-N and immobilization of nitrate-N; 4) changes in the solute concentration of soil-water due to oin exchange, solubility of gypsum and lime ($CaCO_3$) and dissociation of certain ion pairs; 5) nitrogen uptake by crops, and 6) additions of soil amendments such as nitrogen fertilizers and gypsum. Models of the type discussed here could be of value in developing management practices for reducing pollution by agriculture.

Predicting Solute Changes for Two and Three Dimension Flow

As discussed elsewhere in this publication, lines of one-dimensional flow can be joined together to consider the two-or three-dimensional case, where the system now becomes a field or a basin. The U.S. Bureau of Reclamation has applied a stochastic hydrology model with a soil-water simulation model, considering saturated flow. This hybrid, three-dimensional model has been tested in Utah. In addition, the same agency has a simulation model for predicting solute in water from tile drains. This latest model considers chemical changes occurring above the water table[5] mentioned above and chemical changes and dispersion occurring in the saturated zone. Another interesting hybrid model of a basin has been reported by Thomas, et al[17]. ·This model utilizes the principles discussed earlier and a general hydrologic model.

SUMMARY

Computer simulation modeling techniques for predicting the solute composition of water in soil-water systems have been developed and verified on a research basis. The concentrations of NH_4^+ and several alkali metals and alkaline earth salts including NO_3^- have been predicted for soil systems, for one-, two-, and three-dimensional flow. Application to several systems of interest concerning reclamation and quality of agricultural return flow water have been made. Other applications include incorporation of these soil-water simulation models with other hydrologic models to form simulation models of irrigation projects of groundwater basisn.

It would appear, on the basis of the simulation models thus far developed, that the technique could be used to develop management techniques for reducing or minimizing the salt problems and/or pollution normally associated with irrigation agriculture.

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Modeling Salinity in the Upper Colorado River Basin

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ABSTRACT

Increased use of water resources produces quality changes (greater salinity or total dissolved solids) that affect downstream users of the resource. Models of river systems can be used as efficient management tools to minimize harmful effects on these users. The discussion concerns a computer simulation model that describes the salinity in the Upper Colorado River Basin. Using mathematical expression, the salinity model describes only the most fundamental and basic processes in the basin, but has value in assessing the quality changes that might result from contemplated development at a particular location within the river system.

Successful modeling and management of the salinity system requires a definition of the Basin hydrology that is accomplished through water budgeting procedures. Available data of historical water flows and salinity concentrations for agricultural, municipal, and industrial uses, are employed to verify a salinity model. Development of a salinity model is illustrated using the White River subbasin which is verified by comparing computed and observed output values.

INTRODUCTION

Greater use of the Colorado River Basin waters is creating a difficult situation in terms of the water resource quantity and quality. Unfortunately, increased utilization of the existing resources, through use and reuse of water for irrigation and by industries, concentrates and adds non-degradable materials that produce a degeneration of water quality. For example, the natural inorganic salts, leached out by percolating waters from the rocks and soils within a watershed, are concentrated through the consumptive use of water in irrigation. The problem is further aggravated by the leaching effects of excess irrigation waters as they percolate through the soils of irrigated areas.

This degradation of water quality from inorganic salts—generally referred to as total dissolved solids (TDS) or, more commonly, as salinity—results from various uses, such as irrigation and industrial; nevertheless, the extent to which each use contributes to the salinity load remains a controversial issue. Promotion of complementary uses and the reduction of controversy and competition for the existing water resources of the Colorado River Basin are necessary aims of good management. In this river basin each upstream use of water has some effect on its quantity, quality, and on the timing of flow occurring at downstream points. The problem of quantitatively assessing these downstream effects is a difficult one. The cause of this is the complex interrelation and variable na-

ture of the many different processes that occur at the same time. In other words, the extent of downstream effects, such as those caused by increased diversions at a specific location, depends upon the dynamic characteristics of the system and the water use patterns that prevail within the Basin. However, many of the factors affecting the system are subject to manipulation and regulation, and through proper management criteria, efficient use of the water resources of the Basin can be achieved.

Since water resources within the Upper Colorado River Basin are now nearing full utilization, application of sound management principles, based upon consideration of various alternatives, is becoming increasingly important. Sound water resource management requires thorough and thoughtful planning in harmony with overall public goals and needs. Water is an important key to successful development of the area. Effective planning must consider the various consequences of water resource manipulation. This objective can be adequately met only by rapid and accurate quantitative assessment of various possible management alternatives. These might involve such variables as watershed treatment, weather modification, increased urbanization, salinity control measures, and changes in irrigation practices within a basin. Consequently, as pressures upon the river basin resources increase, more sophisticated methods are required for planning and management purposes. The advent of modern, high-speed, computers for modeling entire water resource systems provide a technology to use as a tool for the management of water.

Modeling Background

Basic Concept

Development of a specific and quantitative description of a river basin including its salinity dimension is a difficult problem. This is due to the complex and variable nature of the many different processes that occur at the same time within the total basin. The problem is, therefore, first to describe in mathematical terms the various processes that occur and then develop a realistic approach for combining these relationships into models that faithfully describe the system. Measurements, or observations, are made of the model and its characteristics when subjected to conditions similar to those confronted by the prototype. These models allow for easy and quick examination of alternatives posed by planning and management changes within the prototype system (a real-world river basin) being modeled.

The suggested approach in the development of a model that describes salinity in the Upper Colorado River Basin is to consider initially a model that is macroscopic in nature in which only the most fundamental and basic processes are described. Such a model is not refined or sophisticated in terms of describing the specific details and intricate processes that actually occur. The vast area of the basin is subdivided into relatively large, yet descriptive spatial units, and within each of these the basic relationships are defined. Only the important model parameters are used. These variable parameters use average values in the model solution. As a general rule, availability of the data needed by the model dictates the size of spatial unit selected. Temporal resolution is obtained by selecting a specific time increment over which average values of time-varying parameters are used. Development of such a model quickly highlights data limitations and needs. The model is capable of examining various alternatives for the Basin as a whole, or between its subbasin units, but may not be able to pinpoint specific results at exact locations.

Once a model of this nature is developed, definition of the system can be improved by reducing the magnitudes of the spatial units and time increments. The improved model is then capable of solving the same basic relationships as its predecessor as well as solving many additional problems and more complex processes that require detailed description.

For example, considerable interest is now evidenced in the phenomenon occurring within the soil profile relating to the precipitation, solution, and exchange reactions of various ions. These reactions are functions of the composition and concentration of salt in the applied irrigation water, soil properties, irrigation practices, and of other related characteristics. Adequate description and simulation of the reactions within soils requires a small spatial increment. Similarly, precipitation interception rates and

changing snowpack temperatures are processes that can be included only in models based on a small time increment.

Additional improvement of the definition of the salinity system can be accomplished through development of other models. A model is needed that can route salts, both collectively and individually, through a reservoir system. Such a model would require consideration of salt deposition, stratification, and solution from the confining boundary. A model is needed to predict the salt load of water originating from thundershower activity, common to the basin. Similarly, a model, which adequately estimates quantitatively, as well as qualitatively, the chemical composition of water originating on watersheds, would be useful where there are now deficiencies in water quality data. This model would relate such variables as flow rate, vegetative cover, evapotranspiration, geologic characteristics, slope of watershed, vegetative cover, time, and flow path. Each of the models outlined above would have smaller spatial definition and time increments. They would greatly improve the definition of specific processes contained within the general model covering the entire salinity system.

The ultimate in modeling would employ continous time and spatial definition, although the practical limitations of this approach are obvious. For the most part, the complexity of a model designed to describe the salinity within a basin depends upon the magnitude of time and spatial increments used in the model. These should be consistent with the kinds of questions that might be asked of the model.

Once the model adequately describes the hydrologic and salinity aspects of the basin, other dimensions should be added to the model. All water management alternatives need to be considered in terms of existing legal, political, and institutional constraints and should be evaluated through a particular set of social objectives, economic and otherwise. Such a comprehensive model is, of course, a future probability. Modeling can, however, aspire towards such lofty goals.

Use of Computers for Modeling

Modeling or simulation of different systems can be accomplished in different ways. The application of electronic models, those that use high-speed computers, to simulate river basin salinity is a new technique. This procedure involves the use of a computer in order to synthesize a mathematical model of the prototype system. Mathematics become the link between the computer model and the prototype. Time and space scales consistent with the requirements of the problems and data availability are readily selected.

Traditionally, electronic computers have been divided into two general classes, namely, digital and analog. The digital computer employs a sequential procedure to perform step-by-step operations, at high speed and great accuracy, on combinations of discrete data. The analog computer solves problems through electronic components that behave in a manner analogous to the dynamic or time-varying prototype system. A more recent development is the hybrid computer. It combines the desirable characteristics of both the digital and analog computer, both allowing for a high level of efficiency in computer simulation and combining high speed with dynamic accuracy.

Advantages of computer simulation include an opportunity to evaluate proposed modifications at a minimum expense and effort; nondestructive testing of the system; no time loss or inconvenience in the prototype system while improvements or modifications to existing works are considered; and considerable insight into the physical relationships and properties of the system receiving consideration. Computer modeling, or simulation, is valuable in the process of investigating and improving mathematical relationships. In this respect the computer is a valuable tool not only for its calculating potential, but also for its ability to yield optimum solutions. Modeling is also ideal for investigations of the sensitive places in the system.

Salinity Model

Salinity in the Upper Colorado River Basin is dynamic in nature and is totally dependent upon the quantity of water available to transport salt loads. Hence, to describe the salinity in the Basin requires an accounting of the physical, hydrologic quantities at various points within the basin. Using the concept of continuity of mass, water moves or is routed through the system in

the proper relationship to both space and time. In the salinity system salt moves by dilutation and mixing of water flows. Thus, the salinity system is dependent upon the hydrologic system. The salinity level of a given water discharge indicates the mass rate of salt movement with that flow segment. Thus, the hydrologic and salinity systems are related through the salinity concentration at a given rate of water flow. The rate of salt input to a system is estimated from the salinity concentration levels of all hydrologic flow inputs. If consideration is given to storage changes and influences produced by water uses within the system, the mass balance concept provides an estimate of the resultant TDS concentration at the outflow of the system.

An analog computer model is developed to describe the salinity system in the Upper Colorado River Basin. To provide spatial resolution the Basin is divided into 40 subareas or subbasins; each is modeled separately. Then, the subbasin models are linked into a single model of the entire Upper Basin (Figure 1). The subbasin models that correspond to the numbered basins in Figure 1 are given in Table 1. In general, subbasin boundaries are established on the basis of the availability of water salinity data. Only the valley floors are included within the modeled area, with both gaged and ungaged tributary inflows of water and salt from the surrounding drainage areas being represented by either observed or estimated input quantities. The time increment selected for the model is one month. Therefore, time-varying quantities are expressed in terms of mean monthly values.

Appropriate historical data from USGS gaging stations are assembled and used as measured inflows of water and salt loads to a given subbasin. Unmeasured water input quantities are estimated through correlations based on precipitation, snowmelt, and gaged streamflow rates. Salt flow rates are estimated by associating a salinity concentration with each waterflow component. It is assumed that no salts are carried by precipitation quantities. Input flows are routed, delayed, increased, or abstracted within a given system by means of diversion; return flows; deep percolating flows; municipal and industrial activities; exports or imports; evapotranspiration and salt loading from point and diffuse from natural sources; municipal and in-

TABLE 1

SALINITY SUBBASIN MODELS WITHIN THE UPPER COLORADO RIVER BASIN

Salinity Subbasin Model	*Model Number from Figure 1*	*Salinity Subbasin Model*	*Model Number from Figure 1*
New Fork River Basin	1	Colorado River, above Glenwood Springs, CO	21
Green River, above LaBarge, WY	2	Roaring Fork River Basin	22
Green River, above Fontenelle Reservoir	3	Colorado River, above Plateau Creek	23
Big Sandy Creek Basin	4	Plateau Creek Basin	24
Green River, above Green River, WY	5	Gunnison River, above Gunnison, CO	25
Blacks Fork River Basin	6	Gunnison River, above No. Fork Gunnison River	26

TABLE 1 (CONTINUED)

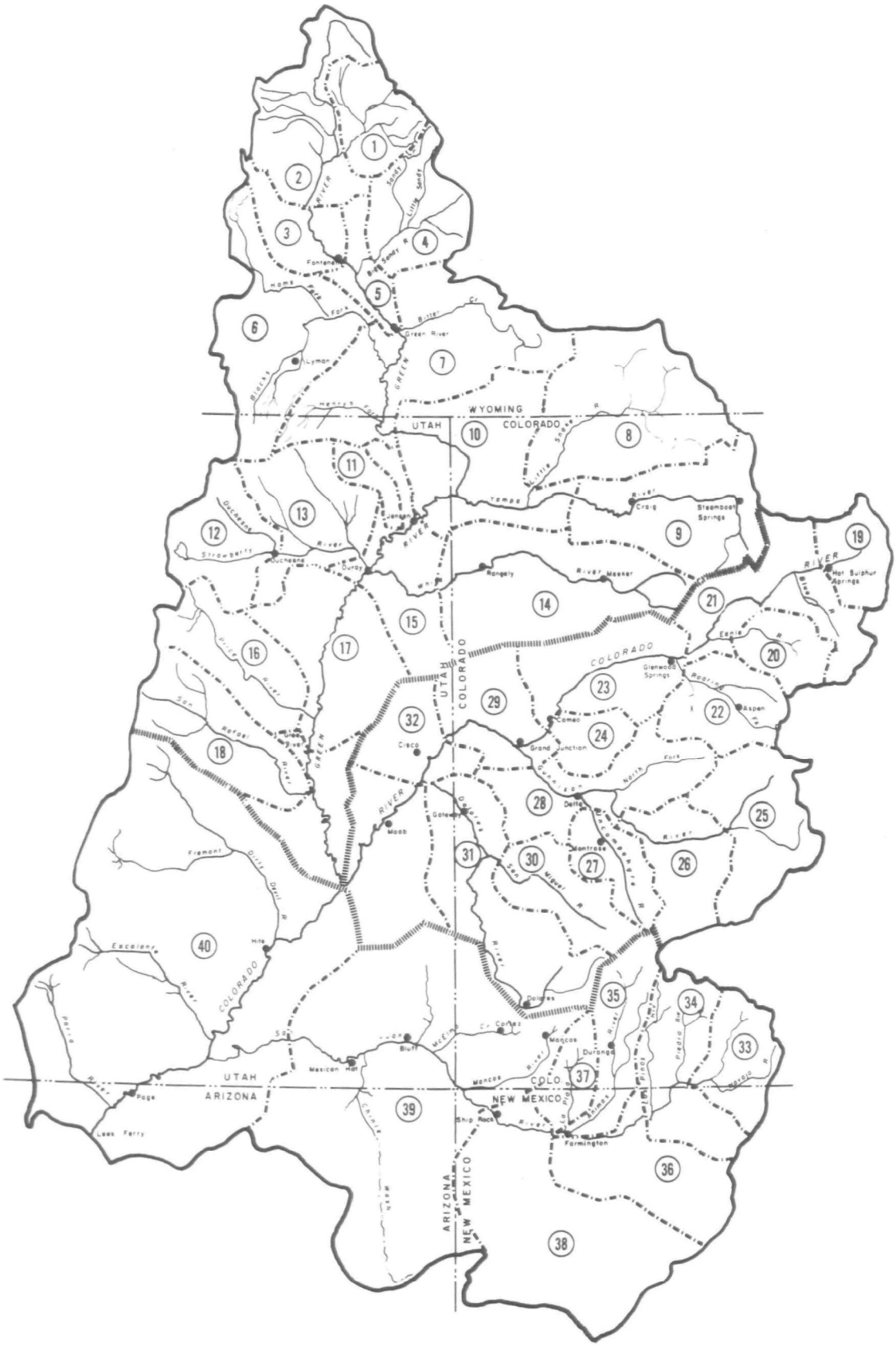
SALINITY SUBBASIN MODELS WITHIN THE UPPER COLORADO RIVER BASIN

Salinity Subbasin Model	*Model Number from Figure 1*	*Salinity Subbasin Model*	*Model Number from Figure 1*
Green River, above Flaming Gorge Dam	7	Uncompahgre River Basin	27
Little Snake River Basin	8	Gunnison River, above Grand Junction, CO	28
Yampa River Basin	9	Colorado River, above CO-UT State Line	29
Greer River, above Jensen, UT	10	San Miguel River Basin	30
Ashley Creek Basin	11	Dolores River Basin	31
Duchesne River, above Duchesne, UT	12	Colorado River, above Cisco, UT	32
Duchesne River, above Randlett, UT	13	San Juan River, above Arboles, CO	33
White River Basin	14	San Juan River, above Archuleta, NM	34
Green River, above Ouray, Utah	15	Animas River Basin	35
Price River Basin	16	San Juan River, above Farmington, NM	36
Green River, above Green River UT	17	LaPlata River Basin	37
San Rafael River Basin	18	San Juan River, above Shiprock, NM	38
Colorado River, above Hot Sulphur Springs, CO	19	San Juan River, above Bluff, UT	39
Eagle River Basin	20	Colorado River, above Lee's Ferry, AZ	40

dustrial loads; and of irrigation pickup by leaching soils.

The evapotranspiration rate is estimated from an empirical relationship that is dependent upon surface air temperature, latitude, available soil moisture, and crop species. No abstractions from the salinity flow system occur through the evapotranspiration process.

The rate of natural salt pickup is determined from an empirical relationship based on the


WYOMING
UTAH
COLORADO
ARIZONA
NEW MEXICO
Green River
Lyman
Rangely
Craig
Steamboat Springs
Meeker
Hot Sulphur Springs
Glenwood Springs
Aspen
Eagle
Cameo
Grand Junction
Cisco
Moab
Gateway
Delta
Montrose
Durango
Mancos
Bluff
Mexican Hat
Page
Lees Ferry
Hite
Farmington
Ship Rock
Durango
Dolores
Fontenelle
Duchesne
Roosevelt
Vernal
Dutch John
Fremont
Escalante
Green
Colorado
Yampa
Gunnison
Dolores
San Miguel
Animas
Piedra
Navajo
Little Snake
Bear
Weber
Provo
Sevier
Virgin
Paria
Escalante
Dirty Devil
Muddy
Price
Duchesne
Strawberry
Uinta
Yampa
Eagle
Roaring Fork
Gunnison
Dolores
Animas
Piedra
Navajo
Little Colorado
Virgin
Muddy
Paria
Escalante
Dirty Devil
Fremont
Green
Colorado
Yampa
Little Snake
Bear
Weber
Provo
Sevier

degree of interchange between surface and subsurface flows within the Basin. In addition, an annual salt balance (no storage) within the agricultural system is assumed.

Water and salts that flow through the system are changed both spatially and temporally as water with its accompanying salt load moves through a hydrologic system and as storage changes and abstractions occur. Resultant response or output functions of the model represent the integrated effects of the many physical and chemical processes that occur within the Basin.

Change in flow of water and salts is determined by mathematical expressions describing the various system relationships (mentioned in the preceding paragraph). These expressions, synthesized into a program for the electronic analog computer, contain certain coefficients or model parameters that are evaluated and fixed during the model calibration procedure. Under this procedure, data for a given subbasin are input to the computer. The model coefficients are then adjusted until observed and computed output functions closely match. A model was calibrated for each subbasin by matching observed and computed functions for water and salt over a period of 24 consecutive months. So far as is possible, the calibration period was selected to represent a wide range of flow conditions.

Illustrative Example of a Salinity Model

Outlined in this section is a brief, non-mathematical explanation of the processes involved in developing a salinity model. In actuality, these processes are really described by mathematical expression that relate the different parameters and incorporate them into a model. However, for the sake of simplicity, the different processes are discussed in general terms; a more rigorous explanation is found elsewhere.[1]

The development and verification procedure that is followed in obtaining a salinity model of the Upper Colorado River basin can best be illustrated by referring to a specific example. The subbasin selected for illustrative purposes is the White River system. Each river system differs slightly from one to another, but the basic procedure in the development of a model for a subbasin is illustrated well by the White River subbasin. Development of other subbasin salinity models followed the same logic, as outlined in the following paragraphs, for the White River model.

The White River lies primarily in west-central Colorado, with water flowing westward to the point of confluence of the White and Green Rivers in east-central Utah. The river basin is bounded, on the north, by the Yampa River, and on the south, by the Colorado River. Livestock production, irrigated agriculture (primarily feed and forage crops, comprising about 29,000 acres), and production of oil and natural gas provide the economic base of the area. The 1970 population in the subbasin is about 5,200 with more than one half the persons living in the towns of Meeker and Rangely. The elevation of the river system varies from approximately 5,000 feet at the outlet (assumed to be the U.S. Geological Survey (USGS) monitoring site located near Watson, Utah) to about 12,000 feet in the upper reaches of the headwaters. Because of this elevation difference, the climate is variable with wide temperature extremes in the settled areas. The average annual frostfree period for cropland varies from 60 to 125 days. Similarily, the average annual precipitation varies from 9 to 30 inches.

Model Development

The first step in developing a salinity model of the White River is to define the model boundaries. The boundaries include all the subbasin area located between the inflow and outflow points of the system.

The inflow of water and salt to the system are taken at the USGS monitering points on the White River near Buford, Colorado (no. 9-3028); South Fork White River at Buford, Colo. (no. 9-3040); Big Beaver Creek near Buford, Colo. (No. 9-3041); and Coal Creek near Meeker, Colo. (No. 9-3043). These stations were generally located upstream of the agricultural lands and other human activities of man in the subbasin. Salinity data are available and relatively complete at both input and output points for the years 1964 and 1965, and these data are used in verifying the White River subbasin model. Water salinity data are lacking for both Big Beaver and Coal Creeks. However, because of the topographic and geologic similarity of these drainage areas to those of South Fork of the White

River, salinity concentration measurements for the South Fork, near Buford, are assumed to apply to both creeks, Big Beaver and Coal. The measured inflow, per month, of water and salts to the White River Basin, for the years 1964 and 1965, are in Table 2. These values are given in acre-feet, and the average salinity concentration in mg/l, is obtained by weighting, on a flow basis, the various water and salt inflows.

Monthly ungaged inflows of both water and salt to the basin were estimated by a correlation technique that considers three hydrologic parameters, namely a gaged tributary inflow—the White River, near Buford, Colorado—times a proportionality factor; precipitation times a proportionality factor; and the rate of snow melt times a proportionality factor. The rate of snow melt is determined from the available energy and quantity of precipitation stored as snow.[1] The monthly ungaged inflow quantity, computed by the model and given in Table 2, is estimated primarily from the first correlation technique outlined above. The assumption is made that the average salinity concentration of water entering the White River basin from unmeasured inflow sources equals that of measured inflows.

Recorded precipitation and temperature values for the years 1964 and 1965 were averaged using data collected from climatological stations located at Meeker and Little Hill, Colorado. The values used in the model are given in Table 2. Precipitation values are used in the model as a water inflow. Air temperature is the parameter used in the model as a criterion for establishing the form of precipitation and as an index of the energy available for the snowmelt and evapotranspiration process.

The evapotranspiration relationship used in the model [Blaney-Criddle] requires, in addition to mean monthly temperature, the monthly percentage of annual daylight hours and a monthly crop growth stage coefficient.[2] The crop distribution pattern used in the model for the irrigated area is 29 percent clover, 27 percent alfalfa, 34 percent pasture and meadow hay, and 10 percent grains. The acreage of phreatophytes within the basin is estimated to be equivalent to a concentrated stand of 3,800 acres.

The actual evapotranspiration rate computed by the model is equal to or less than the potential rate computed. As the moisture content of a soil is reduced by evapotranspiration, the moisture tension which plants must overcome to obtain sufficient water for growth is increased. When the plants begin to wilt because soil moisture is a limiting factor, an empirical linear relationship is assumed between available soil moisture quantity and actual transpiration rate. Thus, the actual evapotranspiration rate is reduced to something less than the potential rate.[3] The amount of water transpired by crops and phreatophytes, as calculated in the model, is given in Table 2.

The quantities of irrigation water diverted to the agricultural lands during 1964 and 1965 were obtained by distributing a yearly volume of water according to monthly canal or ditch records that generally represent the water distribution patterns of the area. Both the yearly volume of water diverted and the individual representative ditch records were obtained through the State Engineer and the appropriate Irrigation Division Engineer in the State of Colorado. These quantities are listed in Table 2.

Transfers of water either to or from the subbasin (imports and exports) and groundwater pumpage are not significant in the White River drainage. Therefore, these processes were not included in this particular model.

It is postulated that the natural saltload is contributed to the waters of the Upper Colorado River Basin through an interchange process between surface and subsurface waters. Influent flow from the main stream enters the groundwater basin and, under conditions of equilibrium, an equal volume of effluent flow enters back into the stream in a lower reach of the channel. The salinity concentrations of the effluent waters are assumed to be equal to those of the groundwater. In this study the rate of interchange flow for each subbasin of the Upper Colorado was expressed empirically as a percentage of the flow rate at a particular point in the main surface channel. For the White River system this relationship was based on the surface flows at Watson, Utah. The salt load from the interchange phenomenon is computed as a function of the percentage interchange, basin outflow, and groundwater salinity concentration. Total basin outflow rates for both water and salt and for the salt load contributed by nat-

TABLE 2

AVERAGE MONTHLY HYDROLOGIC FLOWS AND SALINITY LOADS WITHIN THE WHITE RIVER SUBBASIN

Year and Month	*Surface Inflow, a-f* White R. near Buford	So. Fork White R. at Buford	Big Beaver Creek	Coal Creek	*Ungaged Input correlations*	*Weighted Input salinity mg/l*	*Precipitation inches*	*Temperature °F*	*Evapotranspiration* Crops	Phreatophytes	*Canal diversions*	*Salt load from natural sources tons*	*Water outflow Watson Utah, a-f*	*Salt Outflow at Watson, Utah, tons*
									a-f					
1964														
Jan	6600	4790	111	86	4000	197	0.66	18.1	0	0	0	13100	17100	15800
Feb	6980	5170	138	92	4300	192	0.56	19.3	0	0	0	12900	18760	16050
Mar	7650	6260	202	139	4700	186	1.34	26.3	0	100	0	15300	26040	21570
Apr	8540	6810	704	311	6400	177	2.72	40.9	3000	500	12000	15900	30320	26760
May	38530	39790	5250	1050	24400	117	1.63	51.9	9800	1300	32000	23600	84210	34820
June	49900	62620	1440	770	31000	103	2.07	58.5	10400	1800	57000	24300	99350	33370
July	20490	15070	50	108	12500	164	0.79	68.8	17500	2800	23000	16000	30220	19190
Aug	12980	9560	39	119	7900	171	2.08	62.7	10700	2000	9500	15000	24680	20140
Sept	9560	6980	23	94	5800	177	0.59	55.5	6200	1200	12000	12300	15700	12900
Oct	9780	6520	46	86	6000	177	0.22	47.9	1900	700	7500	13800	20060	15580
Nov	8960	6240	177	101	5500	174	1.50	31.0	0	200	0	13600	20350	16670
Dec	9310	6370	182	111	5800	200	2.20	25.3	0	0	0	14200	21540	20450
1965														
Jan	8710	6530	103	86	5200	190	1.10	25.4	0	0	0	15700	23350	21150
Feb	7600	6650	229	119	4600	181	0.89	24.3	0	0	0	14700	22390	19430
Mar	7870	6080	385	206	4800	197	0.77	27.1	300	100	0	18000	33460	31030
Apr	10750	7760	1261	441	23500	175	1.14	42.9	3700	500	16000	17900	35100	33220
May	45000	33160	6511	1890	39600	120	2.94	50.4	7100	1200	57000	26500	98050	45840
June	71340	80610	2707	1190	51600	127	1.98	57.3	10700	1900	62000	31900	157700	59840
July	34290	23810	254	285	21700	129	2.74	65.3	13900	2400	30000	23400	69380	45580
Aug	18250	11790	244	165	11200	177	0.90	62.2	11200	1900	25000	17800	31910	23520
Sept	14340	9810	306	131	8700	190	2.00	50.5	5700	1000	13000	17600	32520	23220
Oct	10710	6520	159	119	6500	167	0.30	48.7	4200	700	0	18100	33560	22780
Nov	9810	6240	280	148	6000	171	1.32	38.1	800	300	0	16600	27800	19890
Dec	8410	6370	158	98	5100	186	2.99	25.5	0	0	0	16700	26580	21940

ural sources, as estimated by the interchange process, are given in Table 2. The actual value of the salt load contributed from natural sources requires further research to define adequately its magnitude.

Several other single-valued parameters are required in the model, such as soil moisture capacity, the rate of snow melt, various correlation coefficients, and delay times for movement of different flow components in the ground water system. These parameters, once determined through a trial and error verification process, are assumed fixed for a given subbasin.

The appropriate routing of inflow water and salt through the system in relation to loss, and additions, which occur over space and time, results in a flow at the outlet point (Watson, Utah) that is both surface and subsurface. Active network delays on the computer simulate the long transport times necessary for groundwater flows and deep percolating waters from irrigation return flows to be routed to the outflow gaging station.

Model Verification

Computer output from the verified model of the White River subbasin is shown in Figure 2. (The model was calibrated with 1964 data and tested over the 12 month period of 1965.) A comparison is made between computed and observed values for both water discharge in acre-feet and salt discharge in tons for both years at the monitoring station near Watson, Utah. On an annual basis the differences between the computed and observed values of discharge do not exceed about three percent for water and seven percent for salt. On a monthly basis discrepancies are slightly higher, but in general, good fits were obtained for both the water and salt discharges. As a point of interest the agreement between the computed and observed salt outflow rates for the White River subbasin proved to be among the least accurate of those obtained for all of the subbasins of the Upper Colorado River drainage.

Additional output functions, from the White River basin model, that illustrate the kind of information available are shown by Figures 3 and 4. Time variation of the soil moisture level in the plant root zone of the basin is illustrated in Figure 3. Snowmelt produces the sharp rise in soil moisture storage during April. In early May the capacity is reached. Irrigations and rainfall are sufficient to virtually maintain this level throughout the remainder of the year. In subbasins, where adequate supplies of irrigation

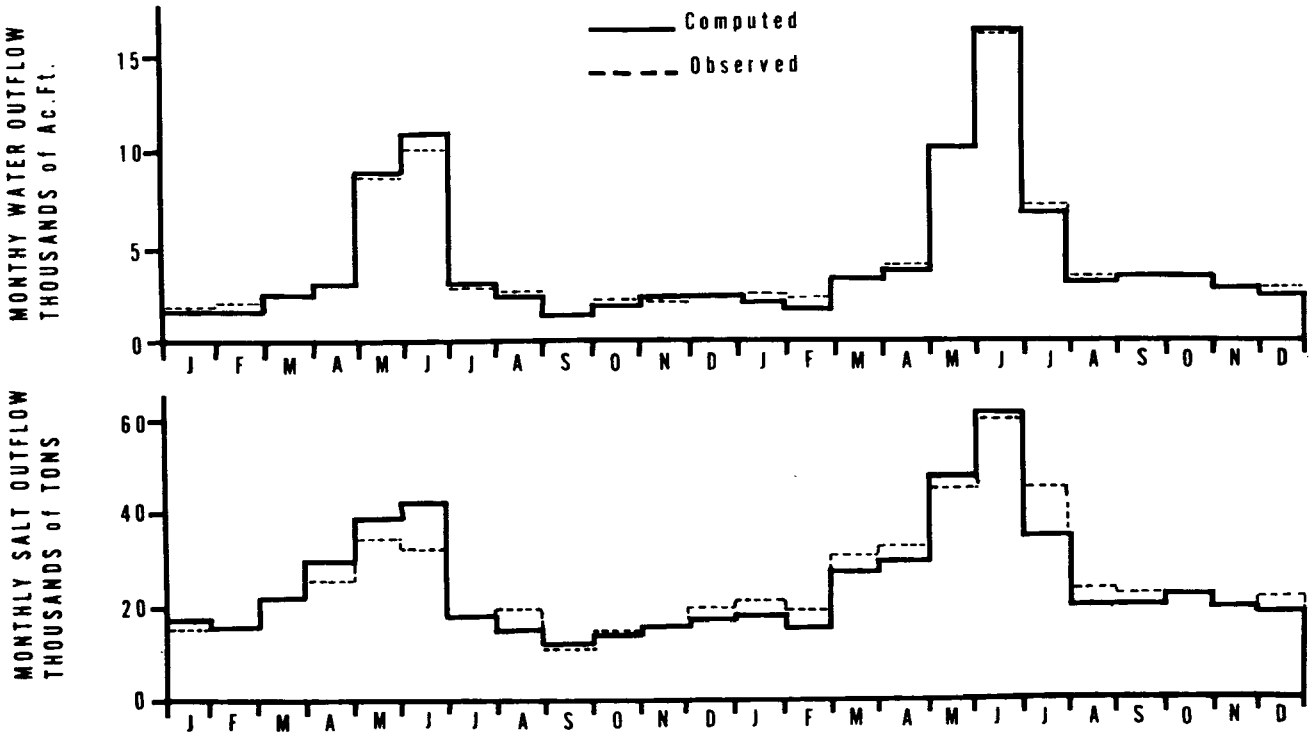


Figure 2: Computed and Observed Monthly Discharge of Water and Salt

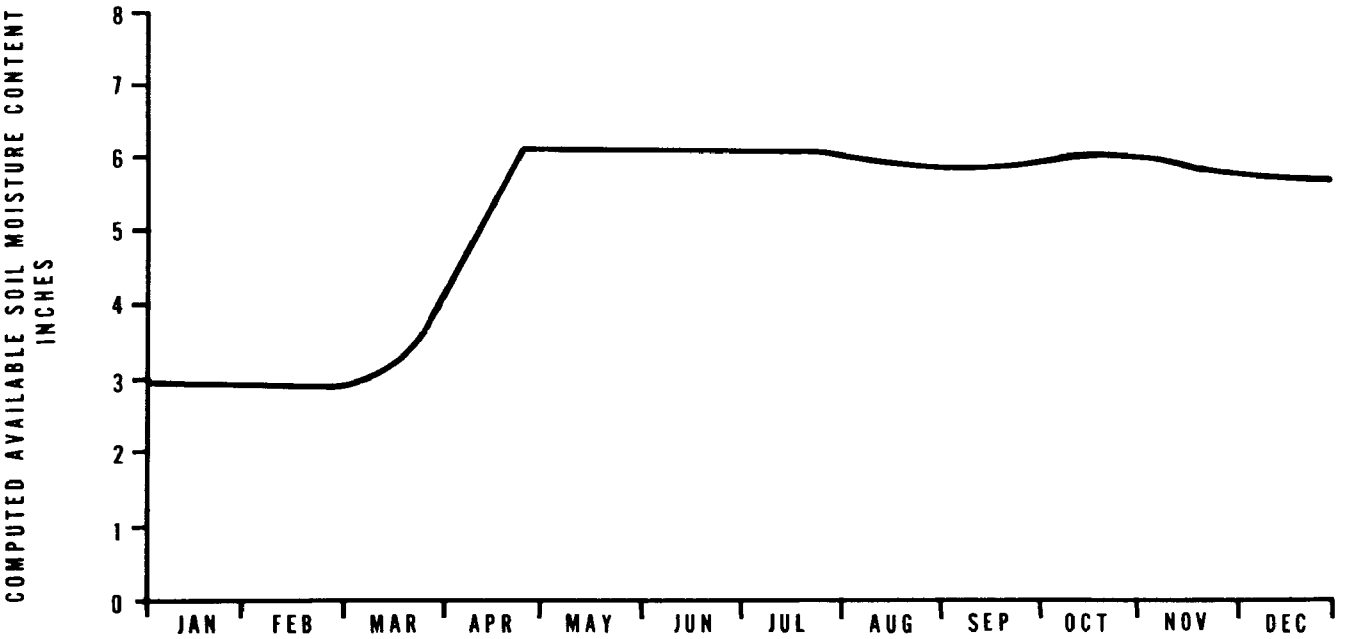


Figure 3: Available Soil Moisture in Agricultural Area

water are not available, soil moisture levels might not reach capacity during the irrigation season.

Deep percolating waters from the agricultural lands are believed to move through the groundwater basin, eventually to appear as effluent flow in the main surface channel of the subbasin. The discharge function for the salt load carried by these waters, as computed by the model of the White River basin for 1964, is shown in Figure 4. These flows were delayed by 3.5 months (3.5 seconds computer time) from the time of percolation to the time of outflow from the groundwater system.

Salinity Model Results

The general procedure outlined in the preceding section for the development of a salinity model of the White River subbasin was repeated for each of the 40 subbasins considered in this study (Figure 1). The subbasin models are then linked into a single model of the entire Upper

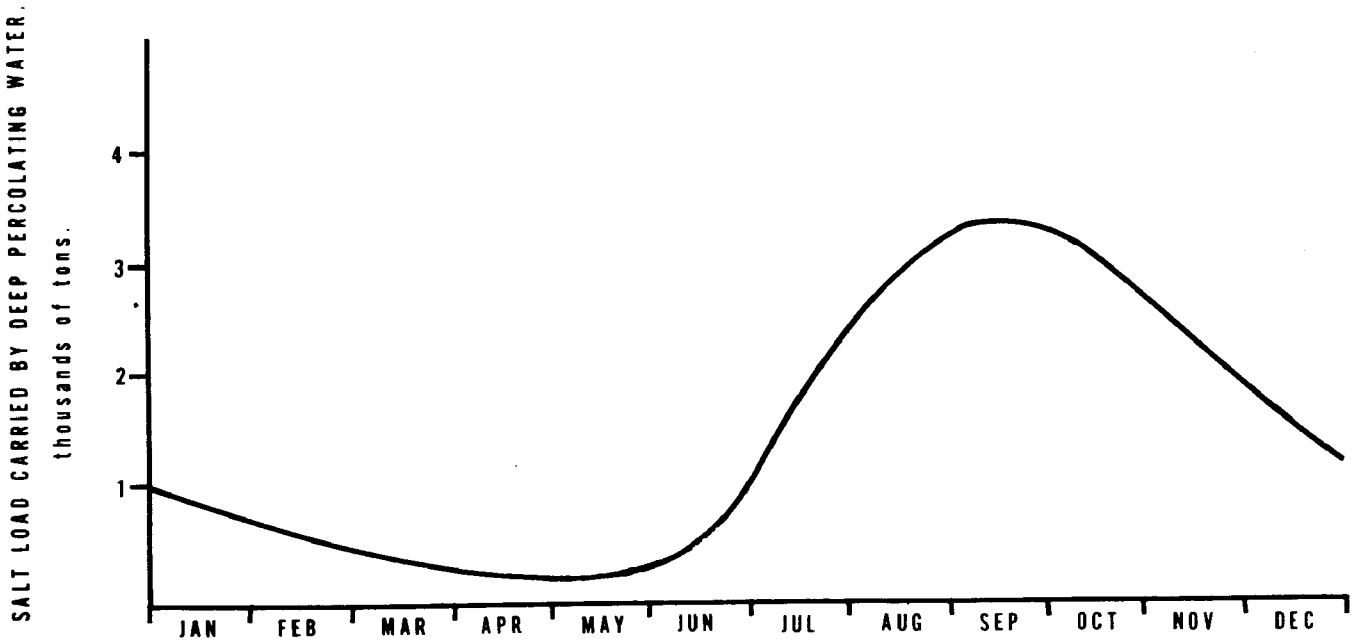


Figure 4: Rate of Salt Movement with Deep Percolating Waters from Agriculture Area

Colorado River Basin.[1] Some general results obtained from the salinity models are given in the following paragraphs.

The average annual water discharge rate from the Upper Basin, modified to 1965 conditions, is estimated to be 10,900,000 acre-feet. The average annual virgin flow at Lees Ferry is about 14 million acre-feet per year of which about 10,500,000 acre-feet of water is measured directly, as to it's source of origin, at points on tributaries to the main stem rivers.

The average annual salt discharge from the Upper Basin above Lees Ferry is estimated to be 8,600,000 tons. This salt discharge produces an average salinity concentration at Lees Ferry of 580 mg/1. Within the Upper Basin it is estimated that average salinity concentration at Lees Ferry is increased by about 20, 45, and 115 mg/1 by reservoir evaporation, consumptive use by phreatophytes, and by agricultural evapotranspiration, respectively, from what is would be with no concentration of salts by these consumptive depletions.

Salinity measurement of tributary streams within the various subbasins of the Upper Basin measure about 1,700,000 tons of the total average annual salt outflow of 8,600,000 tons recorded at Lees Ferry. On the basis of these figures, only 20 percent of the average annual salt flow from the Upper Basin is measured with respect to its area of origin. This limitation of available salinity information explains in part the difficulty encountered in simulating the salt flow system. The simulation models indicated that the remainder of the total average annual salt load originates from the following sources: (1) 1,100,000 tons from ungaged tributary inflows; (2) 1,500,000 tons from pick-up of salt by irrigation return flows; and (3) 4,300,000 tons from natural diffused and point sources within the system. It is recognized that the magnitude of salt load contributed from the latter two sources requires additional research to adequately define this portion of the salinity system.

SUMMARY

Many of the factors that affect the quantity and quality of water resources of a river basin are subject to management or regulation. Optimum water use, assessment of management alternatives, and logical criteria for regulation and administration of the water resources are needed. With increasing pressures upon the Colorado River Basin water resources more sophisticated models are required for planning and management purposes.

A general model of the salinity flow system of the Upper Colorado River Basin is proposed and synthesized on an electronic analog computer. The basis of the model is a fundamental and logical mathematical representation of the various salinity and hydrologic flow processes. The salinity model is macroscopic in nature and describes only the basic salinity system within the basin. The model is not refined or sophisticated in terms of describing some of the specific details and intricate processes that actually occur. Additional improvement of the definition of the salinity system can and should be accomplished through the development of other models that describe these complex processes. Such models could then be incorporated into the general salinity model to improve both the spatial and temporal definition of the flow of salts in the Upper Basin.

Inadequate data frequently restrict the ability of a model to define a system. In this study more complete data would enable refinement of the major salinity processes within the model and thus provide one that more accurately simulates the salinity flow system. The level of complexity of a model that describes a salinity system depends upon the fineness in time and spatial data that are used in the model.

Modeling the salinity of the Upper Basin is accomplished by tracing the average monthly mass rate of water and salt through the various paths in the hydrologic system. The Basin is subdidived into 40 smaller units or subbasins. A salinity model is developed for each subbasin by routing stream inflows, diversions to irrigated lands, evapotranspiration, municipal and industrial uses, return flows, changes in ground water storage, and stream outflows through the system. The salinity concentration associated with a given segment of water flow determines the volume of salts that are transported by that particular flow segment. Unmeasured quantities of water and salt are estimated through various correlation techniques. Salt loads from point and diffuse natural sources are determined from

an empirical relationship. The resultant output from the model represents the integrated effects of the many physical and chemical processes that occur within the basin. Verification of the model is accomplished by comparing the recorded outflow from the basin with that computed by the model. The 40 subbasin models are then linked into a single model of the entire Upper Basin.

The development and verification procedures that are followed for subbasin model are illustrated using the White River system (in western Colorado). Each of the 40 subbasin models were developed in much the same manner. Some results from the general salinity model of the Upper Colorado River Basin are given.

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Hydrologic Modeling of Ashley Valley, Utah

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ABSTRACT

A mathematical model for predicting the mineral quality of irrigation return flow water is presented. The model has been tested using data collected from an existing irrigation project.

In concept the model incorporates the use of deterministic and/or probabilistic inputs and demands and in turn measures the system's responses or yields under a multitude of variable systems, operation criteria and design features. Two of the five computational blocks are described in detail, the data analysis submodel and the simulation submodel. The data analysis submodel is designed to measure the worth or information content of all input data sets. The simulation model has been designed using a nodal scheme which allows many configurations in the simulation of the whole water resource system.

Representative graphical output from the use of the Vernal Unit data is included. The "goodness of the prediction" results somewhat from repeating data to fill in missing years or months.

INTRODUCTION

The objective of this study is to provide a technique for predicting and assessing more precisely than now possible the mineral quality of irrigation return flow. The means for accomplishing this objective will be through the use of mathematical models and high-speed computers. The mathematical model is primarily a mathematical formula or expression attempting to duplicate conditions encountered on an irrigation project. The study utilizes data from existing irrigation projects in order to verify the technique. If it is possible to duplicate or nearly duplicate existing conditions with the model then confidence is established and the method can be used, with a small amount of water quality data, to predict mineral quality from return flow.

The next step would be to predict mineral quality of return flow under modified management to see if improvements could be achieved through irrigation scheduling or improved irrigation systems.

The Vernal Unit in northeastern Utah was chosen for the initial modeling effort. The selection was made partially on the basis of available data and the fact that the inflow and outflow salt loads and water quantities from the project could be easily measured. Considerable water quality and quantity data were collected in this area prior to completion of a storage reservoir and continuing through the beginning of project operation.

Initial runs on the computer using existing Vernal data are encouraging and the possibility of success in predicting salt loads in return flow now seems to be assured.

The most important requirement in a study of this type is to have reliable and consistent data, especially flow and quality and consumptive use. Application of the model to the Vernal data turned up several inconsistencies in the basic data, the most serious being the estimated consumptive use and the determinations of the chemical exchange in the return flow waters.

Description of Model

The mathematical model is being designed within the context of systems engineering utilizing general aspects of systems theory, probability, and mathematical statistics. It also utilizes computer science, engineering, mathematics and numerical analyses.

In concept, the model incorporates the use of deterministic and/or probabilistic inputs, demands, and in turn measures the system responses or yields under a multitude of variable systems operation criteria and design features. The systems model under this concept consists of five fundamental computational blocks which could be considered as primarily submodels of the overall system model. Each primary submodel can be used independently or collectively to provide flexibility in the design of an overall model for a particular system objective and alternatives thereof. The five computational blocks or submodels are listed below in the sequence pertinent to the flow of the complete model as conceived:

1. Data analysis submodel
2. Simulation submodel
3. Sensitivity and impact analysis submodel
4. Optimization submodel utilizing linear programming theory, i.e., the ability to maximize or minimize a linear objective function (dual simplex algorithm) on the basis of pertinent constraint equations
5. The best plan submodel utilizes a modified form of dynamic programming theory (Buras, Bellman, et al.)

Some of the primary submodels have been used to study the Vernal Unit water resource system. The system study which was a conjunctive use analysis has been completed using historical data for the period January 1958 through December 1962. All inputs and responses for this study were in a monthly time frame.

The objective of the Vernal study was to use a model in predicting changes in capacity and the associated water quality distribution of the aquifer and also the quality distribution of the water as surface effluents from the system. The water quality distribution was reported in terms of concentrations of calcium, magnesium, sodium and potassium combined, sulfates, bicarbonates, carbonates, chlorides, and in total salts as tons per acre. The prediction of the system responses was compared with the historical data (drain data and aquifer data), both quantity and quality distributions, as a measure of the reliability of the model. With the exception of widely divergent comparisons of aquifer capacities, all other comparisons appeared adequate.

It was concluded from the study of this historical period that the divergence in aquifer capacities was an accumulation of errors perpetrated throughout the system analysis.

Each of the primary submodels described above is further subdivided into sets of minor submodels or subroutines. Each of the subroutines was designed to be used either independently or collectively in any of the particular primary submodels.

The following description of the various functions contained within the model as subroutines will focus primarily on how the model could be used for the purpose of studying an irrigation scheme and the prediction of quality distribution throughout the conjunctive use system as affected by such an irrigation scheme. It must be recognized, however, that the model has the capability of handling simultaneously multipurpose conjunctive use water resource systems which will accommodate the operation of the system for flood control, municipal and industrial requirements, power requirements, salinity control and recreational requirements.

Data Analysis Submodel

Initially all available historical data pertinent to the water resource system would be collected and compiled. These data would consist of surface flows and associated quality distributions, temperature, solar radiation, irrigation data such as acreage under irrigation, types of

crops being irrigated, acreages under nonbeneficial use, soil data such as depth of soil column, degree of saturation, quality distribution,aquifer characteristics, etc.

Hydrologic processes may be deterministic or stochastic (probabilistic) or a combination of both. A process where a definite relationship exists between the hydrologic variable and time is called deterministic. In this case, the function defines the process for all time and each observation in succession adds no new information concerning the process. The opposite of this case is called stochastic (probabilistic) and is represented all or in part by a random mechanism. Generally, hydrologic data are a combination process and the data analysis is directed toward isolating these components.

The hydrologic and climatological processes (historic data sets as part of input to system study) will in all cases be treated first as a discrete time series. The time interval can be daily, weekly,biweekly, or monthly. It will then be assumed that the series is first order stationary (mean) and second order stationary (variance). The next important assumption made is that the series is homogeneous in time or that each event has the same recurrence interval at all times. A test is made at this point and if the series is found to be nonhomogeneous in time or the non-homogeneity exists at a single point (event) i.e., the criteria of equal probability is violated, an attempt will be made to remove the nonhomogeneity. If the removal is not possible, the series decomposition of these data will be terminated and all statistics will be saved for further treatment in obtaining a transfer of filter function for these data in a subsequent portion of the data analysis submodel. On the positive side the series decomposition will continue. When criteria of homogeneity are violated, such violation may be caused by man's intervention or, for that matter, any natural phenomenon. Natural changes or phenomena include among other things trend and periodicity. Changes due to man's intervention may include the effects of dams, diversion works, watershed management, and/or other causes.

The subroutines used in the data analysis submodel for the evaluation of the deterministic components are:

1. Fourier analysis for the detection of and subsequent removal of the cyclic or periodic characteristics of the first moment (mean) and the second moment (variance) of the series.
2. Autocorrelation and spectrum analyses[1] subroutine. This is also a multiple-entry subroutine and at present handles the spectrum of the first through third order linear autoregressive models. A simple modification to this subroutine can be made to accommodate higher than third order autoregressive models.
3. A complete regression analysis for simple linear and simple curvilinear as well as multiple linear (step-wise)[2] with the inclusion of 10 or so transforms and acceptance and rejection criteria on a basis of "F" levels.

Minor subroutines used in evaluation of the stochastic (probabilistic) component of the time series are:

a. A ranking routine which ranks the series in ascending or descending order of magnitude, and then divides the rank series into cells of equal frequency or equal probability.
b. A routine that computes the frequency function, the cumulative distribution function for the standardized normal distribution where the integration for the cumulative distribution function is obtained using Simpson's rule. A second entry into this routine is utilized to determine the nonstandardized variate with a simple transform as a function of the standardized variate with the computed mean and variance, i.e., mean not equal zero and variance not equal one. A third entry into this subroutine will compute the inverse of the cumulative distribution function which simply finds the value of the variate for a given probability and again in this case a simple transform from the standardized variate to the nonstandardized variate is performed. Several algorithms are available in the literature for the computational accomplishment of those factors considered in the subroutine.

4. A multiple-entry subroutine that treats the Poisson's, Exponential (single or double branch), Beta, two and three

parameter gamma functions. The subroutine contains all the necessary approximations to the inverses of the integrals of these functions.

5. A subroutine which is actually a third degree spline fitting function which would allow a fit through each of the points of the cumulative distribution functions and integration of same, and in turn with the use of the simple regression analysis can be transformed to the standardized or nonstandardized normal deviate. Transforms for all of the functions as described above have been designed in terms of the standard or nonstandardized variate.
6. As the time series decompose in this manner, the residuals which represent the final unexplained variance of a totally decomposed series are also examined. This is done by a subroutine which computes the Chi square value for the comparison of the fitted and computed distribution functions. A critical Chi square value is assigned at the discretion of the analyst, which in turn is a function of the overall study objective.

To summarize the capabilities of the data analyses submodel it can be said that within the structure of the various subroutines all historic data (input to model) can be evaluated as (1) a series, homogeneous (or homogeneous if nonhomogeneity can be removed), preserving first and second order statistics, with probabilistic (stochastic) preserving third and fourth moments, i.e., shewness and kurtosis such that larger sample periods can be generated from the smaller historic sample period, and (2) transfer of information from one point in the system to another point in the system by (a) filter function, (b) transfer function, both of which can be deterministic, probabilistic, or a combination of both. Further, all pertinent statistics will be preserved with respect to mean, variance, covariance, and the classical cumulative distribution functions (including multivariate, probabilistic). It is now obvious that the data analysis submodel is designed to measure the worth or information content of all input data sets and such measures and related statistics will be used extensively in the sensitivity (statistical) and impact submodel.

Description of Simulation Submodel

The simulation submodel has been designed using a nodal scheme. Each node has all the characteristics of the simulation submodel as a whole and each node is an entity. The nodal concept allows many configurations in the simulation of the whole water resource system; consequently, it provides maximum flexibility in the design of alternate schemes of operation for the system without major modification to the overall system simulation. A node can represent the simulation of subbasin within the whole water resource system or it can simply represent a point of measuring responses for a single dimension within the system.

The number of nodes that can be accommodated within the simulation submodel is dependent upon the capabilities of the computer system being used for the analysis. Most modern computer systems such as the CDC 6000 to 7000 series can handle as many as 100 nodes without overlays or segmentation.

The simulation submodel, like the data analysis submodel, is composed of several subroutines or minor submodels, as shown in the flow diagram, (Figure 1).

Any of these subroutines can be used independently or collectively, as is the case with those in the data analysis submodel.

1. Control Subroutine — This particular subroutine is used in conjunction with a set of input control cards which designate the sequence of each node in the system and the features of each node. The sequence assigned each node provides the key as to the direction of flow within water resource system. The control subroutine also sets the indices for entry or nonentry of constraint equations pertaining to any particular node.
2. Run of River (out of kilter) Subroutine — This subroutine is a multiple-entry subroutine which purposely sets the whole system out of kilter or balance at the start of each "ith" iteration through the simulation submodel and at the end of each iteration maintains and updates the delta flows (quantified) required as entering or leaving each node to balance the water resource system.

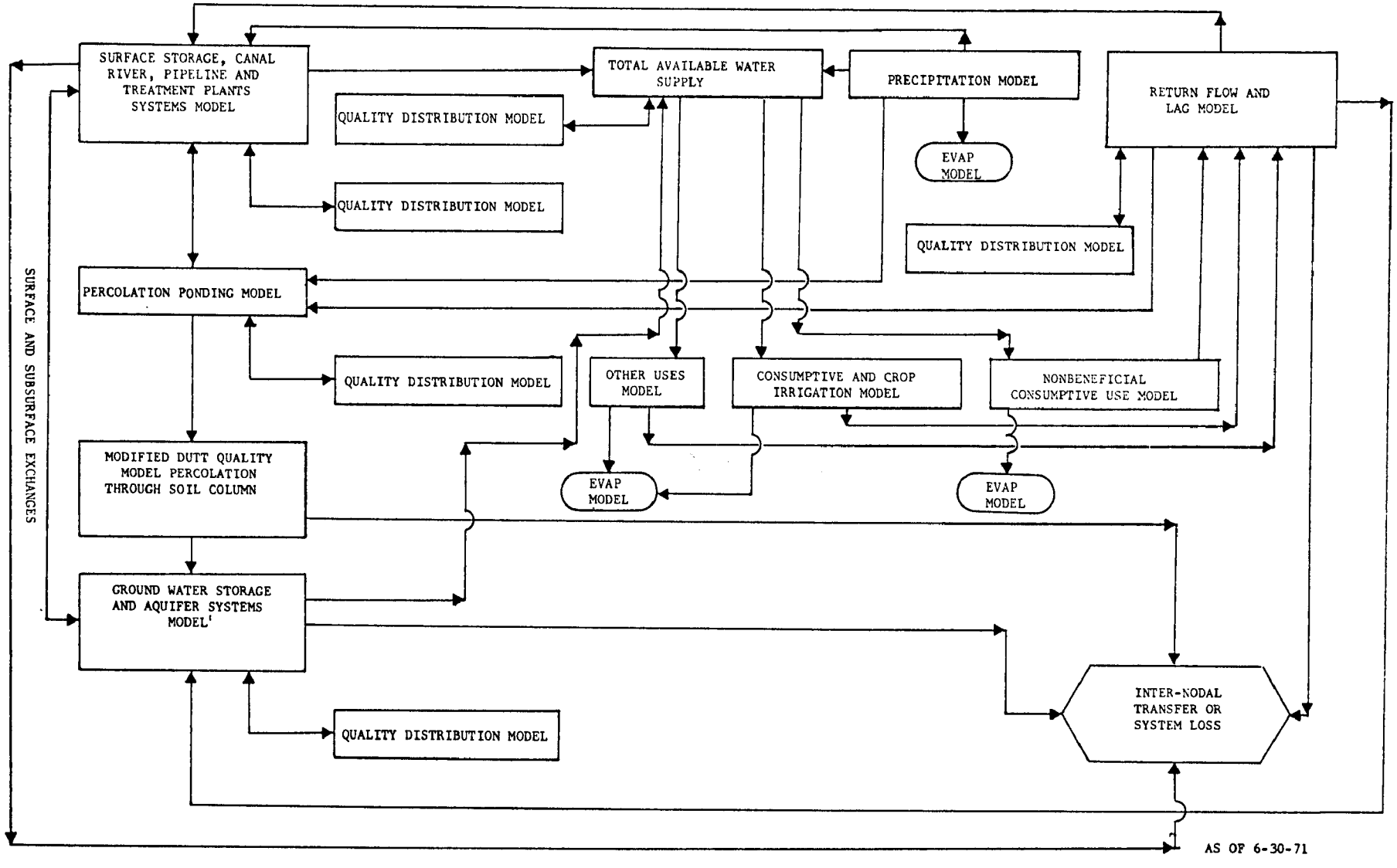


Figure 1: Hydraulic System for Simulation Submodel

3. Reservoir Storage Subroutine — In this subroutine an index is obtained from the control subroutine as to (a) mathematical relationships or area and capacity as functions of reservoir levels; also, from an index obtained from the control subroutine the computation enters (b) a subroutine to compute evaporation (multiple entry) as a fixed value, as a function of temperature and precipitation (deterministic), or as a multivariate probabilistic distribution function of temperature (ambient) and precipitation at a pseudo random probability level. With the use of another index obtained from the control subroutine, the computation enters (c) a multiple-entry subroutine to simulate water quality changes at 10 strata in the reservoir where the upper boundary of the first strata is the updated reservoir level from the last iteration and the lower boundary is fixed at a point of the lowest outlet elevation. The quality distribution of the water leaving the reservoir will be the average quality distribution for all strata above the reservoir level obtained at the completion of this at "ith" iteration. Constraint equations pertinent to the reservoir operation will be obtained as indices from the control subroutine.
4. Irrigation Demand Subroutine — This subroutine will also be a multiple-entry subroutine based upon indices obtained from the control subroutine where the irrigation demands will be used as constraints or as variables which include losses in the transmission added to the consumptive use requirement as obtained from the consumptive use subroutine which can be the Blaney-Criddle, Jensen-Haise (deterministic models) or a multivariate distribution of solar radiation, precipitation, and crop species (beneficial or nonbeneficial) and updated by number of acres irrigation (indices from control program).
5. Return Flow Subroutine — This is also a multiple-entry subroutine where return flow is simply the difference between the irrigation demand and consumptive use (with or without a time lag). Where the return flow can be directed to an internodal transfer (surface or a ponding facility) or is a loss to the system, the quality distribution of the return flow can be deterministic or probabilistic as distribution obtained from historic data of drain outflow, quantity and quality wise. A constraint equation will enter into the subroutine to determine violations of salinity standards, and at the "ith" plus one iteration the irrigation demand will be reduced to meet the salinity standard and in this case the reduction will not be considered as a shortage in maintaining the ideal irrigation demand.
6. Percolation Subroutine — This is a multiple-entry subroutine where an index as obtained from the control subroutine will indicate a lateral transmission at a particular level in the soil column and the lag time required as simulated in the ponding facility which is really a function of the flow rate (vertical) through the soil column. For example, if it takes 2 months for a unit of water to percolate from the surface down through the soil column to the aquifer, the water to be percolated will be held in the ponding facility for the 2-month period and the simulation to the soil column will take place during the next time interval. All water held in the ponding facility will be percolated through the soil column as a stepped-piston effect. The percolation subroutine is the original Dutt model with the use of modified algorithms. Figure 2, is a diagram of this part of the program.
7. Aquifer Subroutine — This is also a multiple-entry subroutine where an index obtained from the control subroutine first updates the aquifer quality and quantity wise with any lateral internodal transfers. At present, the quality distribution model for this transfer is a simple linear function. Constraint equations for each of the aquifers will be obtained as an index from control subroutine. No internodal transfers (lateral or vertical) will be made at the "ith" iteration until after the aquifer has been updated and considered as being in a static state. This update will also include

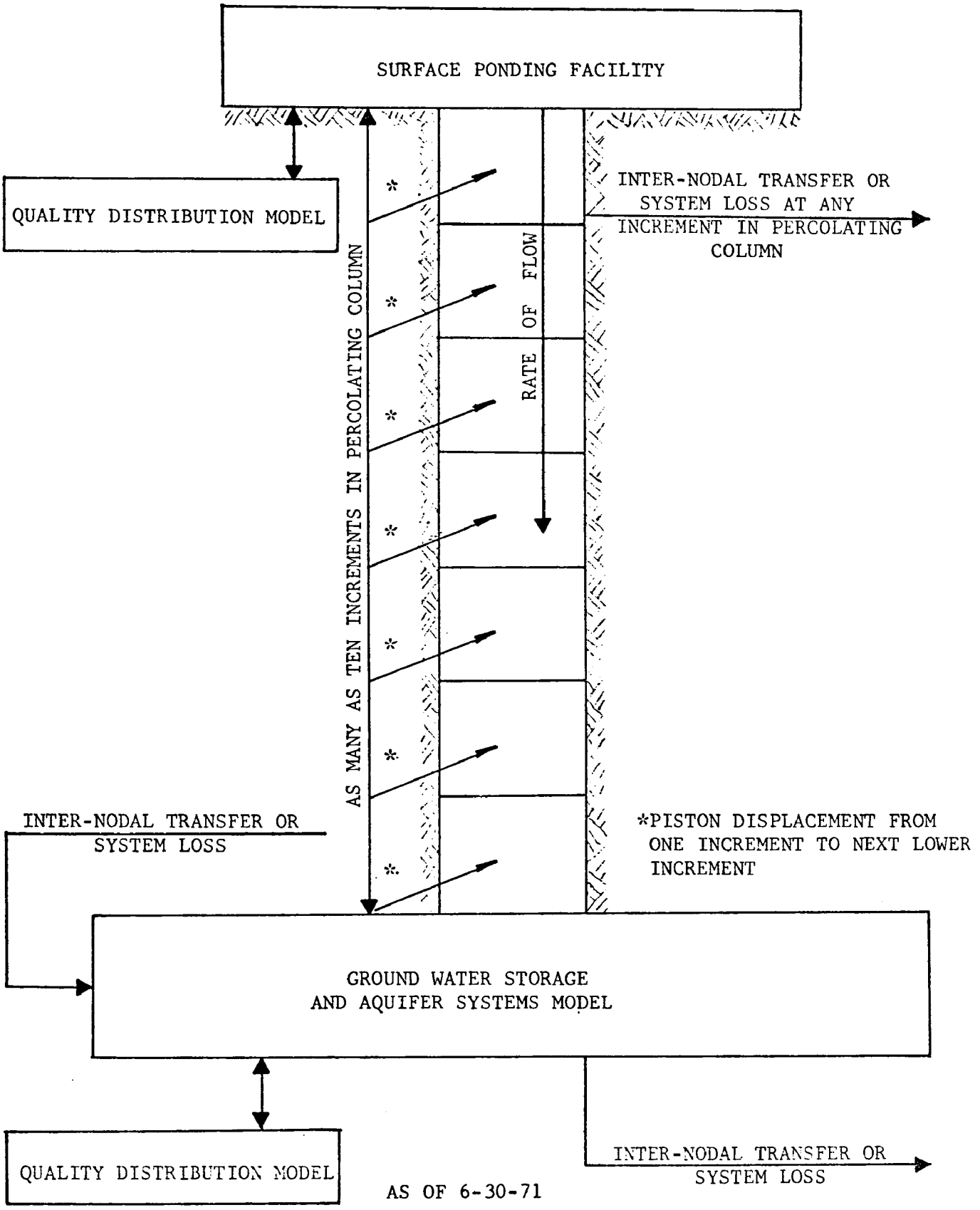


Figure 2: Detailed Diagram of Dutt's Percolation Model as Contained in Simulation Submodel

all waters as percolation through the soil column. At the present time the model of quality distribution for the percolated waters and those in the aquifer is simulated with the use of a simple linear function.

As mentioned earlier, all of the subroutines in the simulation submodel can be used indepently or collectively. Therefore, with the exception of physical demand constraints, these subroutines can be modified at will without interruption to the logical flow of the subject model or violation of the overall concept of the simulation submodel. Such modification will also not violate the concept of the complete systems model.

The computer output and input formats for the simulation submodel can be printed or graphical CRT representations. The output can also be modeled to set varied report objectives. Input and output subroutines will be designed as per the desires of the analyst and in all cases will not be included as an integral part of the systems model.

Irrigation Return Flow Simulation Model

In addition to the mathematical prediction model thus far described, an irrigation return flow simulation model has been developed that will permit prediction of return flow patterns for lands drained by tile drainage systems. This is a modification of a model that will be described later by Dr. Gordon Dutt. Both quantity and quality variations are predicted by the model. Where desired, these predictions will be incorporated into the overall system model.

In this separate program the process is treated as deterministic and the movement of water is traced through the soil system, starting at the soil surface and ending at the drains.

As presently utilized, this later "Dutt" program involves or requires the use of three other programs. The Dutt program itself consists of two programs, one an unsaturated flow model and the other a chemistry model.

The three associated programs are:

1. An irrigation scheduling program to obtain inputs for the unsaturated flow model.
2. A saturated flow model that transfers the percolation to the ground water to a drainage system.
3. A drainage system design program that adjusts the output of (2) above into a drainage outflow pattern.

The irrigation scheduling program was developed to predict timing and amounts of irrigations and is used in an applied research study to improve irrigation efficiencies. Climatic data (solar radiation, temperatures, wind movement, humidity, and precipitation), soil data (moisture holding capacity), and crop data (types, planting date, and harvest date) are used as input to the program. The program computes a running balance of soil moisture and schedules timing and amount of irrigation. Consumptive use is adjusted for soil surface wetting and the drying of soil profile.

In the Dutt program, infiltration into the unsaturated soil zone, the removal of water by evapotranspiration processes with depth, and the movement of water under unsaturated conditions are simulated by the numerical solution of a nonlinear form of Darcy's Law. This form arises when permeabilities and tension heads are taken as functions of the moisture content. Saturated flow is treated by combining a steady-state potential flow drainage solution with a transient solution to calculate the water table buildup due to intermittent recharge and the corresponding drain discharge. The steady solution is merely used to obtain the relationship between flow down a finite number of stream tubes.

The assumption is made that flow rates and consumptive use are independent of water quality. Consequently, quality considerations are treated separately once water movements are predicted. Processes modeled include ion exchange as well as precipitation and solution of ammonia, calcium, sodium, magnesium, bicarbonate, chloride, carbonate, and sulfate in both the saturated and unsaturated systems. Only base soils are treated. In addition various nitrogen transformations are also simulated under aerobic conditions. These transformations are relatively slow and must be treated as kinetic. Nitrogen uptake by plants is included.

A large number of inputs are required by the model. For a given group and site, those include:

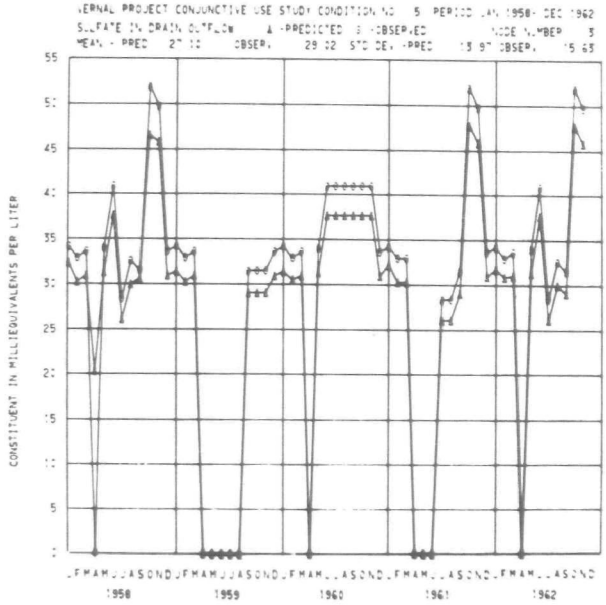
1. System Geometry
   Depth to barrier
   Depth to drains
   Drain spacing
   Drain filter design
2. Unsaturated Characteristics
   Conductivity-moisture content relationship
   Diffusivity-moisture content relationship
3. Saturated Flow Characteristics
   Permeability
   Specific yield
   Porosity
4. Initial Conditions
   Soil extract analysis for both saturated and unsaturated soils
   Initial moisture contents
   Initial water table position
   Initial quality of ground water in storage
   (These are not strictly necessary.)
5. Water Inputs
   Irrigation applications and dates
   Precipitation applications and dates
   Semimonthly consumptive use
   Root distribution
6. Quality Inputs
   Irrigation water chemical analysis
   Chemical fertilizer applications, dates, analyses and application technique
   Organic fertilizer applications, dates, analyses, and application technique
   Plant uptake of nitrogen
   Temperature data in soil profile

Inputs under Item (5) are determined by using climatic data, moisture holding capacities, and crop information when irrigation scheduling is practiced.

When combined with the saturated flow and the drainage system design programs the output includes moisture contents, water table positions, flowlines, and drain discharge for flow. Quality of the soil water can be monitored at the water table or at the drains. Accumulated pickup by the drains as well as yearly rates can also be computed. Output includes both the usual printed listings and graphical results (microfilm) produced by a cathode ray tube plotting system under control of the digital computer.

During applications of the model to the Vernal Unit, several inconsistencies in the basic data were found. The most serious was the estimated consumptive use and the explicit determination of the chemical exchanges in the return flow waters. The inconsistencies in data concerning consumptive use were dampened in the overall systems analysis by allowing the inconsistencies to accumulate in the aquifer storage facilities. All effort to obtain explicit or deterministic analyses of the chemical exchanges in the return flow waters was discarded in favor of statistical inference which measures the chemical exchanges on a probabilistic basis. It was found that the use of statistical inference enables the prediction of return flow chemistries, constituent by constituent, at about 92.5 percent level. To obtain data for the statistical inference study, it was assumed that all waters available for diversion, with the exception of extremes, were applied to irrigation and further, the measured aquifer chemistries from each node (drain outflow) represented the chemistry of the return flows. Even though there was some significant difference in the distribution functions, constituent by constituent, it was found that if the distribution function obtained for the chemical constituent of highest concentration was used, all other constituents could be estimated with a simple transform with respect to the fitting parameters. This technique was justified because of the low sensitivity of those constituents of lesser concentrations. It was found that not only had the daily sampling fluctuations been dampened by the longer time period of monthly reporting, but also in several cases, the supposedly observed data had been obtained for missing periods by simply using the mean as the expected value. This particular manipulation would also account for the inconsistency in the distribution function for the lower concentrated constituents.

At the conclusion of the above described analyses and with the use of statistical inference techniques, several simulations were made of the Vernal Unit using the conjunctive use model. In each of these simulations, parameters describing the allotment of inflow waters to each of the nodes were manipulated until the system was in balance hydraulically or quanti-


CONSTITUENT IN MILLIEQUIVALENTS PER LITER
1958
1959
1960
1961
1962

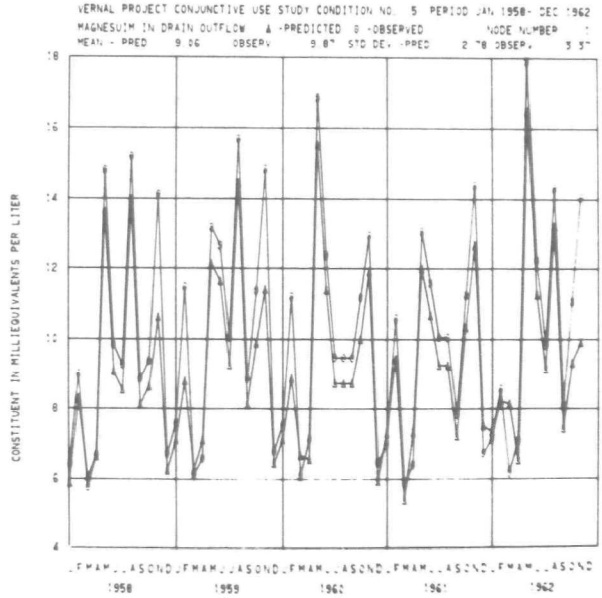
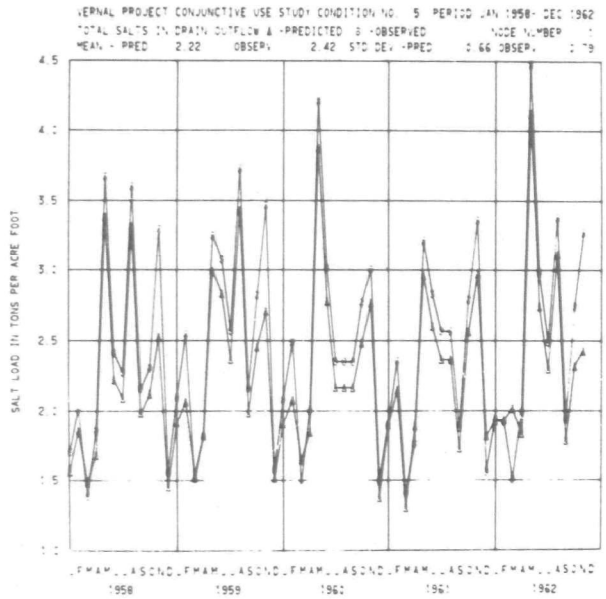

CONSTITUENT IN MILLIEQUIVALENTS PER LITER
1958
1959
1960
1961
1962

Figure 3.


SALT LOAD IN TONS PER ACRE FOOT
1958
1959
1960
1961
1962

tatively. The last of these simulations was one that compared predicted aquifer capacities with those as computed for the historic period 1958 through 1962. In each of the nodes, with the exception of one, it was found that a high rate of divergence existed between the aquifer capacities as observed and those that were predicted with the use of the model. The divergence was expected because the inconsistencies of consumptive use had been accumulated in the aquifer.

No effort was made to simulate waters percolating through the soil columns. This simulation was not required because of the very low sensitivity to the overall objective as provided by this type of simulation. Also, the rate of change of chemistry in the aquifer, time period by time period, was not significant. Subsequently, each of the analytical results of the Vernal applications with the use of the model depicted graphically by photographing on 35-mm film the image of the graph as projected on a cathode ray tube. Examples of the results of the graphical analysis are shown in Figure 3.

From these several applications, it can be concluded that the total objective in studying the Vernal area with the historic time sets had been satisfied. It was further concluded that the on-going sampling format of data in the Vernal Unit would have to be changed to render a more meaningful predictive model for the Vernal area. Some of the expected ramifications of the data presently being collected with the changed sampling format are: (1) a lower level of predictability with the use of statistical inference because of the impact of the true sampling fluctuations, (2) a higher degree of consistency in the estimate of consumptive use, and (3) the elimination or at least a considerable reduction in the divergences of the experienced and predicted aquifer capacities.

Model Testing with Additional Data

Data were collected on the Vernal Unit during the 1971 irrigation season and will be collected again during the 1972 irrigation season. The model will be tested using these data.

It is also planned that data collected by the Geological Survey on the Cedar Bluff Unit in cooperation with the Kansas State Department of Health will be used to test the model and determine if the concepts are valid under a different set of geologic and hydrologic conditions. A substantial amount of data has been collected over a period of about 6 years and this covers the entire period since irrigation started on the Cedar Bluff Unit.

Data collected on the Grand Valley Project right here in Grand Junction will be analyzed to determine if it would be feasible to test the model under these conditions.

CONCLUSIONS

Although model testing is not complete and development of all the mathematical submodels is not complete, it appears at this point that a satisfactory model has been designed to predict the mineral quality of return flow from irrigation projects. Completion of the submodels will extend capability to impact analysis, optimization and best plan.

The implication for water resource projects is that farm operation could be designed to use the least amount of water, return the smallest, amount of salt to the river and permit the farmer to obtain the greatest possible return from his farm.

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Modeling Subsurface Return Flows in Ashley Valley

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ABSTRACT

One possibility for optimizing the control of the quality of irrigation return flow is to properly manage the application of irrigation water. Such management depends upon knowledge of water and salt movement through the root zone of the crops. Two models are presented for flow of water and salt through the soil with extraction of water by evapotranspiration. One model was designed for use as an irrigation management tool while the other model was initially intended to provide a detailed understanding of the water and salt flow through the soil. Field testing of the models indicates that the best management model will probably result from a combination of the two present models. Timing of irrigation has been tested as a management variable. With all other conditions the same, the model predicts that as the time interval between irrigations increases the season totals of salt removed from the root zone, salt remaining in the profile, and water required for leaching tend to level off. However, the interval between irrigations has a significant effect upon when the salt is removed during the season. The results indicate that managing irrigation for control of return flow quality requires good control of depth and timing of irrigations.

INTRODUCTION

The recent (February 1972) session of the Federal-state Enforcement Conference on the Colorado River in Las Vegas, Nevada, re-emphasized the problem of salinity in the Colorado River Basin. The considerations of the session were based mainly upon a report by Regions VIII and IX of the United States Environmental Protection Agency (EPA) entitled "The Mineral Quality Problem in the Colorado River Basin."[1]

In 1960, the Colorado River Basin Water Quality Control Project was established and charged with the responsibility for identifying and evaluating the most critical water pollution problems in the Basin. As a result of early Project investigations, salinity was identified as a pressing water quality problem. The report[1] summarizes the results of the salinity investigations begun in 1963. Included in the conclusions of the report are the following:

1. Salinity is the most serious water quality problem in the Colorado River Basin.
2. Salinity concentrations in the Colorado River system are affected by two basic processes: (a) salt loading, the addition of mineral salts from various natural and man-made sources; and (b) salt concentrating, the loss of water from the system

through evaporation, transpiration, and out-of-Basin export.

3. Salinity control in the Colorado River Basin may be accomplished by the alternatives of: (a) augmentation of Basin water supply; (b) reduction of salt loads (including improvement of irrigation and drainage practices); (c) limitation of further depletion of Basin water supply.

This paper deals with the possibility for controlling the quality of irrigation return flow by proper management of the application of irrigation water. Such management depends upon knowledge of water and salt movement through the root zone of the crops. Two different models were developed for describing flow of water and salt through the soil with extraction of water by evapotranspiration. The two are called "simplified" and "detailed" models for the purposes of this paper. Each model is discussed in considerable detail below.

The simplified model was intended to provide a tool for irrigation management. It was formulated to require a small amount of computer time and a minimum of field data as input and to allow consideration of a wide range of factors affecting the quality of irrigation return flow. It was expected that the model would predict gross effects rather than the detailed ones. The simplified model will be updated and improved by considering factors determined to be necessary for description of water and salt movement adequate for irrigation management.

The purpose for the detailed model was to understand the specifics of simultaneous water and salt flow through the crop root zones. This model will help in the analysis of field measurements and serve as a basis for determining how much detail must be incorporated into the simplified model to obtain an adequate tool for irrigation management for controlling the quality of drainage effluent.

Simplified Model

Description

The simplified model is based upon the concept of temporarily storing salt in the soil profile and leaching only when necessary to prevent the salt from becoming too concentrated. The root zone of the crop is divided into "n" layers of equal thickness. A constraint is set on the allowable concentration in each layer. The calculation begins by adding to the top layer sufficient water to fill the available soil water reservoir for the entire root zone. The computer program calculates the movement of water and salt from layer to layer through the profile. If the concentration constraint of any layer is exceeded, then the computer program iterates by adding more water until the constraint is satisfied. After the proper depth of water to be applied in a given irrigation has been determined, the final conditions existing in the profile (after passing of the time interval between irrigations) become the initial conditions for the next irrigation. Thus, the entire irrigation season is covered in one computer run.

The crop is assumed to extract pure water leaving the salt behind in the soil moisture. The water and salt are assumed to move downward through the soil — lateral and upward movement are not allowed. The model uses a so-called "field capacity" concept; i.e., after an irrigation, downward drainage of water occurs until the soil reaches the upper limit of field moisture, after which all downward movement of water ceases. The upper limit of field moisture must be determined for each soil layer under conditions to be encountered in the field. For layers near and including the water table, the upper limit will be the saturated moisture content. Whenever the term "field capacity" is used in this paper it means the upper limit of field moisture as defined above.

Figure 1 shows a typical layer of soil with the symbols defined as follows:

DX is the thickness of the layer.

ET is the total depth of water extracted from the layer by evapotranspiration.

d_e is the depth of water entering the layer.

θ_o is the initial moisture content of the layer.

θ_{fc} is the moisture content when the soil is at field capacity.

θ_f is the final moisture content existing in the layer at the end of the irrigation interval.

d_l is the depth of water leaving the layer.

C_e, C_o, C_{fc}, C_f, and C_l denote the corresponding concentration of salt in the water.

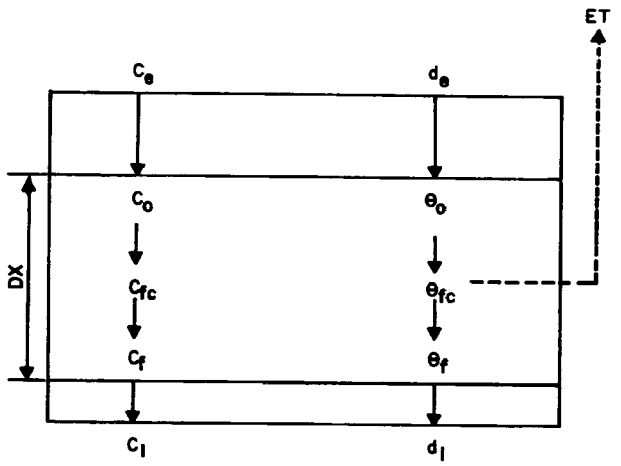

Figure 1: Typical Layer of Soil in the Root Zone in Simplified Model

The movement of water is treated in a fairly simple manner. Since drainage from a particular layer ceases when the soil reaches field capacity, the depth of water leaving the layer is equal to the depth entering minus the depth required to bring the soil layer to field capacity. After the soil reaches field capacity, the only loss of water from the layer is by evapotranspiration. Thus, in general, the final moisture content of the layer is determined from the difference between the amount of water at field capacity and the amount extracted by evapotranspiration for the period between irrigations.

The movement of salt is more difficult to describe. Since it is assumed that evapotranspiration removes salt-free water from the layer, the mass of salt in the layer does not change as the moisture content is reduced from θ_{fc} to θ_f; however, the salt becomes more concentrated in the water remaining in the layer ($C_f > C_{fc}$). A mass balance on salt of any layer can be written as

$$C_e d_e + C_o d_o = C_l d_l + C_f d_f \qquad [1]$$

in which d_o and d_f are depth of water corresponding to θ_o and θ_f, respectively. All terms in Eq. 1, except C_l and C_f, are known or can be determined. The final concentration, C_f, is not allowed to become greater than a certain value (concentration constraint) and can be solved for only if C_l is known.

Using soil samples from the field, a laboratory method of calibrating the soil to estimate C_l was developed.[2,3] This calibration technique was based upon a leaching factor, LF, defined as

$$LF = \frac{C_l d_l}{C_o d_o + C_e d_e} \qquad [2]$$

It was concluded from the laboratory data (See Table 1) that the measured leaching factor could be described as a function of d_l and θ_o. From the measured leaching factor and Eq. 2, C_l can be determined and from Eq. 1, C_f can then be found. The leaching factor function is contained in a subroutine, thus only the subroutine needs changing to model a different field soil.

TABLE 1

Summary of results from laboratory technique of soil calibration to determine leaching factor (LF) for Hullinger farm soil

Effluent Ratio (d_l/d_{fc})	*Leaching Factor (LF)* $\theta_o = 0.05$	$\theta_o = 0.15$	$\theta_o = 0.20$
0.1	0.201	0.118	0.084
0.2	0.275	0.192	0.143
0.3	0.303	0.261	0.195
0.4	0.365	0.312	0.272
0.5	0.412	0.359	0.303
0.6	0.432	0.393	0.353
0.7	0.461	0.441	0.394
0.8	0.495	0.461	0.422
0.9	0.520	0.485	0.462
1.0	0.541	0.519	0.483
1.25	0.586	0.572	p.553
1.50	0.633	0.621	0.606
1.75	0.681	0.662	0.652
2.00	0.719	0.702	0.681
2.25	0.741	0.733	0.713
2.50	0.763	0.757	0.735
2.75	0.787	0.771	0.762
3.00	0.798	0.793	0.776

Input Data

The data necessary as input to the computer for the simplified model include:

1. The number and thickness of the soil layers.
2. The concentration of salt in the irrigation water.
3. The length of the season and the interval between irrigations in days.

4. The number of days between the initial soil sampling and the first irrigation.
5. The moisture content and concentration of salt in each layer at the initial sampling date.
6. For each soil layer the fraction of total evapotranspiration, the upper and lower limits of field moisture content, and the maximum allowable concentration of salt in the soil moisture.
7. The daily evapotranspiration for the entire irrigation season.
8. The leaching factor function (as a subroutine) for the particular soil.

Output Data

A selection of the desired output is made from the following:

1. All input data.
2. Immediately prior to the first irrigation and after each irrigation interval, the salt existing, the moisture content, and the salt concentration, respectively, for each layer, and the total salt existing in the profile.
3. For each irrigation, the depth of water applied, the amount of salt leaving the root zone, the amount of leaching water, the leaching requirement in percent of applied water, and the evapotranspiration for the interval following the irrigation.
4. The totals for the entire season of depth of irrigation water applied, amount of salt leaving the root zone, amount of leaching water, leaching requirement, and evapotranspiration.

Results of Field Tests

The model required verification or testing in the field. An approach to field testing might have been to run the model for the entire season to produce an irrigation schedule and conduct the field work according to this schedule. Maintaining a strict schedule in the field would be difficult. The irrigation water was not available on a strict demand nor was its quality accurately predictable. An accurate forecast of the daily evapotranspiration was not available. The above approach to field testing was abandoned. Instead, the field work was scheduled according to a reasonable overall plan and necessary data for testing the model were collected. The operation of the computer program was changed so that both the salt concentration and depth of irrigation water were input for each irrigation and the flow of salt and water was simulated irrigation by irrigation through the season. The iteration of applying water to maintain salt concentration of the soil moisture below a pre-determined level was suppressed.

The model was tested using field data collected during 1971 on the Hullinger farm near Vernal, Utah. The crop was alfalfa which was seeded with oats as a nurse crop in the Spring of 1970. Because of a relatively light stand of alfalfa, additional seed was applied without destroying the existing alfalfa early in the Spring of 1971. In order to assure good germination of this reseeding, rather frequent irrigations were applied to the entire field until the first cutting in June. The data for field testing the model were gathered for the rest of the season. The salt and moisture contents of the soil profile were determined on June 22. These data furnished the initial conditions for computations with the model. Additional field samples were taken on August 3 and September 9. Figure 2 shows some results of the field tests of the simplified model. Each of the measured values is the average of measurements at six separate locations. Complete detail of the field tests will be included in a research report which is presently in preparation.

The results for moisture content shown in Figure 2 are reasonable since the soil profile was considered homogeneous in the calculations. The model is not limited to homogeneous soil, but further testing would have to be conducted. For instance a larger value of field capacity at depths of 1.5 and 3.5 feet would result in better agreement of calculated and measured moisture contents.

The electrical conductivity (EC) data comparison of Figure 2 is not as encouraging. Rather poor agreement is shown between calculated and measured results. Reasons for the disagreement can be either inaccuracy of the measured data or inadequacy of the model. Both of these reasons are discussed below.

Table 2 shows a comparison of the measured and computed amount of salt (expressed as tons per acre) in the soil profile when the field samples were taken. To convert electrical con-

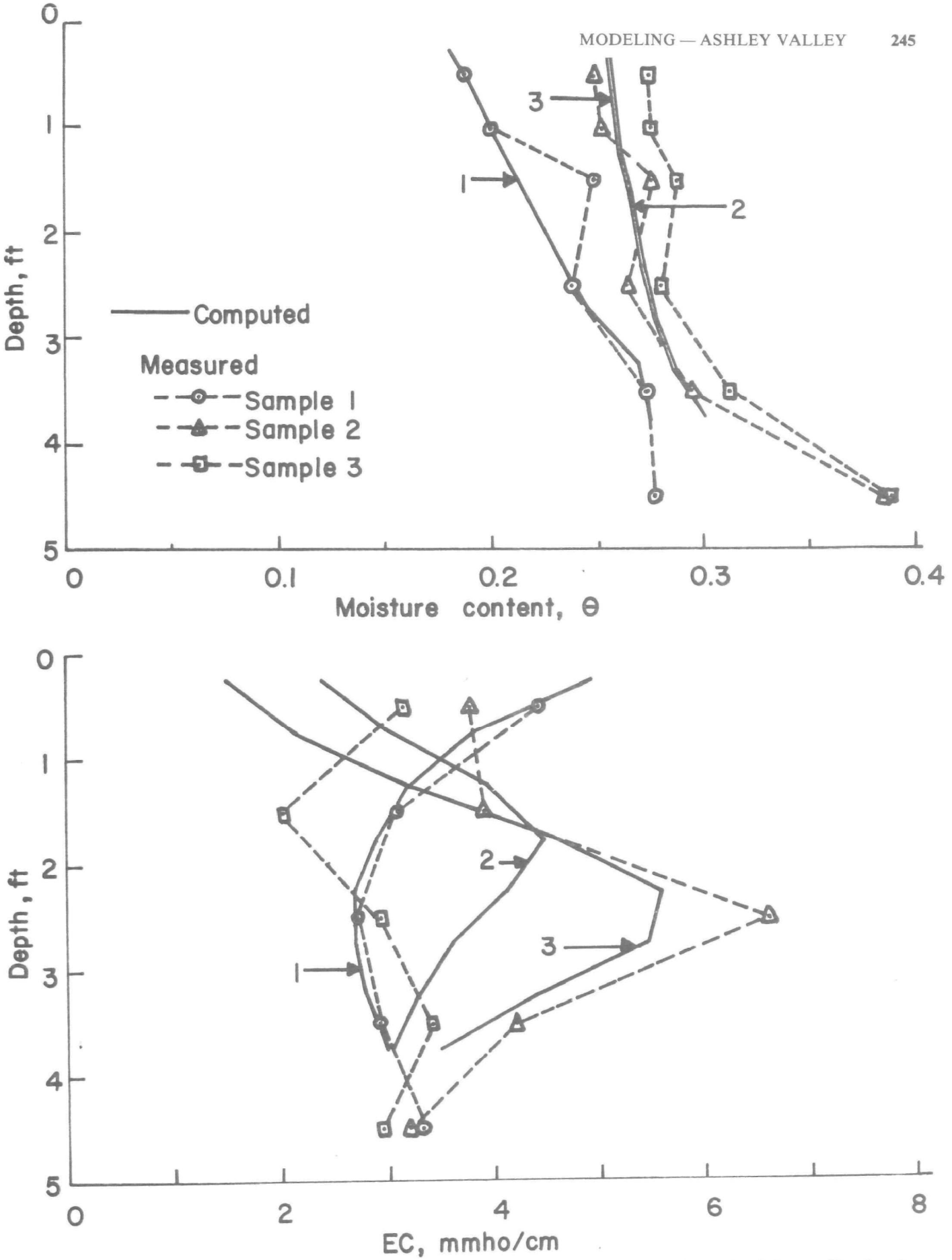

Figure 2: Comparison of measured and predicted moisture content and electrical conductivity profiles for simplified model in 1971 for alfalfa

TABLE 2

Comparison of measured and computed amount of salt in the soil profile when field samples were taken (Sample 1 - June 22, Sample 2 - August 3, Sample 3 - September 9)

Depth (ft)	Sample 1 Measured (T/Ac)	Sample 1 Computed (T/Ac)	Sample 2 Measured (T/Ac)	Sample 2 Computed (T/Ac)	Sample 3 Measured (T/Ac)	Sample 3 Computed (T/Ac)
0-1	0.72	0.70	0.82	0.60	0.74	0.40
1-2	0.67	0.57	0.94	0.97	0.50	0.90
2-3	0.56	0.56	1.52	0.92	0.71	1.31
3-4	0.69	0.69	1.07	0.81	0.93	1.00
TOTAL	2.64	2.52	4.35	3.30	2.88	3.61

ductivity of the soil solution to equivalent tons per acre of salt, one mmho/cm was taken as equal to 640 ppm of salt.[4] This constant factor was used for all measured data and in the computer program. Table 3 shows the irrigation water and imported salt during the periods between field samples. Between sample one and sample two a total of 9.83 inches of irrigation water containing 0.88 tons of salt per acre was applied. The model showed a discharge of 0.10 ton per acre during the period giving a mass balance on the salt (2.52 + 0.88 – 0.10 = 3.30). The measured data showed a net gain of salt during this period of 0.83 ton per acre (2.64 + 0.88 + Gain = 4.35). The only possible source for this net gain would have been upward flow of moisture from the water table. If we assume that the EC of the water in the saturated zone is 3 mmho/cm, which is about the value at 4.5 feet depth as shown in Figure 2, the net upward movement of water from the water table would have had to have been 3.8 inches. More likely the water below the water table had EC equal to about 1.8 mmho/cm giving an estimate of the upward flow of 6.4 inches. Similar calculations performed for the period between sample two and sample three show a loss of water and salt from the root zone to the water table. The net salt loss would have been 1.93 tons per acre in order to have 2.88 tons per acre remain at the time sample three was taken. This would have meant a downward percolation of 14.8 inches of water at an EC of 1.8 mmho/cm or 8.9 inches if EC = 3 mmho/cm. However, only 7 inches were applied as irrigation water between sample two and sample three.

TABLE 3

Irrigation water and salt imported between June 22 and September 9 by sample period

	Depth (in)	Conc. (mmho/cm)	Salt (T/Ac)
	Samples 1 to Sample 2		
	3.00	1.27	0.28
	3.00	0.98	0.21
	3.00	1.53	0.33
	0.83	1.00	0.06
TOTAL	9.83		0.88
	Sample 2 to Sample 3		
	4.00	0.94	0.27
	3.00	0.86	0.19
TOTAL	7.00		0.46

The above discussion points out some inconsistencies in the measured salt content of the soil profile. Perhaps these are sufficient to explain the differences shown in Figure 2. However, the simplified model has some assumptions which are also subject to question. Operation of the computer program has shown the results to be very sensitive to the leaching factor. Better methods for obtaining this function are needed. The model neglects upward movement of soil moisture and long-term downward movement. The root extraction pattern is difficult to obtain directly in the field. More field data on bulk density and the upper limit of

field moisture as functions of depth in the soil profile might improve agreement between actual conditions and those predicted by the model.

Although good field verification of the simplified model has not yet been obtained, the model is expected to predict general trends and influences of various factors upon water and salt movement fairly well. Use of this model to predict effects of certain factors on the quality of irrigation return flow is discussed later in this paper.

Detailed Model

Description

This model considers the details of soil water and salt flow in small increments of depth and time. The general water flow equation, which is solved by a numerical approximation, for each increment of time and space is

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(K_\theta \frac{\partial H}{\partial z} \right) + A(z) \qquad [3]$$

where θ is water content, H is hydraulic head, z is depth, K is hydraulic conductivity, t is time and A(z) is root extraction. This model is quite general and will account for unsaturated or saturated flow either up or down or in combination.

The salt flow component of the model considers mass flow of salt, exchange and precipitation and solution of $CaCO_3$ and $CaSO_4$. The mass flow is computed from a solution of the water flow equation after which corrections are made for exchange, precipitation and solution.

As presently used the model does not consider hysteresis or layered soil although both of these have been considered earlier.[5,6] Further assumptions are made that the soil properties, primarily the hydraulic conductivity-water content relation and the pressure head-water content relation do not change with time (there is no change in soil structure).

This model also requires some assumption regarding the partitioning of potential evapotranspiration into potential transpiration and potential evaporation directly from the soil. At present this partition is done rather crudely based on an estimate of percent of cover of the plant.

Input Data

The input data needed are as follows:

1. Hydraulic conductivity-water content and pressure head-water content tabular data covering the range of water content to be encountered during the period of interest (basic soil property).
2. Plant water potential below which the plant wilts and the actual transpiration will be less than potential transpiration (basic plant property).
3. Air dry and saturated soil water contents (basic soil data).
4. Root distribution with depth (active roots for adsorbing water) for the period. At present the model has no provisions for changing this with time (basic plant property).
5. Water content-depth tabular data at the beginning (initial conditions).
6. Chemical composition-depth tabular data at the beginning (initial conditions). This involves knowledge of the chemical analysis of the important chemical species. At present we consider Ca, Mg, Na cations and Cl, SO_4, and CO_3 anions.
7. Potential transpiration and potential evaporation rate or potential irrigation or rainfall rate as a function of time for the period (boundary conditions).
8. Chemical composition of the irrigation or rain water (boundary condition).
9. Presence or absence of a water table at the bottom of the soil (boundary condition).

Output Data

The type of output data that is available is almost unlimited. Consequently, a selection of the desired data is made from the following:

1. Soil water content and pressure head vs. depth and time during the period.
2. Chemical composition of the soil solution vs. depth and time during the period.
3. Estimated evaporation and transpiration as functions of time.
4. Water flow into the water table or up from the water table as a function of time.
5. Chemical composition of the water going into the water table or up from the water table as a function of time.

6. Estimated plant water potential as a function of time.

Results of Field Tests

The model was tested in the field at Vernal, Utah, in 1970 and 1971. Figure 3 shows a comparison of water content-depth profiles at the end of a 9-day run in 1970 on oats seeded to alfalfa. No actual measurements of the root extraction function were made so Figure 3 was

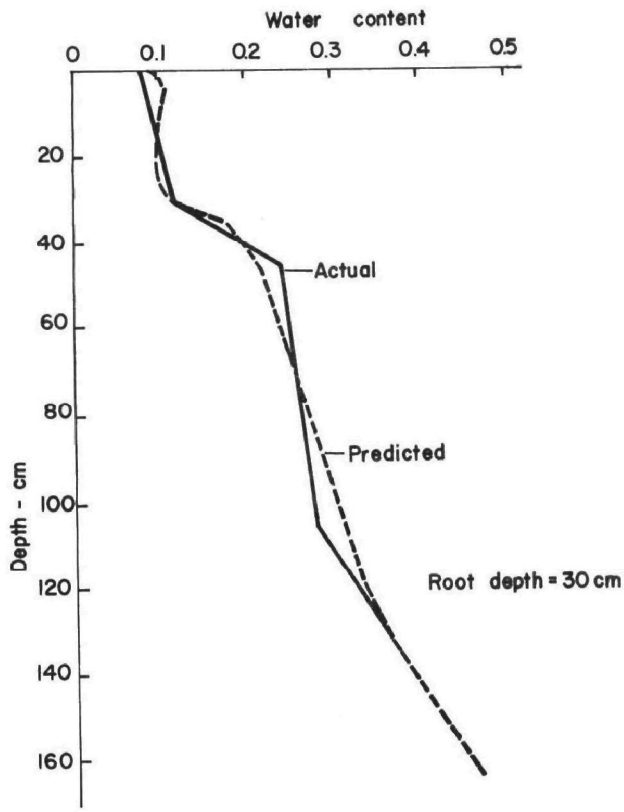

Figure 3: Comparison of water content profiles as predicted and measured for oats in 1970

computed using the assumption that the roots were in the top 30 cm. The data of predicted and actual measurements of soil water content are quite close. However, this agreement using estimated root distributions in 45 and 60 cm depth of root zones was not as good.

Figure 4 shows a comparison of potential, actual and predicted ET using the three root depth distributions. The 30 cm root extraction model predicted 4.9 cm cumulative ET which was 0.4 cm less than actual (measured) ET. The 45 and 60 cm root extraction models predicted 5.8 cm cumulative ET which was 0.5 cm more than actual. Thus, it would appear from these data that the true root distribution depth was

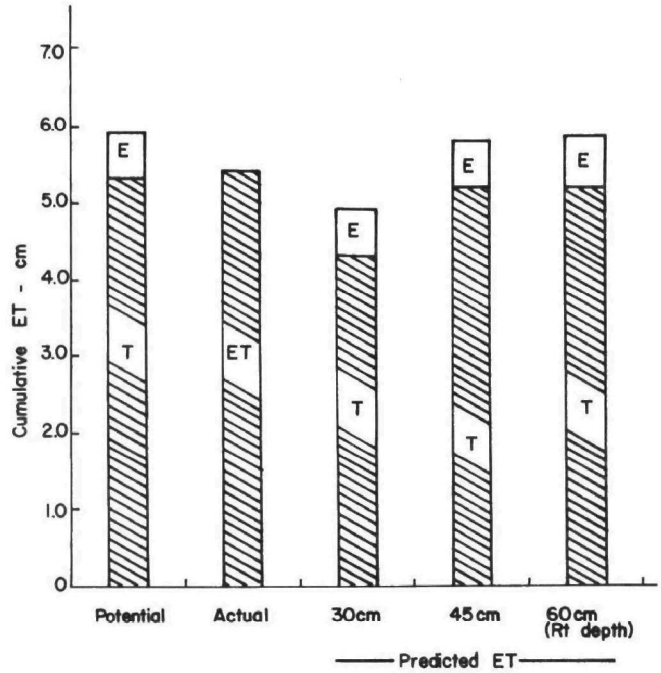

Figure 4: Comparison of actual, potential, and predicted evapotranspiration using three different root distributions for oats in 1970

between 30 and 45 cm assuming other variables used were correct.

Figure 5 shows a comparison of actual and predicted upward flow from the water table. At the end of the 9-day period actual upward flow was 2.1 cm which compares with 2.2, 2.3 and 2.7 cm predicted by the 30, 45 and 60 cm root extraction depths, respectively. From these

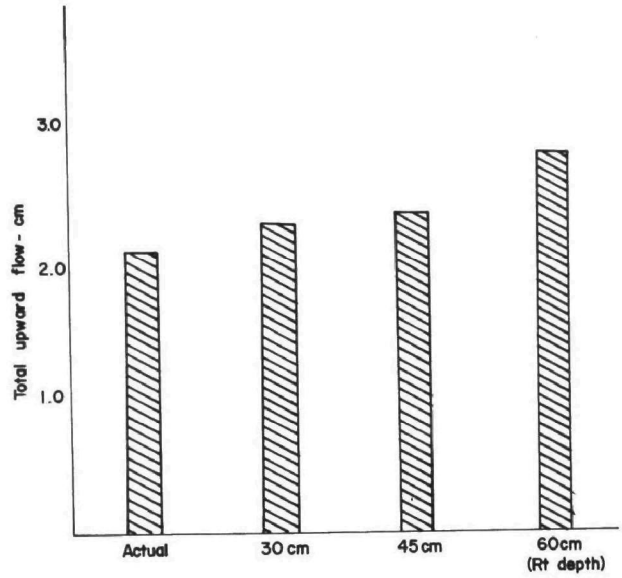

Figure 5: Comparison of actual and predicted upward flow from the water table for oats in 1970

data the 30 cm root extraction depth appears to give the most correct values.

Much more data were collected in 1971 with alfalfa as the crop. Figure 6 shows a comparison of water content profiles as measured and predicted. The data show best agreement on July 7 and June 22 which were several days after any water addition. The poorest agreement is on June 29 and July 10 which are right after irrigation.

Figure 7 shows a plot of water content as a function of time for the predicted and measured values. The agreement is very good with no apparent "growth" of errors. Because of experience in 1970 with water flow up from the water table, considerably more irrigation water was added in 1971 to get more downward flow. Consequently, the actual evapotranspiration and potential evapotranspiration were the same for this year. Thus, the agreement may be partially due to the "forcing" of the water removal by evapotranspiration to be the same as measured.

However, there were no such constraints on the water flow up or down from the water table. Figure 8 shows the water flow there as compared to the measured data at several times during the year. The data show some difference between the predicted and measured values of up to 4 cm. There does not seem to be any growth of errors with time.

In summary, regarding the water flow data, the model seems to predict well. It appears to sufficiently describe the system that subtle influences, like water flow up instead of down, from a water table are detected.

The data on chemical composition of the water within the soil and drainage water are not as satisfying. The field data showed very little change in chemical composition of the water in the soil or drainage water during the normal course of the season. Consequently, it was difficult to really test the model since nothing very different was occurring. Figure 9 shows the predicted depth and salt concentration of the drainage water during a period late in 1971.

Field attempts were made to alter the chemical composition of the irrigation water in several instances in 1971. However, most of the changes were small and it was difficult to measure any effect in the field. Figure 10 shows a comparison of measured and predicted data for a problem with dry salt added to the surface layer before irrigation. The predicted salt concentration profiles right after irrigation and several days subsequent to irrigation are also given. The predicted data show the salt build-up at the surface due to evaporation and the increase in concentration due to root extraction of water. Figure 10 also shows the predicted salt concentration and that measured from electrical conductivity of water extracted 324 hours after irrigation. The agreement is fairly good with evidence that the concentration peaks are different by 15 cm. This difference is within the error of the field measurements, however.

Implementation of Results

The best model to use for managing irrigation to control quality of drainage water is probably a combination of the two models presented above. It is believed that the simplified model can adequately evaluate the effect of certain parameters upon the quality of drainage water. Figure 11 shows the results predicted for a hypothetical problem with irrigation intervals of 20 and 8 days, respectively. For a period of 121 days, irrigation water with constant EC = 1.5 mmho/cm was used and the EC of the soil moisture was not allowed to exceed 6 mmho/cm. Leaching water was applied only when needed to maintain the EC of the soil moisture at or below this level during any interval between irrigations. The 121-st day was included to make a valid end point for comparison. An irrigation occurred on the 121-st day with no subsequent ET. Thus all computer runs for the different intervals between irrigations began with the same moisture deficit and ended with the soil moisture at field capacity. For the 121-day period, intervals between irrigations of 2, 3, 4, 5, 6, 8, 10, 12, 15, and 20 days were used. A 24-day interval dried the soil below the wilting point somewhere in the season and hence was not acceptable.

Figure 11 shows the trend of longer intervals between irrigations releasing salt from the root zone earlier in the season and over a longer period of time than the shorter intervals. This trend was evident by considering all the intervals but space does not permit inclusion of results for each interval here. Figure 12 shows the

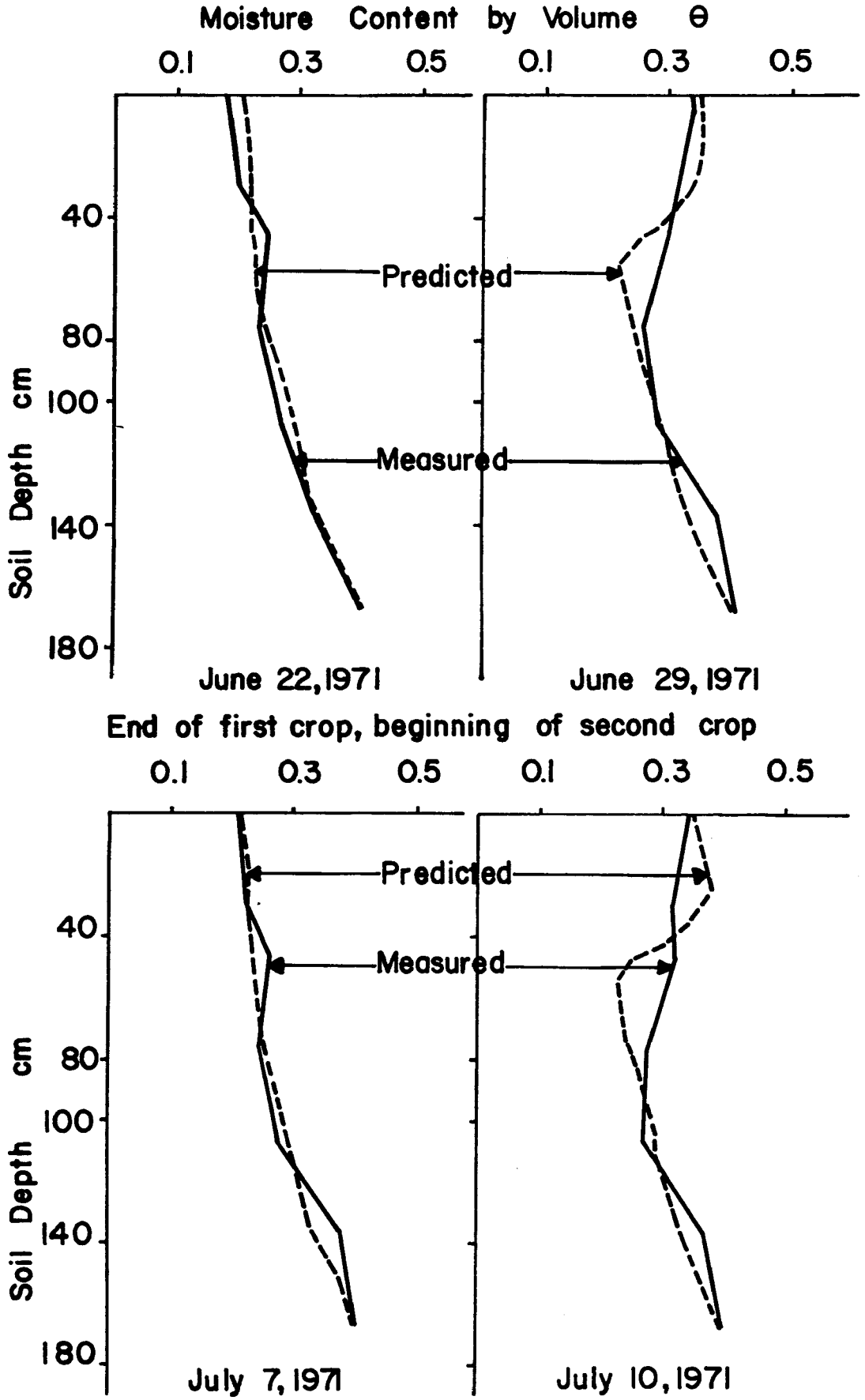

Figure 6: Comparison of predicted and measured water content profiles in 1971 for alfalfa

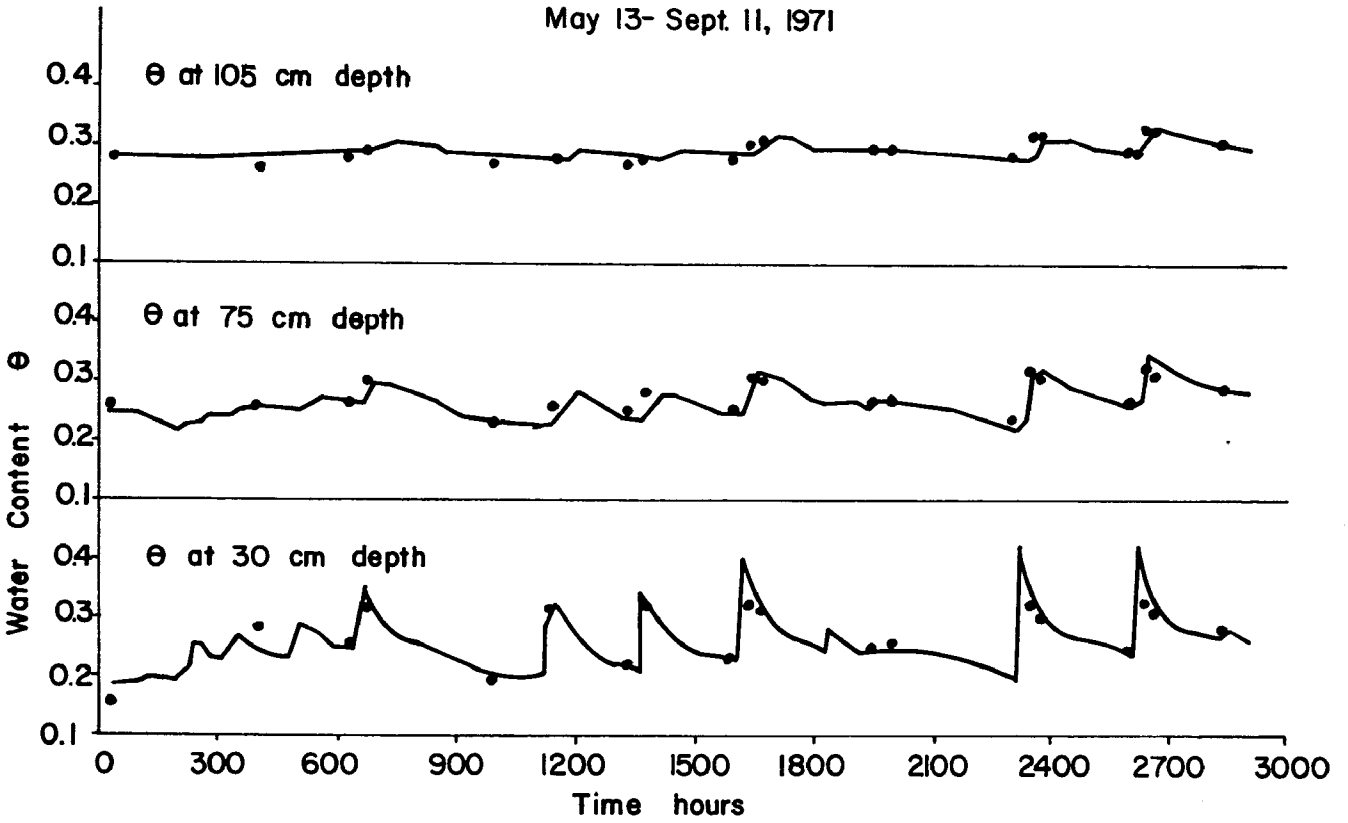

Figure 7: Comparison of predicted (solid lines) and measured (dots) water content at three depths for alfalfa in 1971

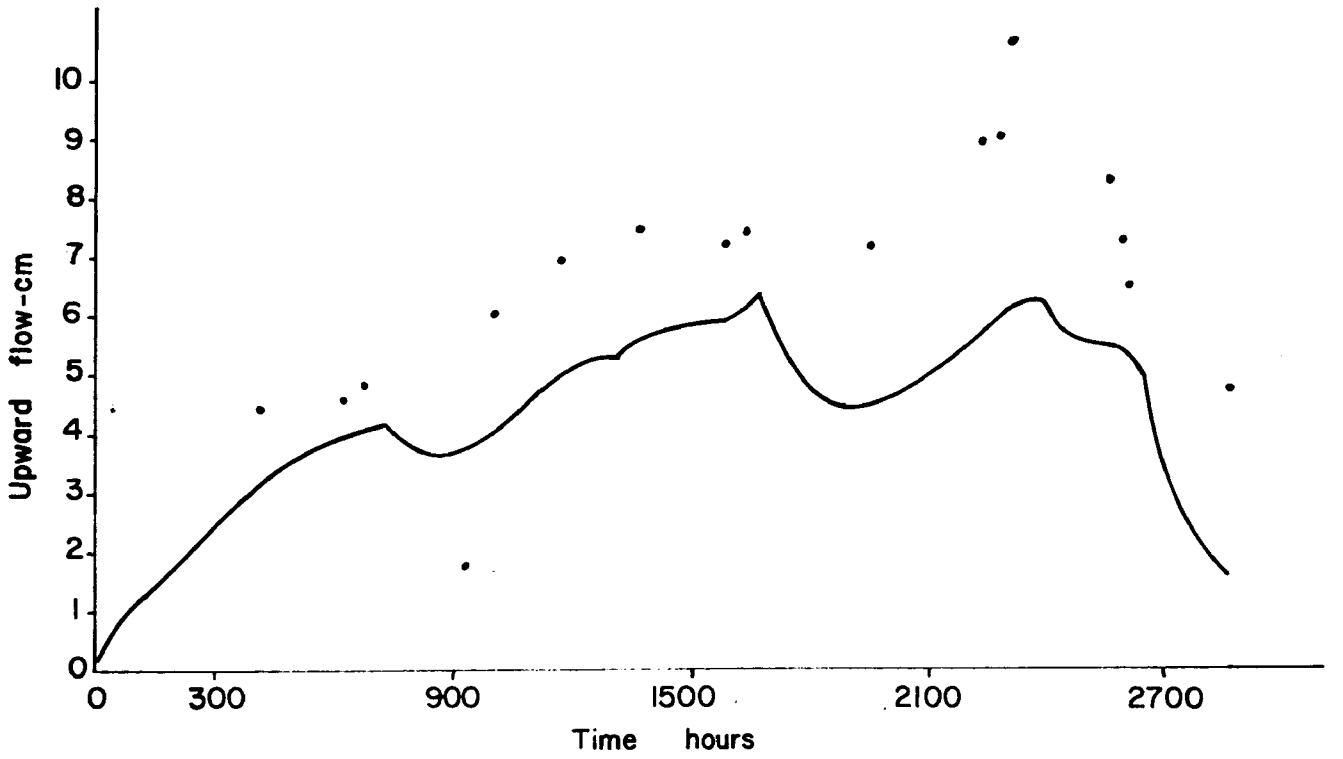

Figure 8: Comparison of predicted (solid curve) and measured (dots) upward flow for alfalfa in 1971

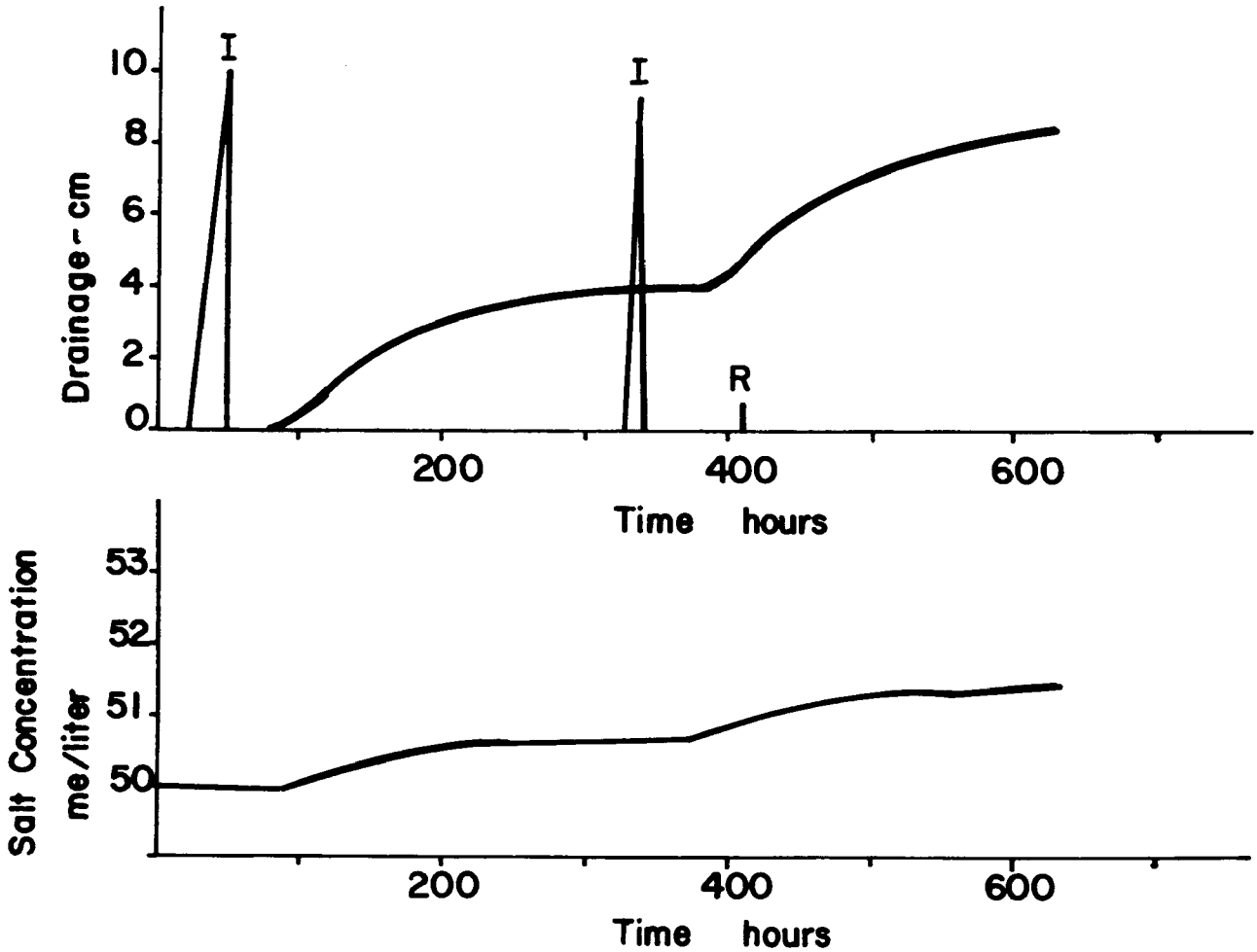

Figure 9: Predicted drainage and salt concentration of the drainage water for a period in 1971

results at the end of the 121-day season as a function of the interval between irrigations. The very short intervals do not require much leaching water and store a maximum amount of salt in the profile during the season. As the interval increases the leaching water reaches a maximum after which it drops off slowly. Coincident with the leaching water maximum, the salt removed from the root zone tends to level off as does the total water applied. The salt remaining in the profile continues to decrease although not very significantly. The important aspect from a management standpoint is that there is a considerable range of irrigation frequencies over which seasonal results do not change significantly. However, the time of salt discharge during the season is affected by different irrigation frequencies.

The above example was produced with the simplified model. The detailed model or the best management model could be used to study these same effects.

The above results indicate possibilities for control of drainage water quality as it leaves the root zone. On a valley-wide basis two possible alternative modes of management might be: (1) Irrigate different farms at different frequencies so as to maintain a nearly constant quality of drainage effluent during the season; or (2) Irrigate all farms at nearly the same frequency so as to peak the salt discharge at some convenient time. This peak of salt discharge might be diverted to an evaporation basin or other suitable salt sink in areas where man-made drainage systems are extensive.

Considerable further work is needed in order to predict the fate of the water after it leaves the root zone until it arrives as return flow in the stream or groundwater body. Study must be given to factors such as residence times, travel

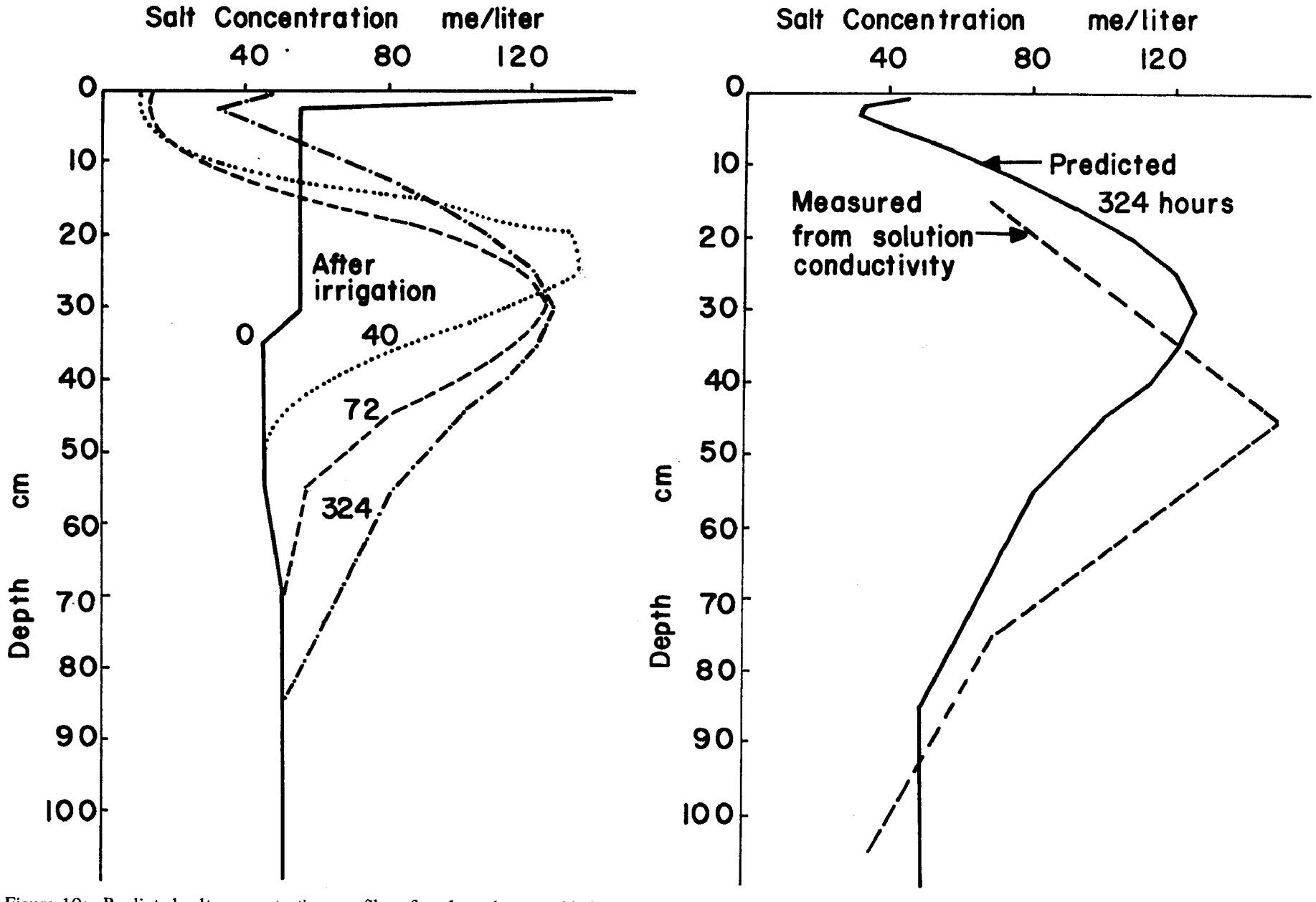

Figure 10: Predicted salt concentration profiles after dry salt was added to the soil surface just before irrigation as compared to measured salt concentration profile in 1971

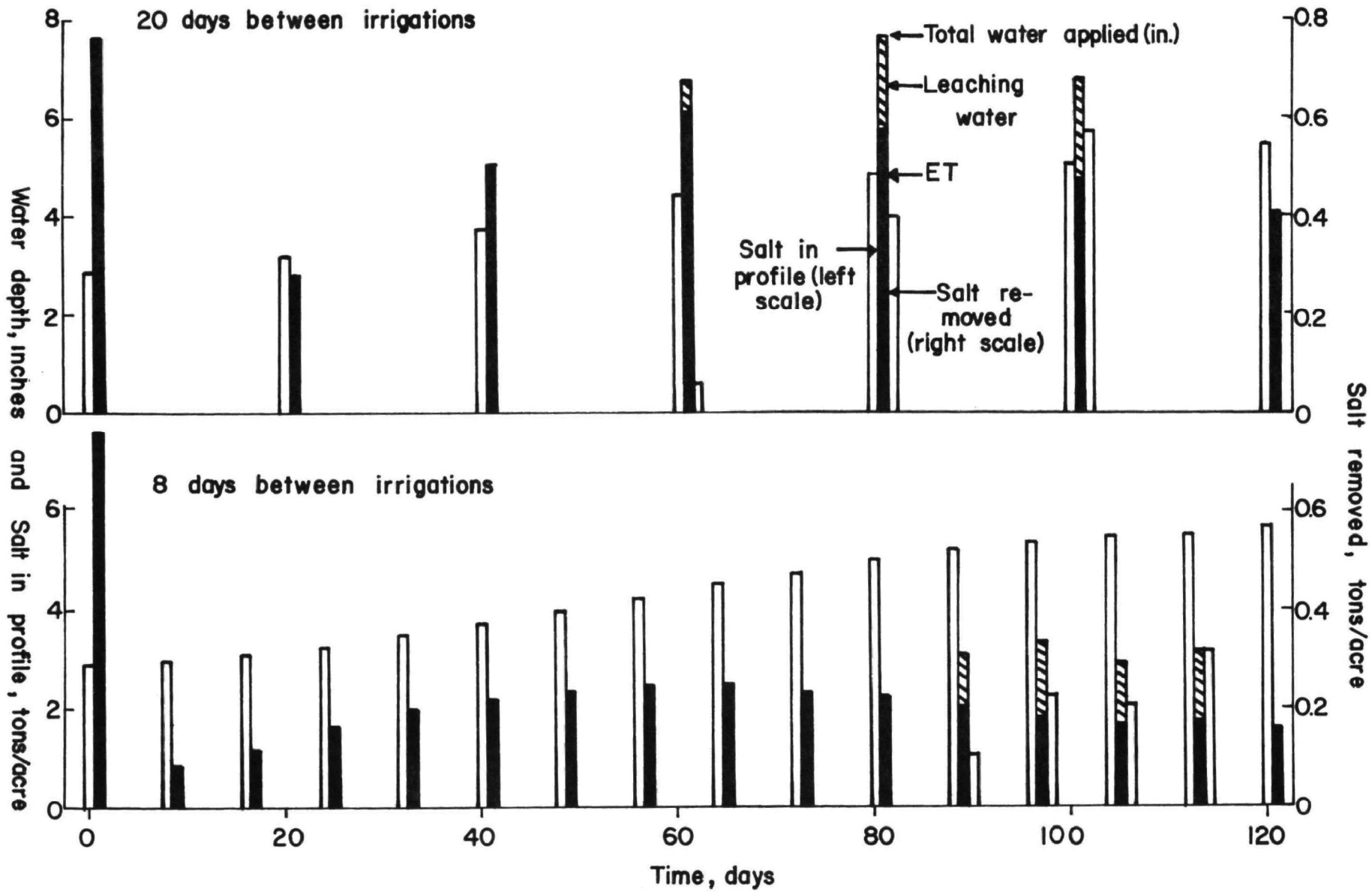

Figure 11: Results from simplified model for two different intervals (8 and 20 days) between irrigations

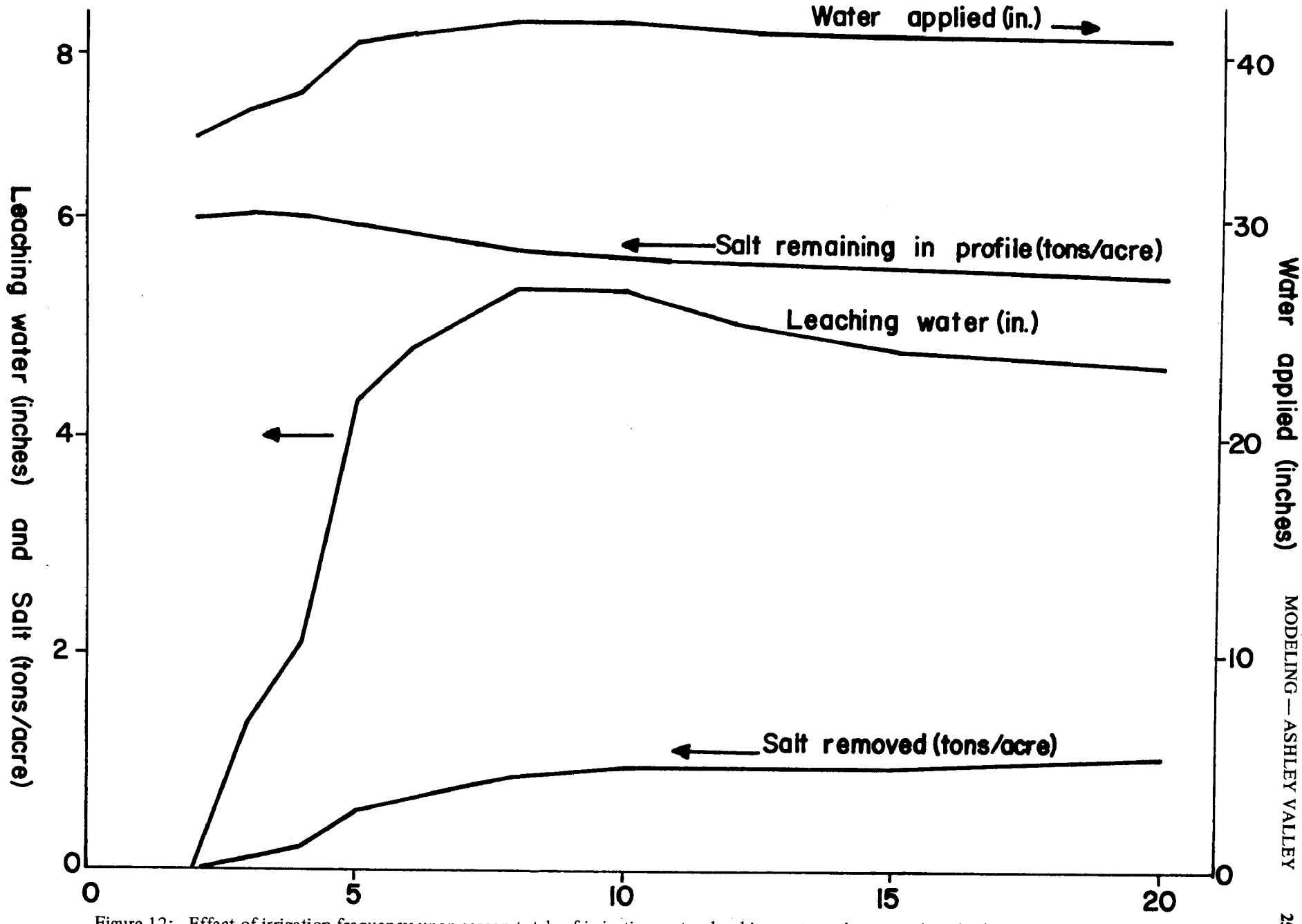

Figure 12: Effect of irrigation frequency upon season totals of irrigation water, leaching water, salt removed, and salt remaining in profile

paths, degree of mixing with groundwater underflow before full evaluation can be made of managing irrigation to achieve water quality control. It is evident from the work on control in the root zone that very sophisticated irrigation systems capable of precise control over depth and timing of irrigation are necessary. Such systems do now exist but are rather expensive.[7] For full benefit considerable man-made drainage systems having short residence times and capable of flexible control are also deemed necessary.

CONCLUSIONS

It is concluded from the research work that:

1. Models can be developed which adequately describe the simultaneous flow of water and salt through the crop root zone for use in managing irrigation for control of drainage water quality. The best model for management will be a combination of the detailed and simplified models described above. The models need further development and field testing.
2. Precise control of depth and timing of irrigations is necessary for control of root zone effluent quality.
3. The interval between irrigations affects the timing of salt discharge from the root zone during the season.
4. There is a considerable range of irrigation frequencies over which total seasonal effects are not significantly different.

ACKNOWLEDGMENTS

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Surviving with Salinity in the Lower Sevier River Basin

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ABSTRACT

The maximum utilization of the water supply of a river system requires that a minimum basic supply must have equal priority along the system. Shortages must be spread over the system as far as possible and development will take place only to the extent that the shortages are tolerable. The distribution and extent of excess reservoir capacity coupled with flexible diversion rights dictate the ultimate utilization of the water resources of a river basin. These factors are now becoming an integral part of water quality management in the Sevier River Basin.

Water quality, deteriorating downstream on the Sevier River with continual reuse of the water, indicates that the practical limit of the use of the return flow is between 40% and 50% of the total diversions for any year. The regions most affected by salinity in the basin adapted to that condition by implementing an agriculture based on alfalfa seed production with grain rotations to add nitrogen and organic matter, and provide a leaching opportunity for controlling salinity levels in the soils.

INTRODUCTION

The Sevier River Basin, shown in Figure 1, is one of the major drainage systems in the Great Basin which has had no seaward drainage since the period when prehistoric Lake Bonneville was at its highest level. The river originates in southern Utah in the 7,000 to 10,000 foot divide between the Great Basin and the Colorado River Basin.

The Sevier River begins as two principal forks. The south fork originates near the town of Hatch, Utah in Panguitch Valley, while the east fork begins in Plateau Valley some twenty miles east. The two forks join just above Piute Reservoir, then the river flows northward approximately eighty miles until it is joined by the San Pitch River and enters Sevier Bridge Reservoir. From the Sevier Bridge Reservoir, the river courses westerly through what is known as Leamington Canyon, and then southwesterly about forty miles to Gunnison Bend Reservoir two miles west of Delta, Utah. Before the complete development of the river occurred, it extended another twenty-five miles southwest to

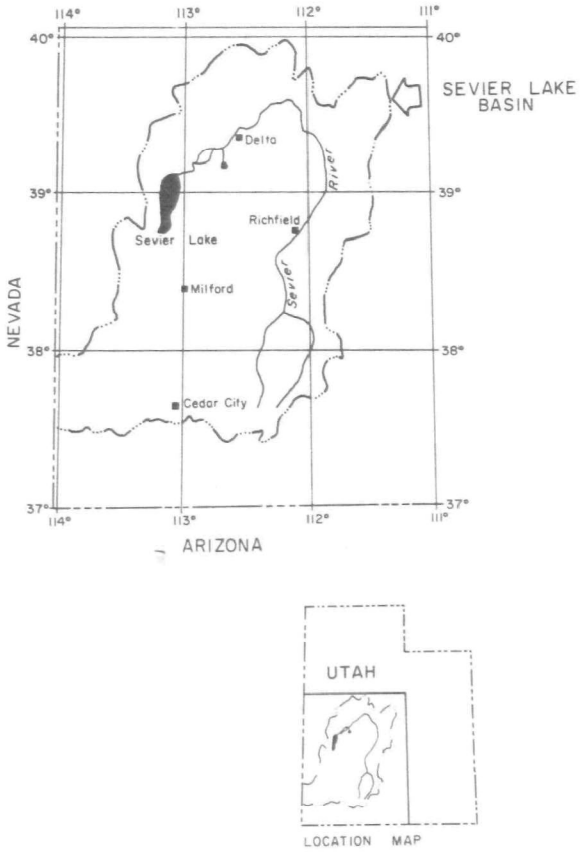

Figure 1: The Sevier Lake Drainage Area

what was its natural end, Sevier Lake, a total length of approximately two hundred fifty miles.

Of the entire water supply in the basin originating as precipitation, only about one percent is not consumed within the basin; the remainder is ground water and surface outflows. In fact, in only two years since 1922 has any appreciable quantity of water escaped the irrigation system. A comparison of streamflow data indicates that between 40% and 50% of the diverted water is from irrigation return flows from lands upstream and on the tributaries. For example, in the twenty-four mile stretch between the gaging stations at Sigurd and Gunnison, the total tributary and surface inflows were 59,000 acre-feet, while the outflow into Sevier Bridge Reservoir was 103,000 acre-feet. Thus, 44,000 acre-feet were added in the reach from ground water return flows. This point illustrates the nature of the Sevier River System as being a series of tubs of which the river is the overflow.

The agricultural use of the Sevier River accounts for approximately 25% of Utah's irrigated acreage, but the river's flows are less than 10% of the supply in the Great Basin. In order to operate the system in such an effective framework, it is necessary to have complete control of the system throughout the basin. This is accomplished both by the location and the excess capacity of the reservoirs along the river, as illustrated in Figure 2. The available storage capacity of the major reservoirs in the Sevier River Basin is currently 424,000 acre-feet, of which only about 45% is utilized in an average water year.

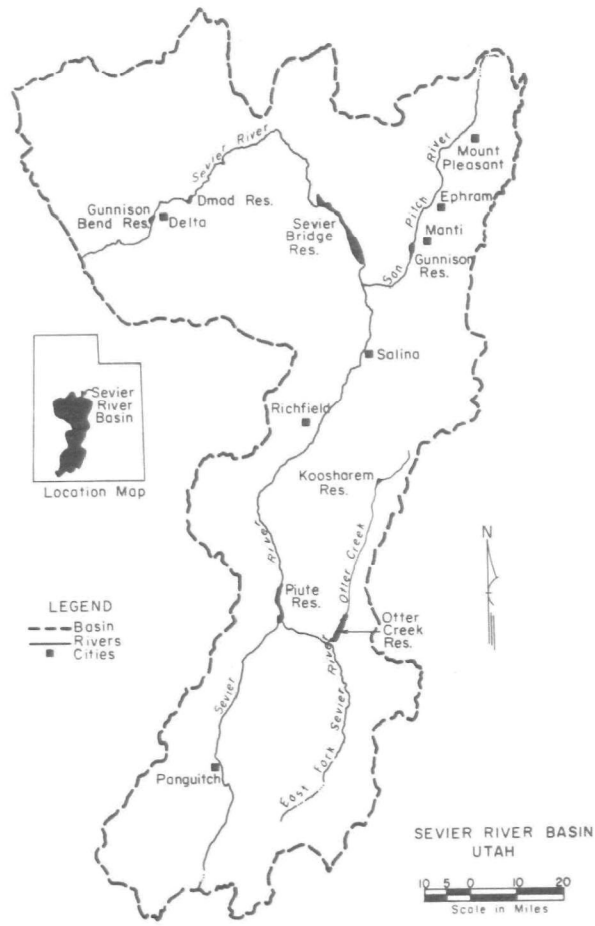

Figure 2: Sevier River Flow Network

Water Rights

It should be obvious to the reader that in the total developed river system, the water quality of the flows reaching the lower users is usually highly degraded. In addition, the management of salinity, for example, is highly dependent upon the allocation of water within the system. In the Sevier River Basin, the storage rights that developed to divide an inadequate storage water supply are now the mechanisms for maintaining an agriculture in the Delta, Utah area by provid-

ing a means of regulating and controlling salinity.

Development of the waters of the Sevier River began almost simultaneously throughout the length of the basin. In January of 1860, a group came to what is now Deseret, Utah to build a dam and excavate a canal to the lands to be irrigated. During periods when the temperatures were often 20° below zero, brush had to be burned on the land to take the frost out of the ground so the wheelbarrow canal excavation could proceed. Many problems were encountered by these early settlers when numerous flood periods destroyed the brush and rock diversion dam or when an Indian threat appeared. However, by 1890 nearly all of the lands that could be irrigated by these direct diversions had been developed and Gunnison Bend Reservoir, the first permanent storage facility on the Sevier River, had been constructed. Although the water supply had at times been excessive, the late 1890's brought a series of very dry years in which a time came when no water reached the town of Deseret with which the local farmers could mature their crops. By then, the Supreme Court of the United States had affirmed the decisions of the State Supreme Court that "first in time was first in right," but there was no enforcement agency to maintain such a concept so the priority had little effect. As a result, an upstream user felt no obligation whatsoever to release water down to a lower user and so each diverted all the water possible at his headgate. In typical western reaction, the water users of Deseret organized an armed force to go up the river and destroy the dams of the subsequent appropriators; however, by the time the group had returned, the dams had been replaced. Many of the communities upstream have their own legends of how they protected their diversions, but in reality probably one or two dangerous eye to eye confrontations were enough to end this type of adjudication.

In about 1899, the Deseret Irrigation Company initiated legal action against upstream users to gain an equitable solution to the questions of water rights. In most cases, the early testimony was so conflicting that the courts placed most direct flow rights on common priority to be prorated when the supply was insufficient to meet the listed right. In the meantime, people began to look at the possibilities of utilizing the water that had been going to waste during the winter months.

In 1902 the site for Sevier Bridge Reservoir was filed upon and construction started that fall. The average flow during the month of October 1902 was only seven second feet of water and this low flow was a prime factor in the success of the construction. The scheme to finance the dam at Sevier Bridge was unique. A man and team was paid at the rate of $2.50 per day. Payment was in stock of the Deseret Irrigation Company at a par value of $5.00 per share. Then each fall the Deseret Irrigation Company levied an assessment of $5.00 per share. Consequently, whenever a stock holder could spare the time, he loaded his provisions on a wagon and went up to the dam to work.

After some adjudication, the people realized that the funding necessary to legally settle every claim in the system would be much greater than the water was worth, so regional committees were formed to work out differences. The plan that eventually evolved is known as the Cox Decree and represents one of the truly remarkable, mostly voluntary, arrived at agreements between individual water users in the state. The specific mechanisms of water distribution in the Sevier River system are extremely complicated.

Because the system of water rights along the river is the criterion for managing the system, previously from a quantity standpoint and now from a quality standpoint, it is best to relate a specific example. Presently, the Sevier River network is divided into two zones which are separated at what is known as Vermillion Dam. Thus, Sevier Bridge Reservoir is the principal reservoir in the lower zone and Piute Reservoir is the principal one serving the upper zone. In the settlement of the disputes among water users as to certain rights, Sevier Bridge Reservoir was awarded the first 89,280 acre-feet in the river, with Piute Reservoir getting the second 40,000 acre-feet. Subsequent quantities, if available, were divided so both reservoirs fill at the same time. In addition, the solution allowed all physically able rights to place their water on a call system. This meant that all of the users on the main stem from below Piute Reservoir to the end of the river were able to use the two main

reservoirs as credit banks to regulate water in the most beneficial manner.

The West View Irrigation Company, which operates between the two principal reservoirs, has the right to 24 cfs when the accumulation between Vermillion Dam and Delta is 295 cfs, and a weighted percentage when the accumulations are less. This diversion must be made on a daily pro-rata basis between March 1 and the 15th day of April. However, from April 15 to the 10th of October, this pro-rata right can be accumulated and credits given to the company; or in other words, during this period the water is on call. After October 15, they have a right to 30 cfs for fall irrigating that is not subject to the pro-rata. The formulation of this right was based upon historical records which showed the company had on occasion diverted 24 cfs in March and 30 cfs in the fall, but had not continuously diverted the water. Since the conditions under which the company would divert this water could not be known until the very day it was to be taken, circumstances such as a cold spring, unseasonal snow storms, or a wet fall which would make the users in the company wish not to irrigate, give vested rights to other users for the water not diverted. As a result, a very serious problem arises. The original participants eventually pass on so the personnel actually computing the water allocations are the only people that see the day to day operation and thus understand it. Then, when a new generation of users, government agencies, or study groups desires to determine a right, the Cox Decree must be consulted. In the case noted above, they would read that West View Irrigation Company is entitled to 24 cfs without fully understanding the limitations thereof. Obviously, there are many conditions under which the company cannot use 24 cfs, so these interested parties seek a way to change the operation to make more beneficial use of the water and more completely use the right as stated in the Decree. The official policy of the State of Utah is that transfers must be allowed if they will lead to a higher and more beneficial use. But in the Sevier River Drainage, all the water is used, so that water that is transferred for beneficial use at one point is simply decreasing a beneficial use at another. On a totally diverted river system, the only change possible is the point of consumptive use.

Water Quality

The final scheme for deriving an equitable distribution of water among users in the Sevier River Basin came about through regional compromise. The obvious catalyst was the fact that the potential use demands far exceeded the average annual supply. However, the complicated and interrelated system "accidentally" saved the lower Sevier River area, and the Delta area in particular, from complete devastation from high salinity concentrations in the irrigation water.

The head waters of the Sevier River are of a suitable quality for most uses, but the concentration of total dissolved solids drastically increases as the flows proceed downstream. The concentration varies from about 60 ppm in the headwaters, to about 1700 ppm in Sevier Bridge Reservoir, to over 2000 ppm in the Delta area. The increase is not a uniform one, but is influenced by the ratio of surface and ground water inflows in different reaches of the river. In general, the water quality of the main stem flows changes from a calcium carbonate to sodium chloride type waters by the time they reach Sevier Bridge Reservoir.

The identification of the quality of return flows, surface inflows, and the role of the reservoirs in managing water quality in the system can be best illustrated by considering some 1964 data collected by the U.S. Geological Survey[1]. Data from the gaging station at Vermillion Dam (Figure 3) shows the water releases from the upper zone satisfying the first storage priority of Sevier Bridge (89,280 acre-feet) have a salinity concentration of approximately 500 ppm. Later in the season, the water quality of the flows in a short reach below Vermillion Dam rises to above 900 ppm, indicating the effect of irrigation return flows. In addition, the tributary inflows in this reach, composed of small flows in Lost Creek and Salina Creek combined with return flows from the irrigated acreage along these streams, have had salinity concentrations as high as 10,000 ppm. In the reach just downstream from Salina Creek, three irrigation companies divert water. Their rights are such that the total river flows are often diverted at each point, so that the diversions amount primarily to return flows. The specific conductance of these flows ranges all the way to 3250 micromhos/cm, indicating a danger to agriculture in these areas.

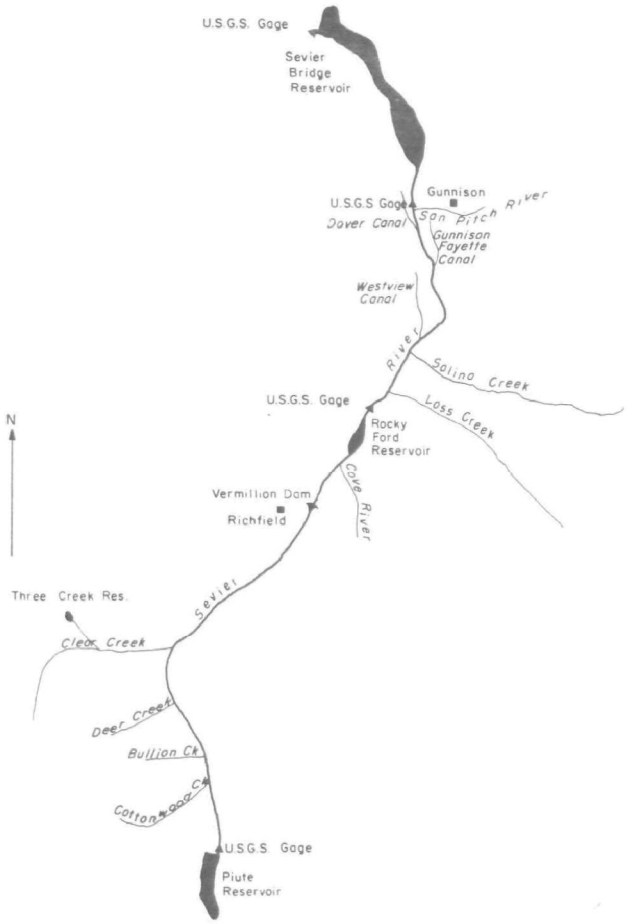

Figure 3: Sevier River System Between Piute Reservoir and Sevier Bridge Reservoir

The significance of the location of the largest reservoir with a first priority being towards the end of the system is now apparent. Without some high quality water being released downstream for dilution during part of the irrigation season in the dry years, it is doubtful that the irrigation system in this reach could maintain the present type of agricultural production. The value of the flexibility of their rights is also apparent in that during dry periods when salinity is most severe, much more early spring and late fall water is used which is usually of acceptable quality. In this manner, the irrigated acreage in this area is able to maintain acceptable salt concentration in its soils.

Also without the high quality water released from Piute Reservoir during the dry years to mix with the return flow water accumulated in Sevier Bridge Reservoir, agricultural production downstream from Sevier Bridge Reservoir would be seriously affected.

Although salinity is a problem to irrigators above Sevier Bridge Reservoir, their soils are usually well drained so leaching is no problem. Below this reservoir, such is simply not the case. The outlet of Sevier Bridge Reservoir is characterized by a specific conductance of 2300 micromhos/cm and indicates the water quality which is available to most of the irrigated acreage downstream. At the end of the river, the specific conductance may reach a level of 4000 micromhos/cm depending upon the operation of the river. The storage within Sevier Bridge Reservoir, however, does allow the quality to change from a very high salinity and high sodium hazard to a medium to high salinity and low to medium sodium hazard because of the mixing of winter flows with summer return flows. When this mixing is sufficient, the releases from Sevier Reservoir, along with the inflows to the river from various points, can maintain a specific conductance in the Delta area to around 2000 micromhos/cm, although this may also vary with other agricultural diversions between the reservoir and Delta.

It is now being realized that the excessive reservoir capacity at the end of the river can be used in conjunction with the present water rights to manage the water quality of waters being used for irrigation.

Use of Saline Water in the Delta Area

The Delta area is the major area in the Sevier River Basin where the salinity problem is large and universal. The soils are generally of a heavy clay nature and of low permeability. The irrigated acreage has ranged between 120,000 acres during the high flow years for the 1920's to about 40,000 acres in the 1930's. This large fluctuation in irrigated acreage was not a result of local planning, but simply an effort to meet the challenges of each new year as they became necessary. Prior to about 1910, a large growth period was experienced in which no realization was made that drainage might become a problem. A tile drainage system was constructed to alleviate the large salt accumulations in the soils and the high water tables. The funding for the drainage system was provided by bonding when inflation rates were very high and the repayment unfortunately came with decreasing farm prices and eventually depression dollars. Even with the almost totally devastating financial crisis that was encountered with the drain funding, probably the worst blow came when most of the

drains failed because of poor designs. The solution was painful but obvious; open drains were dug throughout the area to solve the problems.

By 1935 when the lowest flow year on record had occurred, a pattern had been developed for survival under these adverse conditions. In excess of 90% of the irrigated crop land remained in alfalfa because alkaline conditions caused by either high water tables or spreading the water supply too thin made alfalfa the only reliable crop. Thus, the farmers enlarged their alfalfa seed operation whenever the water supply became too short. For the Delta area, alfalfa has proven to be a remarkable plant in that well rooted young alfalfa in the heavy clay soils will produce a seed crop for several years with no irrigation and will grow in alkaline slick areas that barely support harvesting machinery. Evidence thus supports the theory that with the meager rainfall the alfalfa plant is able to extract from the capillary zone above the water table enough moisture to produce a seed crop. In fact, alfalfa that will grow under these conditions while not giving the largest yields is the most certain to produce a crop of alfalfa seed. One other practice when water is short is to irrigate alfalfa once and then let it go to seed; or to cut a light crop of hay, creating a dust mulch, and then let it go to seed. The salt buildup under these programs is extensive; however, by leaching irrigations on the remaining acreage during a grain crop rotation for a couple of years, most of the farmers manage to stay in business. This indicates than an annual leaching irrigation is not required on all these saline soils but that adequate leaching of a part on a rotation basis can be a practice to manage a deficient water supply of minimum quality. Studies have been made that suggest the most economical course would be to shrink the acreage to fit the water supply, but the people making the studies just don't have the same perspective as the farmers. In the first place, who knows what next year will bring, and if the farmer can stretch his water supply one or two years he might be able to catch up later. Secondly, how does the outlying farmer pull up stakes and move into a shortened system each drought cycle? Is there a place for him and who puts up the capital? One other reason for not abandoning the tighter soils is that they are the more consistent alfalfa seed producers since the salt seems to act as an effective control on the plant growth for seed production. Nature aids in one more way—the salt buildup encourages an increase in the alkalia bee, which is probably the best pollinater available for alfalfa.

Of course, this practice of little or no leaching could not go on forever and during the thirties the Delta area was in serious economic trouble. The crop production here was only 53% of the state average[2]. In 1936, the water supply cycle started trending up and 1942 filled all the reservoirs on the Sevier River. It was an opportune time to give the land a good leaching, but new problems developed which restricted this practice. The expensive tile drainage system had failed in many places and this emphasized one fundamental fact, that leaching attempted without adequate drainage further aggravated the adverse salt conditions.

Starting in the late 1950's, the inevitable dry cycle started again. However, in a few years it became evident that history would not repeat itself as unit crop production continued to increase instead of decline. During the period of 1965 to 1967, observation farms were established to determine the production per acre-foot of water applied, and an especially well managed farm was selected to show what could be done. The results were twelve tons of corn silage per acre-foot of water applied and three tons of alfalfa hay per acre-foot. Some land that had been recommended for abandonment by various studies was now yielding one hundred bushels of small grains and crops of five hundred pounds of alfalfa seed per acre. Hindsight gives some explanation for the improvement.

The Abraham and Deseret Irrigation Companies in the area have a right to the first 10,000 acre-feet made below Sevier Bridge Reservoir during the winter months. The effective fluctuating capacity to hold this water, Gunnison Bend Reservoir, was only around 3,000 acre-feet. Consequently, the Central Utah Water Company would divert the good quality make in Leamington Canyon as early as possible, the residue and downstream accumulation going to satisfy the 10,000 acre-feet. The specific conductance of this water is, as mentioned, between 3,500 and 4,500 micromhos/cm. The practice was to issue small dividends whenever it was necessary to

create more capacity and this very poor quality water was then delivered to lands of these two companies which are furthest out, lowest, and least able to tolerate the salty water. In 1960, D.M.A.D. Reservoir of 11,000 acre-feet capacity was constructed to enable Deseret and Abraham to place this winter water on call. Also at this time, the four lower companies started a program of tapping the deep aquifers for irrigation wells and pumping this water into the D.M.A.D. Reservoir. By careful management, the reservoirs were completely emptied at the end of the irrigation season, and because of the increased capacity, an agreement was reached to store Central Utah's water in D.M.A.D. We now had water coming into D.M.A.D. and Gunnison Bend reservoirs of 1600 to 1700 micromhos/cm. The irrigation companies now were able to start the season with 14,000 acre-feet of water of a quality nearly as good as that entering the lower zone. From the standpoint of water quality management, more reservoir capacity at the end of the river system could be economically justified to dilute and mix the water supply. Some accommodation of poorer quality water would then be possible with the increased capacity.

Extensive canal lining commenced and the well drilling continued. These projects have increased and stabilized the low base water supply. It might be of interest to note that canal lining has continued at an increased rate during the recent wet cycle. The farmers have demanded these projects for water table control and drainage benefits. Improved water quality was not, however, one of the planned objectives of these projects.

The visible evidence of improving the heavy clay soil by mechanically shattering deeply has been before the farmers since the tile drains were installed. After more than fifty years and long after they had ceased to function, the course of the tile drains can be traced and in some of the tight Abbott clay series there is no crop production whatever except over the old tile line and here it is good. The outlines of dumps of manure on the salty spots are discernible more than twenty-five years later by the increased growth. These conditions spelled out what was needed to produce good crops on very tight soils with a saline water supply, level the land so that the water can be controlled to make an even application of a given quantity, mechanically breaking the soil as deeply as possible to accelerate the leaching process, and a program to encourage the formation of humus for free-sodium tie up to improve crop production.

The farm operators have always known that the heavy clays were rich in all plant nutrients but nitrogen. The reclaiming of alkaline spots by adsorbing the free-sodium by humus has long been practiced, but it took the arrival of the 100 hp + tractors, the heavy applications of nitrogen, the planned large crop residue management, and water supply-water quality management to put it all together.

The Delta area has come to the point where they are now past the trial, error and coincidence method. The information necessary for good planning was probably always available, but the insistence of the farmers on the privilege of making their own mistakes resulted from a combination of the scientific community being unable to "sell" their expertise and the means not being at hand to apply the knowledge. It appears that water quality, water supply, and farm management are finally coming together to stabilize agriculture for this locality.

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Water Right Changes to Implement Water Management Technology

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ABSTRACT

Water in the western U.S. is allocated and distributed according to the concepts and rules of the prior appropriation doctrine. This doctrine was developed during the mid-1800's as a solution to conflicts arising between those competing for available stream flows. Few changes have occurred in the substantive or procedural aspects of this law, resulting in a lag between water management technology and the law's capability to incite implementation of these developments. The added problem of water quality not included in the appropriation doctrine complicates the management scheme.

The principal legal concept in the appropriation doctrine which has served as the constraint to effective adoption of more efficient water practices within the irrigation flow system is the property right in water, a valid and protected right incurring to the benefit of its holder. To potentially resolve the water management problem in the West, recommendations in changing or reinterpreting the doctrine governing the exercise of this right are suggested. Three basic alternatives exist: do nothing, provide incentives within the legal framework, or enforce the law strictly. The recommendations will lead to implementation of water management technology in an attempt to solve the problem existing at the state, interstate, and international level cognizant of environmental consideration, the irrigated land sector of the economy, and other current and potential users placing demands upon available supplies.

INTRODUCTION

Water is undeniably one of the most crucial resources known to man; his very existence depends upon an available supply for his consumption and the needs of his activities which perpetuate his existence. How he uses those supplies within his reach will determine, to a great extent, his future and the future of generations to come.

In the semi-arid western United States, we have reached the apex of progress with natural stream flows. (Figure 1) The majority of all waters have been appropriated to specific uses at a time when certain other needs are just materializing and the factor of quality in water is becoming a major consideration. Projected water demands within the national basins require quantities of quality water that do not exist. Therefore, it is incumbent upon all users to introduce the most efficient management practices on available supplies.

This paper explores the institutionalization of a legal and organizational system that has di-

Figure 1: Potential Surface-water Resources within the United States

rected the course of allocation, distribution and utilization of water in our semi-arid area. One of the dominant features of this system is the concept of a property right in water. It is this author's hypothesis that the property right concept is at the root of current water problems. Through the exercise of this right, not only the quantity but also the quality of water is affected. Both of these aspects are an integral part of effective water management and will be discussed herein.

A general discussion of the appropriation doctrine and the nature of the water right concept is essential, but the heart of this report lies with the call for a reassessment of present legal substantive and organizational machinery in light of water demands, water use practices and technological innovation. The principal candidate for analysis, as aforementioned, is the property right concept in water. All discussions will center on this feature of western water law. Conceptual or structural changes are suggested that will protect the existing right holder but provide means for implementing water management technology.

Continual reference is made to water management technology. It is this author's assumption that such technology has advanced to levels of providing efficient water management schemes for irrigated agriculture. However, this does call to mind the excellent article on the population problem by Garrett Hardin in which he notes it is "an implicit and almost universal assumption of discussions published in professional and semi-popular scientific journals that the problem under discussion has a technical solution."[1] As Hardin goes on to state, although technical solutions are always welcome, there are certain problems to which there is no technical solution. Such is the problem before us now. Regardless of the state of technical development, the water problem of the West cannot be solved without a major emphasis placed upon changing the water rights concept and certain other doctrinal and organizational features.

Water, Water Here and There

In early American history, water, like air and open space, was considered a common or free good. Initially, there was unrestricted use due to the minimal demands on existing supplies.

Miners were the first diverters of water in the West, and initially had little conflict in acquiring necessary supplies. Then the use of the com-

mons became overloaded and the need was recognized to develop some means to regulate the use of this valuable resource. In social terms, there was a willingness for each to give up a little so that all could have more; in economic terms there was a willingness to internalize the costs of the externalities created through the use of this common resource.

The system that emerged was simple and direct. The principles that developed held:

(1) There had to be a diversion from the natural stream.
(2) The water had to be applied to beneficial use.
(3) When completed there was created in the appropriator a water right.
(4) This right insured the holder of continued use for the quantity appropriated.
(5) There attached an appropriation date as of the date of application to beneficial use to govern the appropriator's relationship with other water right holders.

In every state, with time, an administrative agency was established to administer the water provisions and ensure the distribution of water according to priorities. Here again, the early settlers demonstrated a willingness to internalize costs associated with perfecting a system of water use that provided them with the needed security to protect their own investment.

Consistent with developing water codes at the state level, the need to perfect the water right was also voiced. Consequently, it was decided there would be adjudications of water rights in which the right holder would receive evidence of his right. Due to the fugitive nature of water as compared to that of land and other objects, this water right is described as a unsufructuary right; that is, only a right to use the water once it is captured. Once the water is under the control of the appropriator, the corpus of the water itself becomes his personal property for the use so appropriated. In the famous case *Coffin vs. Lefthand Ditch Company*, the court stated, "water in the various streams thus acquires a value unknown to moister climates. Instead of being a mere incident to the soil, it rises when appropriated to the dignity of a distinct usufructuary estate or right of property . . . . . the right to water in this country by priority of appropriation thereto, we think it is and has always been the duty of the national and state governments to protect."[2]

Once the user meets the appropriation requirements of diversion, application to beneficial use and compliance with state statutory requirements, a property right having four basic characteristics is created. First, the right is for a definite quantity of water. This is determined according to the use to which the water will be put. Second, the right is for a definite use. In general, most rights are appropriated for single uses where a direct flow right is sought. Where a storage right is requested, the use may be for a multitude of beneficially recognized uses. Third, there is an established point of diversion from which the water will be acquired in the exercise of the right. And, fourth, the water right is usually for a time period depending upon the nature of use. For example, a municipal water right may be for a yearly diversion, whereas an agricultural direct flow right may only be exercised during the normal growing season.

Because a protected water right exists does not infer the absolute security in exercising that right in an unreasonable fashion. There are doctrinal limitations that vary from state to state which operate as constraints to the right holder. The appurtenancy doctrine, tying a water right to specific land for which the water was appropriated and subsequently prevents transfers to other lands, is in effect in five states.[3] Duty of water concepts range from specific statutory limitations of the amount of water that is reasonably necessary for a particular purpose or use,[4] to allowing administrative discretion in deciding what is an adequate supply.[5]

In addition to specific doctrinal limitations, there are direct statutory restrictions to the exercise of a water right, such as, Colorado Revised Statute Section 148-7-8 providing "during the season it shall not be lawful for any person to run through his irrigation ditch a greater quantity of water than is absolutely necessary for irrigating his land and for domestic and stock purposes; it being the intent and meaning of this section to prevent the wasting and useless discharge and running away of water." Further limiting this right, the Colorado court held in 1893 that no one is entitled to a priority of more water than he has actually appropriated nor for more than he actually needs. Again, in

1912 the court reiterated this limitation by limiting the appropriator to that amount of water that is reasonably necessary to irrigate his lands regardless of the quantity appropriated.

The system of property rights in water serves a dual purpose. While permitting right holders to use this resource, it likewise restricts the use and action by others.[6] In this way, each man's private use of the resource is determinable under the law.

Another unique feature of the appropriation doctrine is that a water right acquired thereunder may be lost if the appropriator does not exercise it for a specified period of time. There are two general methods by which this right can be lost and the waters appropriated thereunder made available for appropriation by others. The first is through the abandonment of the right by the holder. This requires the nonuse and the intent not to use. Both of these elements must be present before a right can be dissolved under this theory. More common, however, is the forfeiture theory which is usually statutory in nature requiring only nonuse for a specified period of time. It immediately becomes apparent that if intent does not have to be shown the dissolution of the right is much simpler.

This is an abbreviated discussion of the legal solution to the water management and utilization problems that occurred nearly a century ago. In general, it allows for the use of water wherever the user could show a beneficial use could be made. It did not restrict it, as under the eastern riparian doctrine, to lands adjacent the water course.

Many irrigation systems began dotting the map throughout the western states. Transmountain diversions have transported the water to areas where uses could be made but natural suppliers were unavailable. Technology and the legal means of acquiring a secure right to a predictable and dependable supply of water have permitted nearly unfettered distribution of water here and there throughout this semi-arid region.

The Solution Becomes The Problem

For nearly a century, agricultural development has taken place in the seventeen western states subject to the provisions of water allocation and distribution proclaimed by the state water codes. Individuals have governed their activities in accordance with their right to use appropriated water and have made investments according to the stability and quality of their right. Irrigation systems developed establishing social communities where its members were the direct recipients of the economic base made possible through the describable use of this resource. The primary and secondary benefits of agricultural development has had its impact throughout the nation in meeting the needs of consumers. States have established relationships with neighbors over interstate streams through negotiation or litigation based upon the principles of their water law. The federal government has upheld the right of states to govern the use of water arising within their boundaries according to the laws, customs and decisions that the states developed.

More basic to agriculture is the fact that its economy rests on security of water rights, particularly in an era when economic maximization and optimization principles question the validity of traditional allocations over more contemporary productive uses.

Given the state of the situation, how has the water right solution of the 1870's become the problems of the 1970's? We can examine the "problem" at two levels — state and interstate — considering both the water quantity and quality aspects.

The real problem of water rights at the state level begins with their issuance. The administrative and adjudicative mechanism was in its infancy when confronted with the task of determining and awarding water rights to applicants. Adequate means of accurately measuring diversions were not developed or used and, consequently, guesstimations were made on the diverted flow according to a number of measurement techniques.

Few questioned the quantity allocated the applicant because sufficient water remained in the streams to meet subsequent appropriators. The amount decreed was not as important as the amount of water remaining in the stream after diversion or return flows. Eventually, however, the tabulation of water rights far exceeded the actual flows. In the mean time, appropriators received valid enforceable water rights which may later be exercised to their full capacity if beneficial use could be shown. This discrepancy is called paper water rights — the difference be-

tween the quantity decreed and that which could be beneficially used or historically diverted. It is difficult, if not impossible, to effectively distribute water or develop a management water plan at the state level when such a discrepancy exists.

A second problem arises from the nature of a water right itself which contains two elements inhibiting the implementation of efficient water management practices. The first arises over a fear of loss through abandonment or forfeiture of the right through the failure to exercise it. As a result, appropriators divert as much of their total allotment as possible to protect their right resulting in overapplication of water and subsequent diminution in quantity flows. The second problem pertains not to the fear of the right but, rather, engendered from the security of a protectable property interest in the continued diversion of the decreed quantity of water and certain limitations upon the exercise of the right that bind current uses to past practices.

Irrigators adjust their operation according to the water supply available and conditions under which they can exercise their right. If their appropriation is sufficient to allow delivery of water needed to produce the intended crop at the point of application, no incentive is provided to reconstruct diversion facilities for transmission canals. Likewise, if the supply is adequate or even over abundant, close management in the application is not encouraged. Return flows may be due to over application, mismanagement or seepage benefiting downstream appropriators dependent upon this source of supply but detrimental to the operations of the system within the state boundaries (see Figure 2). Transfer restrictions found in certain states prevent the utilization of water on more productive lands or uses. These restrictions may be a part of the right itself tying that appropriation to specific lands, doctrinal concepts, such as the area of origin, or purely organizational impediments and red tape discouraging such transfers.

The epitome of the problem is represented by the decision in Salt River Valley Water Users Association vs. Kovacovich.[7] The Arizona Supreme Court was presented with the task of deciding whether or not an owner of land having a valid pertinent water right may, through water

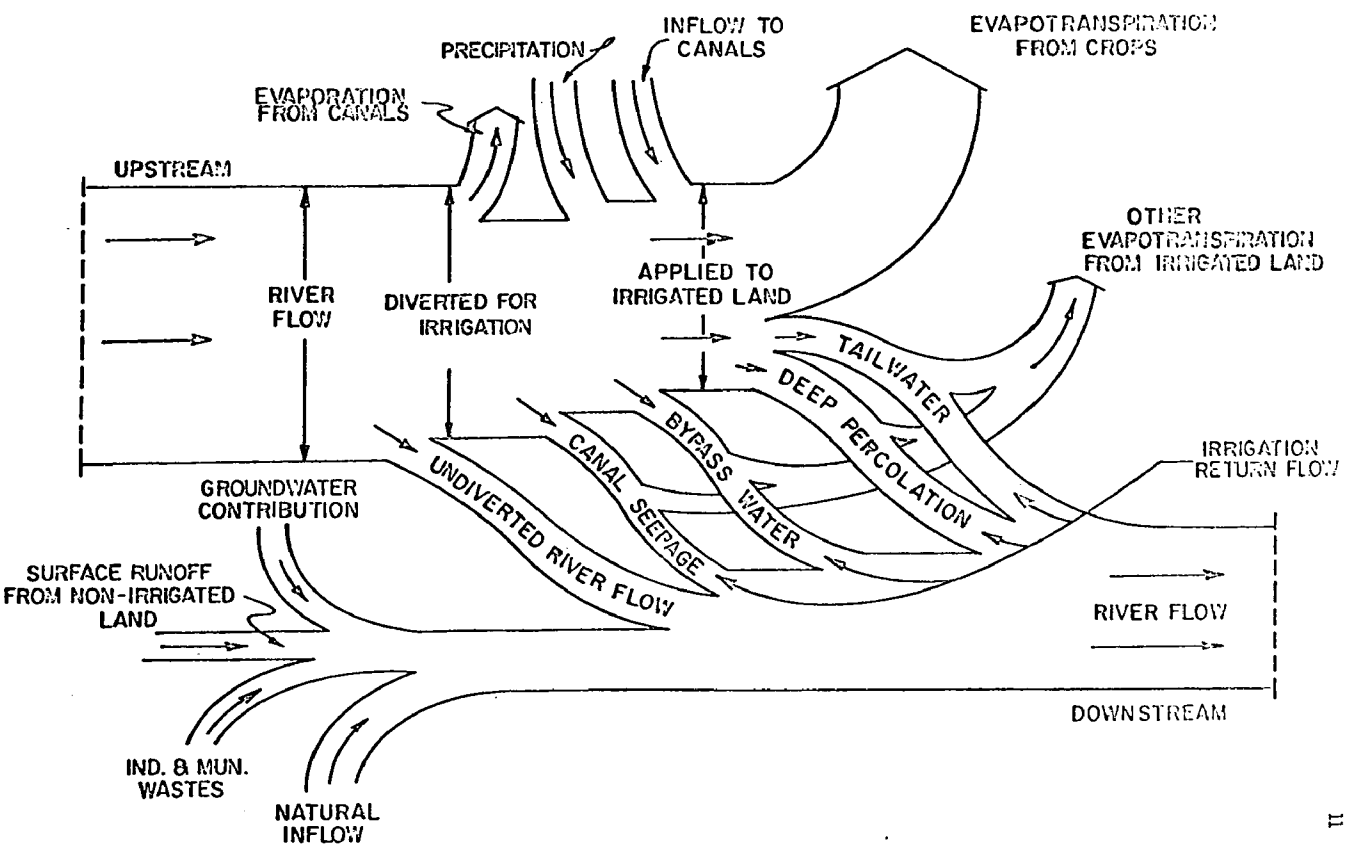

Figure 2: Model of the Irrigation Return Flow System

saving practices, apply the water thus saved to immediately adjacent lands in his ownership without applying for a right to use the salvated waters under the state water code.[8] In this case, the defendant improved certain of the ditches and concrete lined others. The water that was normally lost through seepage or evaporation was applied to 35 acres of adjacent land. The defendants did not increase their diversion from the river. In analyzing the situation, the court stated

> "It was argued that decision of this issue in favor of appellants (Salt River Valley Water Users Association) would result in penalizing a person who, through their industry, effort and expense, engaged in water saving practices. . . This court is of the opinion that water saving practices entered into by appellees (irrigators Kovacovich and Ward) not only resulted in conservation of water but also other benefits to appellees such as weed and vegetation growth control along such irrigation ditches and reduction of time and cost of maintenance of such ditches. Certainly any effort by users of water in Arizona tending toward conservation and more economical use of water is to be highly commended. However, commendable practices do not in themself create legal right.
>
> . . . In an effort to achieve some degree of order. . . our court, through a series of decisions developed and applied what we today refer to as the doctrine of beneficial use.
>
> This court is of the opinion that the doctrine of beneficial use precludes the application of waters gained by water conservation practices to lands other than those to which the water was originally appurtenant. . . Beneficial use is the measure and the limit to the use of water. The appellees may only appropriate the amount of water from the Verde River as may be beneficially used in any given year upon the land to which the water is appurtenant even though this amount may be less than the maximum amount of the appropriation. . . Any practice, whether through water saving procedures or otherwise whereby appellees may in fact reduce the quantity of water actually taken inures to the benefit of other water users and neither creates a right to use the waters saved as a marketable commodity nor the right to apply the same to adjacent property having no appurtenant water right."[9]

It is evident from this decision that Arizona provides no incentive to implement water management technology in individual irrigation operations. Fortunately, the holding in Kovacovich is not the general rule. It is generally held that waters salvaged through man's improvements are subject to appropriation and use by the party saving them.[10] However, the cases establishing the general rule are early cases decided in a period of time when agriculture was king and the multitude of other uses were not placing such high demand upon water supplies. The result obtained in Arizona could be decided in other appropriation states upon a strict construction of the beneficial use concept and definition of an appropriation.

On an individual basis, the water right problem may not appear significant. Taken on the aggregate at the local and state level, however, the impact of this right deserves considerable attention.

Turning to the problem of water quality at the state level we find that quality has never been an element of a water right under the appropriation system. The appropriation doctrine developed in an atmosphere where the significant feature of water was its abundance or lack thereof. Consequently, the only guarantees that the appropriation system offers right holders is the right to a specific quantity of water divertable in order of priority. Cases in a number of jurisdictions have decided the right of appropriators to a usable quality of water but with few exceptions these are early decisions and their holdings subject to question under revised and amended water codes. The issue depends in part upon whether the injured party is a downstream senior or junior user. In the first instance the general rule is stated in Right v. Best: "it is an established rule in this state that an appropriator of waters of a stream, as against upper owners with inferior rights of use, is entitled to have the water at his point of diversion preserved in its natural state of purity, and any use which corrupts the water so as to essentially impair its usefulness to the purpose to which he originally devoted it is an invasion of his rights."[11] This rule is applied in Arizona, Colorado and Utah. In each instance, the injured party was adversely affected by the action of an upstream mining operation. Where water law

theory is deficient, the common law doctrines of nuisance, trespass, negligency and equity provide the remedy to protect the property right injured. In Suffolk Gold Mining and Milling Company vs. San Miguel Consolidated Mining and Milling Company, the Colorado court held "that all property rights are subject to the very equitable principle 'use your property so as not to injure others.' (translated) This is a principle both of morals and of law and there is no principles of absolute right to property which is not measureably subject to this condition."[12]

In a recent Colorado case the Supreme Court upheld the right of a senior downstream appropriator whose domestic water supply was polluted by an upstream fishery. Again, this case was decided upon the property right concept in an appropriation.

The next question is whether a senior upstream appropriator can diminish the quality of water since downstream junior appropriators must take the stream as they find it. There is substantial case authority indicating that the senior has such a right. However, in Colorado the right of the senior to pollute has been denied and the riparian rule of reasonable use applied instead.[13]

In spite of well defined rules set forth in the preceding cases, the real issue is whether a downstream irrigator can prevent an upstream irrigator from exercising his right to use the water for irrigation purposes where through his use the quality of water reaching the downstream user has been impaired. No cases have decided this question. The issue is becoming increasingly important due to the salinity concentrations in certain streams reaching levels adversely affecting plant growth. Because of this deficiency in the appropriation doctrine, it is commonly felt that other means of alleviating the problem must be devised. The nature of the salinity problem is not confined to state boundaries as is the law and concepts that have contributed to the problem.

Technology has succeeded in developing feasible solutions to reducing the salinity problem arising from both man-made and natural sources, but the law has been slow to encourage or direct implementation. The technical possibilities can be divided into two categories: measures to increase the water supply and measures to reduce salt loading in the streams.[14] With respect to agriculture, the water supply can be increased through conservation measures designed to reduce the consumptive use of water or implement improved irrigation practices. To reduce the amount of salt entering the stream from irrigation return flows, proper land selection, canal lining, improved irrigation efficiency, proper drainage, and treatment or disposal of return flows is recommended. It is noted in the government report that various factors such as economic feasibility, lack of research and legal and institutional constraints limit the present application of certain technical possibilities to the salinity control problem.

When examining the total picture of quantity and quality management in the West, the problems facing the individual state seem minimal. To complicate the basin problems, divisions of interstate stream have been made by compact, judicial decision or congressional allocation. These solutions have neglected to include quality as an element in describing the rights and obligations of states on interstate streams.

The question then becomes, what is the role of agriculture and how has the use of water for this purpose contributed to the basin problem? Agriculture, being the largest diverter of water in the Colorado River Basin is likewise the greatest contributor to the problem due to stream flow depletion and salt loads introduced into the stream by return flows. In addition to the salt concentration in remaining waters as a result of stream flow diversion for irrigation, out of basin diversions substantially affect the problem. The total export of water from the Colorado River Basin amounts to 6,569,000 acre feet per year, almost one-half the total Colorado River flow.[15] Having identified the major legal problem, the next section will consider ways in which the law can be changed or re-interpreted to promote the efficient and effective use of water through the implementation of technological innovations.

Water Right Changes to Implement Water Management Technology

In the preceding discussion the villain of the western United States water problem has been described as the property right concept in water created through the appropriation doctrine. It is

Figure 3: Diversions Out of the Colorado Basin

noted that the appropriation doctrine and the right it devised was a solution to a tense situation occurring between water users over a century ago. An examination of state water codes shows little changes in the doctrine over the past 100 years commensurate with the economic, social and technological changes that have taken place in the same region of control. Specifically concentrating upon one sector of our economy which has been statistically described as the largest diverter and consumer of water supplies in the West and collaterally the major contributor to the salinity problem in many drainage basins.

The principal beneficiary of the appropriation doctrine in its pristine state has been the agriculture sector, but, due to mounting state, national and international pressures caused by a multitude of uses demanding water, this same beneficiary now finds itself epitomized as a wasteful, ungrateful and to some extent unnecessary user of water. Economists are quick to show that net returns for quantity of water used are much greater for almost any other use than irrigation. Population shifts have tilted the balance of legislatures to the point where politicians find it politically desirable to attack the continued horrendous diversions of this scarce resource to a sector of society already subsidized in every way except outright dollar grants. Few have really analyzed the beneficial primary and secondary impacts of agriculture upon the total economy and the stability it has given to local and regional societies. True, the water right has allowed agriculture to continue in operation with little modification in management practices of transport and application since the mid-1800's. Under the preference system of the appropriation doctrine, agriculture was even given a superior position to such uses as industry, recreation, etc. In a way, the water right has been a security blanket for the farmer; he has not had to compete on the open market for water as other later developed users because he acquired an early right to available supplies which were guaranteed him so long as he exercises his right. In fact, it is this security which has been hailed by some[16] and condemned by others.[17]

The contemporary push is to compel the maximum use of water to gain the highest economic and social return. Technology has advanced far beyond present agricultural practices to develop new and better water management methods that have not been adopted due to legal, institution, economic and social constraints. It is considered desirable by almost all working in the water resources field that such practices should be accepted and utilized by agricultural water diverters; that the legal and institutional barriers should be removed. To encourage the adaptation of such innovations, certain economists and lawyers recommend that water be made an open market commodity where a right to use it can be traded and sold to the highest bidder. It must be kept in mind, however, that any change in an irrigation practice will cause the incurring of a cost which must be transferred to the product. The multiplier effect of that cost in terms of increased prices or the increased social costs if the economy adjusts too slow and the agriculturalist is forced out of business must also be considered.

Therefore, in light of the water problem status and the role of water rights, two opposing principles must be given recognition in the pursuit of changes to implement technology. The first is to protect the current water right holders and recognize their interest in the vested appropriation, Second, changes must be adopted to

encourage maximum use of available waters through incentives where possible, strict enforcement of the law where necessary, but, more importantly, through the personal initiative of water users and a recognition of their social responsibility.

Recommendations to resolve the water quantity and quality problems of river basins must, in reality, examine the river system as one hydrologic unit regardless of state boundaries. In so doing, the modifications and reinterpretations of the law must be designed to accommodate the overall goal of efficiency and effectiveness in water management. This will require coordination and cooperation by state and federal agencies presently working with water resources management. Although irrigation pollution control is theoretically designed to be covered by pollution control laws at the state and federal level, this still does not provide a solution extensive enough to reach the principal cause of salinity loads. For this reason the water right laws must be examined and necessary changes made to meet this goal.

Focusing upon the agricultural uses of water, yet cognizant of the multitude of other uses in river systems, the first step is to structure the water right around three sublevels of the irrigation return flow system to integrate quantity and quality constraints in formulation of changes in the exercise of the appropriation. The three sublevels are (1) the water delivery system, (2) the farm and (3) the water removal system.[18] In this manner, the various individuals and organizations holding water rights or transporting waters can effectively be included in any water management scheme.

In certain instances a farmer may, through the exercise of his right, divert from the stream through his own conveyance system and apply the water to the land, gathering tailwater, seepage or bypass water into a drainage ditch and discharging it into a water course. At each level, the rights to the use of that water depends upon the water right held. The degree of efficiency in the farmer's operation will depend upon the amount and dependability of the right, at which point the diversion is measured and the physical and legal possibilities of capturing and reusing the irrigation return flows before they reenter a water course.

In other cases, ditch companies or irrigation and/or drainage districts may own and operate the delivery and/or water removal system. The company or district may transport the water owned by the company, district or farmer to the latters headgate. Losses through the delivery system may or may not be charged against the farmers right, share in the company, or rented quantity. Likewise, the irrigation and drainage district may be able to decrease losses in its return flow system in transporting the drained water back to a stream. The law must be conscious of quality implications in each sublevel since each irrigation return flow system is affected by upstream or effects downstream systems.

Three general alternatives are available to promote the implementation of water management technology in the irrigation return flow system. The first is to do nothing with the legal and institutional constraints and depend upon the operations of the market place and social relationships of the user. This obviously will be time consuming, uncoordinated, misdirected and the results unpredictable.

The second alternative is to devise a system of direct legal incentives designed, within the present water rights system, to encourage a social consciousness regarding water use among agricultural and other water users. Conceptual and structural changes or modification in the law are recommended for adoption conjunctively.

The third alternative is to strictly apply the water law concepts against the exercise of a water right and let the burden lie where it will.

I submit the laws are nearly sufficient in their present state to resolve the legal and institutional phase of the problem. Reinterpretation will bring into focus the water law doctrines with technology and the public needs. Many concepts now postulated, if placed in the proper perspective and if applied, would promote more efficient water management.

Conceptual Alterations

The concept that is at the heart of the appropriation doctrine and which could make the most substantial impact in solving the legal and institutional constraints is the concept of beneficial use. This is a very nebulous concept which defines the measure and the limit of a water

right. In general, beneficial use pertains to nothing more than the reasonableness of the diversion according to the use to which the water is to be applied. At present, what is a beneficial use for acquiring a water right may depend on whether that particular use is one recognized by the state constitution or statutes. The concept must be conceived and directed not only to types of uses but to the nature of the use on the farm with respect to the users needs. More importantly, this concept must be viewed with respect to the users responsibility to other downstream users and the public interest.

The concept could be used to implement water management technology. Irrigation scheduling and careful water control could be encouraged through an interpretation of the concept as prescribing to the most advanced technologically feasible management program with respect to on farm use. Conventional methods of water application using ditches and borders and in some cases sprinkler systems have the advantage of being economically inexpensive but conversely place a great strain on the water budget due to losses through evapotranspiration. Where feasible, subsurface application or the trickle method could be encouraged which would have the effect of reducing the quantity of water applied and salt loads in return flows.

A major change in the nature of a water right that would serve to protect the interests of the right holder and later water users would be to add the element of water quality. In so doing, the right holder would have the same assurance and likewise liability in the use of diverted water within the priority system for quality purposes as he now has for quantity flows. This change would be instrumental in encouraging practices to treat or dispose of highly saline waste waters and encourage the proper application of water on the farm.

Significant to five appropriation doctrine states is the appurtenancy concept which ties water to land. This concept breeds inefficiency by promoting irrigation of certain lands that are not as productive as other available lands belonging to the right holder or other land owners wishing to purchase water rights. Elimination of this concept would allow the landowner to make a proper selection of land that would yield the highest agricultural returns to his operation.

States following the rule in *Kovacovich* case discussed earlier regarding the use of salvaged waters could greatly benefit if that decision was distinguished or overturned and instead the rule set out in *Reno vs. Richards* adopted.[19] Reno held: "if one, by his own efforts, adds to the supply of water in a stream, he is entitled to the water which he has developed even though and appropriator with more senior priority might be without water. The reason for this rule is the obvious one that a person should reap the benefits of his own efforts, buttressed by the view that a priority relates only to the natural supply of the stream as of the time of the appropriation."

Another concept existing in certain states pertains to the right of an appropriator to recapture his waste water. A liberal rule was set out in *Binning vs. Miller* granting the right to recapture waste water still on the original land and to reuse it on that land.[20] A more acceptable rule in light of the concept that return flows inure to the benefit of downstream appropriators such that the transfer of a water right can not exceed the consumptive use diverted was set out in *Lason vs. Seely*[21] adding an additional element that if the waste water has re-entered a natural stream so that the appropriator has lost control of it, no right of recapture would exist. Colorado applied both the doctrine in Reno and Lason to salvaged and developed waters and would appear to extend the requirements to waste and seepage water as well.[22] A change in the laws to reflect the above stated rule would permit implementation of a pump back system for tail water running off the end of a field. In addition to allowing the farmer a right to reuse water that has been through his operation, it would also serve as a stimulus to be more careful about applying fertilizers, pesticides and other pollutants on his fields or overapplication of water causing salt concentration in his runoffs since the water would again be placed on his own land to the detriment or benefit of his operation.

A final doctrinal impediment in the exercise of water rights in the transfer restriction of rights within an irrigation system to other uses, or outside of the basin. This constraint may exist in the substantive water law or as a result of the organizational and administrative system of the state. There are few states that prevent the sale and transfer of water rights from within or with-

out the present uses. States restricting transfers rely upon the appurtenancy concept to prevent such shifts. However, the law should be modified or changed to reflect state encouragement in the renting, leasing, transferring or selling of water rights to other uses and places so long as the vested rights of others are protected. Although there are no restrictions on the transfer of water rights in Colorado, the organizational red tape — delay and expense — acts as an impediment. Changes in the administrative and judicial system should be made to facilitate exchanges of water rights. Recognition of such a right and a change in the concept of beneficial use to include recreation, aesthetics, fish and wildlife and other beneficial uses would serve to nullify the fear of loosing that portion of the water right not exercised by permitting the transfer of the unneeded portions to other uses within the system.

Removing these rigidities in the law to give the right holder greater freedom and flexibility will eliminate many of the irrigation problems perpetuated by the appropriation doctrine. Agricultural users are subject to constraints that other users are not, which is frequently passed over when comparing the use of water for agriculture to other uses.

A substantive change in the water laws affecting the administrative organization of the state that should be enacted to enable a greater degree of cooperation between the state agency and water users and at the same time permit the state to concentrate on the development of a desirable state water plan is to enact legislation permitting the state water resources agency or other public organizations the right to acquire water through appropriation, purchase, abandonment or condemnation. The significance can be seen at the state and interstate level by granting the state greater freedom in carrying out its responsibilities and negotiating agreements with its basin users and states.

Structural Alterations

Certain structural changes are recommended which would encourage water users to take advantage of the conceptual changes suggested above. Already in certain states, irrigation districts are used to circumvent constraints imposed by the appurtenancy concept and transfer restrictions. In Wyoming and Arizona, for example, water rights can be transferred to an irrigation district which then has the power to shift the water within the system according to the demands of the irrigators. In Colorado, ditch companies operate to rent and transfer water within their system in order to avoid the cumbersome organizational impediments.

The problem is that these practices are on a very limited scale. What is needed is a means of allocating and reallocating water within the irrigation system by an organization cognizant of the needs of water users within the system, the state water development plan and the basin and international impacts. Suggested is the development of a centralized state brokerage system to operate as a market center for the exchange and sale of water rights or renting of water available under the rights held.

This brokerage system could be organized as a public or private institution. It would permit water users to divert only that amount of water necessary for their operation without fear of losing the unused decreed quantity and lease or rent the difference to other users. Hence, there would be an economic incentive to implement the most efficient water management practices in their operation in an attempt to reduce the necessary quantity of water applied.

A brokerage system created as a public entity could be established in the Office of the State Engineer or water planning and resource department of the state. This office or subdivisions in the various basins within the state would list all available water for rent, lease, exchange or sale. The location of available waters will determine the impact upon other vested rights but the responsibility for delivery and protection of such other rights would rest upon either the water right holder or water acquirer. Uniform prices of units of water could be established or the available water could be transacted to the highest bidder. The adoption of such a system in state organization would require changes in agency laws to permit this type of activity. Likewise, it would be imperative that the state should have the power to purchase, condemn or receive water rights in the name of the state. This would allow the state to take action against appropriators who refuse to implement efficient practices, acquire their unused rights and retain

them for future use while renting or leasing the water during the interim. A percent of the transacted price would be retained for the operation and maintenance expense of the brokerage system.

If a brokerage system was to be established in the private sector of our economy, it is recommended that the organization created be required to submit to the standards of a nonprofit corporation and subject to direction and assistance from the state water agencies. The functions of this private entity would be the same as those above described. However, it is envisioned that problems would be created in establishing such an institution. With time many people will ignore the nonprofit aspects of the agency and create similar profit corporations. Secondly, the redistribution of water and water rights may not be in the best interest of state and interstate basin resource management.

The final alternative to implementing water management practices is to enforce existing laws strictly. Certain rigid rules, if executed would decrease quantities diverted. Applying the concept of beneficial use the court in *City and County of Denver* vs. *Sheriff* stated "what is beneficial use after all is a question of fact and depends upon the circumstances in each case."[23] In *Ericson* vs. *McLean* the New Mexico court said that "an excessive diversion of water through waste cannot be regarded as a diversion to a beneficial use within the meaning of the constitution."[24] And a 1917 Utah case held "beneficial use contemplated in making an appropriation must be one that inures to the exclusive benefit of the appropriator and subject to his complete dominion and control."[25] When excessive water is lost through canal-seepage, evapotranspiration or waste, the state would modify the right to reflect only the water applied beneficially. Thus, the duty of water for the use appropriated would reflect the most efficient means of transporting and applying water. Applying the statutes and rulings in the various states may serve to prod irrigators into implementing more efficient practices into their operation through fear of losing their water right. Socially this is undesirable. To be effective in enforcing the law re-evaluation of the water rights now held would be necessary to free up paper or waste water rights. Every appropriation doctrine state has a sufficient mechanism either through abandonment or forfeiture to attack a water right not being exercised according to the law.

I am of the opinion that strict enforcement of water law doctrines should be implemented only in cases where an obvious discrepancy occurs between the water right decreed and the historical diversion. A more favorable approach would be to enact the incentive recommendations; the same results obtained through strict enforcement would be attained with less cost, conflict and adverse public relations. The State of Colorado is now in the process of tabulating water rights under a 1969 law as a first step in the eventual abandonment of paper and waste water rights. The publication of this first tabulation cost the state $90,000 and it is questionable how many more publications must take place to eliminate errors in the original tabulation. Utah has been going through abandonment proceedings on a sub-basin scale in order to accurately assess the amount of water diverted by water users. It has taken approximately 23 years to perfect the abandonment procedure. Three years ago they felt the system was sufficiently developed to permit a reasonable proceedings without undue expense and delay in the remaining basins. In the meantime, vast amounts of state money and time have been consumed. Appropriators in the unadjudicated areas are attempting to validate their rights through the application of the decreed quantity of water or sell to users who could utilize the entire right.

The question is whether we should follow the letter of the law or be pragmatic. Economic and social consideration should be weighted before embarking on such a policy. Would it have cost less to permit farmers to sell excess water rights to other users? The cost to the public of such a program may warrant the outright purchase of paper and waste water rights by the state with much less adversity.

Why the Push?

The time is now upon us to critically and seriously evaluate the allocation and use of water in the United States and particularly the western states at every level of influence and connection with this resource. It is essential not only to determine the degree of protection and security in

existing rights and performance of duties under current law and practices but also to assess the impact of environmental considerations upon the water picture. Environmental challenges have primarily been the concern of federal government and affected state and private organizations, but the trend emanating from this movement cannot be ignored either by water users or those responsible for its allocation, distribution and adjudication. The emphasis is no longer confined to the jurisdiction of state boundaries. Rather, basin, regional, national and international considerations in both water quantity and quality are becoming an integral factor for state and interstate water agencies.

So why the push? What does all this mean? Let's take the Colorado River Basin for example. Each state has adopted a water code for allocation and distribution of waters arising within its boundaries. In addition, the Colorado River has been subject to compacts, court decrees and congressional allocations in the division of its waters among the respective states. Interstate allocation is only quantity oriented. The treaties with Mexico obliges the United States to deliver certain quantities of water and only recently, through threat of a conflict, have negotiations partially resolved the quality problems in the basin.

Water users in the various states have appropriated water according to the state's system with little concern for the effect upon any user outside their immediate system. These water users still have little reason to be concerned with other users unless their own rights are being affected. With present and projected shortages of water and diminution of water quality in the Colorado River there are few, if any, right holders who should not be concerned, regardless of their location within the basin. Although secure in their own use, the next highest authority may have an obligation which, if met, will dramatically effect the individual user. Someone must meet the deficits if delivery commitments are not met. The question is, who? Someone must alter his practices if the quality of water is decreasing to the stage where downstream appropriators can no longer exercise their rights to the use so appropriated. Again, the question is who — the state or the water right holder?

Initially the state will be responsible to other states for its water uses, but the obligation will not stop there. State water officials will be compelled to examine state water budgets and possibly be required to enforce the law strictly, resulting in unwanted abandonments or forfeiture proceedings.

At this point, the field of environmental law and recent court decisions must be consulted. Many new concepts and doctrines are being adopted due to the assessment of man's relationship with his surroundings. A particularly important case that could have a significant impact upon the salinity problem in the Colorado River and the obligation of states and water users was recently decided by the Tenth Circuit Court of Appeals. In *Texas* vs. *Pankey* the court held that Texas had a right under federal common law to prevent the application of insecticides by defendants in the state of New Mexico in such a manner to damage the water of the Canadian River Watershed in Texas.[26] Citing the *Tennessee Copper Company* case which recognized the right of one state to abate a nuisance occurring in another adversely affecting the former the tenth Circuit Court stated

> the source or basis itself for such a quasi-sovereign ecological right in a state's position in a general political union was not discussed, the right apparently was regarded as having existed in the common law and as being entitled to remedy within common law principles. . .
>
> Federal common law and not the varying common law of individual states is, we think, entitled and necessary to be recognized as a basis for dealing in uniform standard with the environmental rights of a state against improper impairment of sources outside its domain.[27]

The implication of this case in handling the water quality problem of the Colorado River is clear where it can be demonstrated that a lower basin state's rights have been damaged by another state or actions occurring therein.

SUMMARY

Man cannot rely upon technology to solve all his problems nor ignore the true relationship he has with his environment and others within his realm of effect. The water problems of the western United States typify the predicaments of a

society that has relied upon a developed legal and institutional system to solve many of its past problems in governing man's relationship with water. The solution of the 19th Century has become the problem of the 20th.

We are no long justified in isolating our considerations to the immediate locale or region but must lift our sights to evaluate the entire impact of our actions. We can no longer hide behind nor rely upon, with impunity, the security provided by a century old concept that met the requirements of that day. By the same token, we cannot disregard the established system and those who dedicated their livelihood to its features.

Cooperation, coordination and pragmatic planning among water-users, state officials, regional bodies and governmental entities to devise solutions to the current quantity and quality problems are essential. Concentrating upon the agriculture sector in the western states, we note the present practices in use of water and the legal system which permits and perpetuates these practices, the advanced level of technological innovation to improve water management practices within the irrigation return flow system and the obvious discrepancies between the scientific improvements and the legal impetus to implement the same. Changes in the exercise of water rights to induce or require more efficient uses of this resource must and can be made either through voluntary action in which all parties involved benefit or through drastic legislation, judicial intervention, or strict administrative application of current rigid water concepts in which few parties involved are significantly benefited. It is not too late to unify and create a flexible solution to this problem — flexible and pragmatic so as not to itself become the problem as time changes.

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Institutional Influences in Irrigation Water Management*

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ABSTRACT

Among the many institutional influences that affect the development and use of water and land in the Lower Rio Grande Valley are (1) a proliferation of special districts, (2) inappropriate water management policies, (3) uncertainties in water rights and (4) numerous, competing governmental entities involved in planning for and administration of water resources. For more efficient management of water used in irrigation of crops it is recommended that small, underdeveloped irrigation districts be consolidated, and that systems rehabilitation be accomplished. Water meters should be used to measure deliveries of water to reduce the incidence of over-irrigation and extend the supply. To overcome resistance to changes in district organizations and managerial policies, widespread and intensive educational programs, emphasizing the benefits of more efficient water management, will be necessary. To provide for desirable levels of investment in water supply and distribution systems, uncertainties of rights must be eliminated. To promote allocation of water so that it is most productively used, rights should be negotiable. A change in water laws may be necessary. Development of drainage systems to solve problems of flooding, salinity, etc. will be facilitated by cooperative efforts among state, federal, and local agencies having responsibility for flood control and drainage. Integration of water supply, drainage and flood management systems appears necessary. This will require considerable redevelopment of facilities and reassignment of responsibility for control of systems.

Located in the southernmost part of Texas is a highly developed urban, industrial and agricultural region called the Lower Rio Grande Valley. It includes the land and water of most of three counties and covers about 3,000 square miles of land. It is one of three areas in the United States capable of producing citrus fruits and certain vegetables, and large quantities are grown annually. In recent years, about 800,000 acres of land have been cultivated, of which approximately 80 percent were irrigated. The irrigated areas, most of which are contiguous, constitute one of the largest single concentrations of irrigated land in the state.

While the valley is very productive of crops such as cotton, vegetables, citrus fruits and grain sorghums, it suffers from problems relating to land and water use. These problems include (1) periodic shortages of water, (2) inefficient

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use of existing water supplies, and (3) inadequate drainage. Physical conditions of supply and use of water are, of course, important to these problems. The flow of the river has varied from more than 4 million acre feet to less than one million acre feet annually. Water available per irrigated acre is often insufficient for optimum production of important irrigated crops. Obsolete facilities in some of the irrigation districts contribute to inefficient water usage. Unlined, open canals allow seepage, excessive evaporation, and loss of water to weeds and bushes along the ditches. Drainage problems are aggravated by too frequent, excessive applications of water, naturally high water tables and man-made obstacles to natural drainage. These conditions are important to land and water use and they are getting the attention of engineers and to soils scientists. But of equal importance are institutions that affect water allocation, use and conditions of use. They are significant to the efficiency with which we use water and they, therefore, deserve the attention of economists, political scientists, lawyers and others who can deal with them.

Institutions have been described as "well established social structures within which men do collectively the things which seem right and proper, in regard to some fundamental interest in life."[1] With respect to the problems of resource use in the Valley we are interested in those social mechanisms which function to direct and control resources and economic activities. They include such diverse things as water rights, commodity markets, traditional farming methods, water districts and government programs. Such institutions are the product of political acts, court decisions, customs, common law, tradition and other social phenomena. They are complex; they tend to be lasting and inflexible; but they are creations of men and can be altered to suit our purposes.

An important institution affecting the development and use of water in the Valley is the water right. Rights in Texas have been developed under the Spanish, Mexican and Texas civil law. During the reign of the Spanish and Mexican monarchs, rights to divert and use water from the Rio Grande were extended to settlers in connection with the land grants made. Since 1889 water use permits have been granted upon application by the state of Texas. Today all verifiable grants and permits are recognized, regardless of their origin, and they are employed to claim and take water from the river.

An unfortunate characteristic of the early grants and permits was the lack of specification of the amount of water involved. Reference in the grants was to the land area to be irrigated. By the middle of this century authorization to irrigate three-quarters of a million acres of land had been extended, while water in the river for irrigation was ordinarily sufficient for only 600-650 thousand acres. A court action to adjudicate rights was necessary. Rights were classified as to their nature and extent and were made specific as to amount.

Certainty in the water right is of course quite necessary to optimum development and efficient use of water. An individual who is uncertain of rights tends to make less than optimum investments in his water supply. He is somewhat fearful of loss and so he spends just enough to acquire that water for which he has a claim. As a user, the uncertain rights holder tends to exploit his source, "taking it while he can." The short term planning horizon of this individual is especially evident where he holds rights to an underground water supply. He sees himself in competition for the water in the common pool, and he uses it in a manner so that he is sure to obtain his "share." An inefficient use of such water is often the result.

In the Lower Rio Grande a second institution that is quite important to water development and use is the special district. In the three-county area there are 34 irrigation districts, four drainage districts and a few fresh water, navigation and other districts. These all operate to serve their members in various, necessary ways, but the profusion of districts, the variations in purpose and activity, and the competition among the districts do not contribute to efficiency in development and allocation of existing supplies. In a study of the irrigation districts we found them to vary significantly in their physical facilities, their capabilities for service to members and in the operational efficiency of their systems. Some districts can respond to requests for water deliveries quite promptly, i.e. in a few hours. But others, because of obsolete equipment and poor management, required two

or three days for delivery of water. Some districts had storage space for water, lined canals and ditches, underground pipelines and modern gates, weirs, etc. necessary for efficient handling of water. Others had a pump on the river, earthen canals and ditches choked with weeks and trees, and leaky, rusty equipment difficult to operate. Differences in operational efficiency have been found to be significant. Recently rehabilitated systems deliver a half foot more water to customer-members than do older, obsolete systems in a typical, irrigation season.[2]

Benefits from rehabilitation of districts, and in many instances from consolidation of districts to provide for larger operational units, are apparent. Our studies showed rehabilitation to be feasible, at least for the systems now serving the presently irrigated acreage.[3] Reorganization of districts, to increase average size, was also found to be economic. Annual operating costs for districts of 40-50 thousand acres are significantly lower than those for 10 thousand acre districts. But two factors act as deterrents to district reorganization and rehabilitation. First, operating costs of districts, which ultimately are paid by members via service charges, are small when compared with other farm operating costs. Second, and perhaps more significant is the effect of consolidation of districts on the control and management of district operations. With 34 irrigation districts now active in the region, 170 farm operators participate, as district directors, in policy and management decisions in their districts. Any reorganizational plan which would reduce the number of districts would also reduce the number of district managers and the number of farmers on district governing boards. Reorganization would certainly lead to a centralization of power in district management that would be opposed by many.

Associated with the facilities and the management of irrigation districts in the valley is the practice of unmeasured deliveries of water to farmers. This practice or policy is a product of a time when the water resource was plentiful—when there was little use of water in the Rio Grande by Mexico and less than a half million acres of land irrigated in the Lower Valley. It was then not necessary to measure and conserve water. But unmetered deliveries have led to farm management problems, and they are now critical to the efficient use of water which is no longer plentiful. A problem of land management in the valley is heavy clay subsoils. Drainage is poor and salinity is a problem. Too frequent and excessive applications of irrigation water complicate this problem. Increasing attention must be paid to moisture needs of crops to avoid improper applications of water. Measures of water delivery by means of meters would greatly facilitate soil and crops management. Improving the efficiency of use of water on crops will also "stretch" the water resource so that it may be used to irrigate greater acreages of land. Beneficiaries will be existing rights holders and water users who will produce a greater output per unit of water, and those who process and merchandise agricultural produce from irrigated land.

Another problem of institutions in the valley is to be found in the customary "pricing" policies for water. Water is not purchased from some autonomous water supply agency. It is acquired, via the exercise of individual rights, and by means of a water distribution agency (the irrigation district) which is owned and managed by rights holders. The "price" of water is thus simply the cost of delivery of water to users. So, only rights holders can obtain and use water and they use it as they see fit. Now when water is acquired (delivered to the farm) at no more than $10 per acre foot, it can be used for irrigation of almost any crop which can be grown in the valley. In such circumstances, water is used quite indiscriminately, on crops which produce low returns to this increasingly scarce resource as well as crops which produce high returns to water. There is little incentive for water rights holders to allocate this resource among alternative uses so that returns are maximized. When we compared the existing mix of crops on presently irrigated land to a mix of crops which would make efficient use of water and associated resources, we found significant differences.[4] The result is a regional net income which is considerably smaller than that which is possible.

A fairly obvious solution to this problem is a negotiable water right. Rights must be released from the existing tie to land. A change or clarification of water law to permit purchase and sale of rights, or lease of the right to an annual increment of water, would facilitate exchange so that water would be employed in higher value uses.

Farmers holding rights to water who are unable, for various reasons, to make the most productive use of them, would find it much to their advantage to sell all or a portion of their water rights. Individuals not having rights, but able to employ water in uses that produce high returns to the resource, could acquire water via the purchase of the right.

Negotiable rights are a desirable solution to problems of allocation of water whether it is a surface water resource in south Texas or a ground water resource in the high plains of western Kansas and eastern Colorado. Where rights to water are tied to land in specified quantities, there are ridigities in water uses which result in less than efficient allocation of this resource.

Drainage problems in the valley, exclusive of those created by inadvisable irrigation practices, are a result of high water tables, a relatively flat and featureless land without well established drainage ways and barriers to movement of water across the land which include highways, railroads, floodways, etc. The institutions which are important to the problems of drainage are a proliferation of organizations with plans to solve the problems, numerous other organizations with more or less authority and responsibility for drainage and an information system which operates most ineffectively to produce an understanding of problems and possibilities for solutions. Since the turn of the century, some private or public organization has been studying the drainage problems of the valley. There are numerous plans for controlling the route and flow of the river, managing runoff which at times reaches flood proportions, and providing relief from high water tables causing problems of salinity. Responsibility for positive action in flood control and drainage of lands rests with four or five established drainage districts, the International Boundary and Water Commission, and numerous irrigation districts which have been given responsibilities for the provision of drainage within their boundaries. But the boundaries of the drainage districts and the irrigation districts do not coincide and their facilities are not integrated. Many districts have no outlet for their drainage systems except for ill-defined drainageways which may be closed by a highway, railroad or floodway. The International Boundary and Water Commission has provided for the routing of high water flows in the river, through floodways and arroyos that have outlets in the Gulf.

Several, comprehensive flood control and drainage systems have been proposed by federal agencies, private engineering firms and district organizations. But effective means for informing the potential beneficiaries of these systems and for discussion of and comparison of these systems have been lacking. As a result, valley residents are confused, angry and resentful of what they see to be interference with "their" problems. When efforts to obtain appropriations or sell bonds are made, they fail for lack of local support. It is thus quite evident that attitudes, past experiences, suspicion, disorganization, etc. are factors more important to drainage problems than design of drainage systems.

These few institutions affecting land and water use in the Lower Rio Grande serve to illustrate the point. Institutions are significant factors affecting land and water use. We must learn to understand the nature and influence of institutional arrangements, the social mechanisms by which we control and direct resources for productive uses, so that we may change them, modify them, use them to achieve our ends.

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Sociological Considerations in Irrigation Water Management: Facing Problems of Water Quality Control

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ABSTRACT

The paper attempts to present a systematic framework for an examination of social dimensions involved in the analysis of water resources systems and in problems of irrigation return flow quality control. Throughout the presentation, emphasis is placed on the institutional constraints as well as major socio-demographic factors affecting the development and future use of water resources.

A major argument for an understanding of problems of water quality, especially in the Western United States is the changing circumstances and the consequences of four interrelated trends: the continuous population increase and in-migration to the West, the increasing urbanization and metropolitanization increasing industrialization, and, finally, compounded problems from ecological perturbations.

In delineating problems of water quantity and quality, a systems approach is utilized which attempts to integrate physical and social parameters and to incorporate major component parts of irrigation systems designed to achieve maximum productivity. In addition, major systems functions are also elaborated and water quality control problems are examined in connection with various criteria of efficiency, effectiveness, and efficacy.

The conclusion of the exposition rests heavily on the significance of cultural practices, the social forces of resistance to change, and the intricacies and limitations in the interpretation of the western water law. Finally, a number of suggestions are provided concerning water quality control in the context of an urgent need for an understanding of the larger social trends, social awareness, and integrated social and technical considerations.

INTRODUCTION

The present paper attempts to delineate a number of sociological considerations involved in any discussion of a water management system. Emphasis is placed throughout the following text on irrigation systems in the Western United States. The key problem necessitating the present exposition is the increasing degradation of water quality as a result of both natural and man-made pollution. More, specifically, special attention is focused on the prob-

lem of salinity in many irrigated valleys in the Western United States. It has been recognized, that the problem of salinity is closely associated, not only with the natural carry of various rivers in the area, especially the Colorado River, but also accentuated, if not aggravated, by present irrigation practices and attitudes concerning water use in the West.

The challenge for the social scientist, at the present time, is not so much the provision of exact answers on how to implement collective and individual changes, or incorporate attitudes leading to new practices that would alleviate present problems of water management. Moreover, what is needed at this time is a basic framework of understanding the larger social, cultural, and political millieu within which technical solutions can be implemented. At the same time, irrigation, or any water system, have to be understood in the context of larger regional and national trends which influence both the present status as well as future solutions of problems of water degradation.

The core argumentation of the present work centers around the following main points:

1. Larger demographic changes in the Western United States necessitate reconsideration of present and potential major water development systems.
2. Concerted research is needed in order to provide a better understanding of the cultural environment, social practices, and organizational arrangements within which present water systems operate and technology is applied.
3. In order to develop both research priorities and recommendations for action, it is imperative that a framework be developed which incorporates both physical and social parameters of any water system. We should be able to provide an integrated scheme in which the dimensions of both the technical and human conditions, as well as their interrelationship can be analyzed.

The essential argument, then, is that the use of water in any irrigated agricultural society must be socially controlled through a set of institutions known as an irrigation system. It is then assumed that the way in which water supplies, patterns of water distribution and water reclamation practices are regulated in a given irrigated agricultural society will depend largely upon the nature and structure of its irrigation system which like any other system is essentially dependent upon the larger socio-cultural environment, and the specific ecological circumstances of a given region.

One of the most widespread expressions today is the general phrase, "consideration of human factors," or "institutional aspects of . . ." in any major project. It seems almost ironic that such an important dimension as the social and human aspects of any system is relegated to a residual category of concern, which denotes mostly our inability to exactly define the non-physical dimensions of a given system. The problem, of course, here is that there is not only the engineers' or the practitioners' fault that they have not considered the social dimensions of any given project, but at the same time the state of the art, as well as our knowledge of social dimensions, is, to say the least, limited and the general propositions are at most tenuous. As more and more concern is expressed about the technological imperative, environmental disruption and the future dire consequences of man's interference with the biosphere, social scientists are increasingly called upon to provide recommendations and to answer long-standing questions on the human side of any project. Unfortunately, social scientists are ill-prepared to give the kind of answers that are urgently needed at the present time. More than anything else, the difficulty of providing answers rests on the general lack of a cognitive map that succinctly tries to describe the dimensions of the social system and the interconnection of each component part with other types of environments.

What we should attempt to do, in view of the lack of precise data and limited research on environmental questions, is to provide some generalizations and a systematic scheme of incorporating social and physical dimensions in any water resource system. What follows, therefore, is only an introduction to a problem that has only recently come to our attention. Water quality degradation due to irrigation practices, although occurring also in the past, had never the urgency and immediately that is becoming apparent in the changing social and

economic conditions of the Western United States. Most of the work in the past was primarily preoccupied with increasing crop yields and improving the structure of distribution systems with very little attention to associated problems of water quality degradation. The limited precious commodity of water will force a new thinking in which projects will be evaluated not only in connection with the general attempt of increasing national welfare and growth, but also in connection with much more complicated trade-offs and larger questions of social policy. The survival of this part of the country, as well as of the nation, will depend on a proper mix of technological feasibility and social considerations which increasingly will become the major elements for future water use development and for solutions to increasing problems of water degradation.

Perhaps another qualification should be added. Many practitioners and engineers feel that the title "sociologist" is adequate to at least guarantee or provide an answer to any question that incorporates the adjective "social." At the same time, social scientists blithely have been playing the role of social critic of new Jeremiahs, in providing blanket statements and generalized accusations against the "manipulators of the environment", "the engineering mentality", and "the despoilers of man's habitat." It is a happy event, indeed, that a golden mean is attempted in an increasing number of projects and research, and an increasing dialogue between technicians and social scientists is being established. Hopefully, the result of such coming-together will be an increasing sensitivity of the technical limitations and the physical constraints in any kind of a system, and, on the other hand, a recognition of the qualitative aspects of life and of the intangible dimensions involved in any type of a physical structure in the midst of any human community.

To sum up, then, the essential point of the above lengthy introduction we might underline again the need of both; first, an understanding of the larger trends affecting the development and future use of water resources systems in the country, and, second, of the pronounced need for an integrated framework that will bring together technical, social, economic, political, and cultural considerations in any attempt to solve the complex problems associated with natural and man-made degradation of the environment.

Irrigation In The Western United States

Irrigation enterprises are associated from early historical times with every civilized society. Today almost 7,000 years after the beginning of irrigated agriculture in Mesopotamia, irrigation systems continue to be built and provide the basis for national wealth and power for many countries. At the same time, the present level of agricultural engineering and organizational skills are better understood in the context of the larger social and economic environment. In all countries, complex irrigation systems are associated with larger social political changes of the economy and culture of a given region. At the same time, not only irrigation projects, but any larger water resources development has been associated with efforts for local growth and stability and regional and national impacts by providing a diversified basis for choice commodites and solutions to the basic problems of community survival.

As societies become much more complex and diversified and demands continuously increase and expand in scope and intensity, the use of scarce water resources and the preservation of the natural environment become much more important concerns in the planning and evaluation of water resource developments. In any water resource development three major problematic situations give rise to a continuous re-examination of the parameters of any water use system:

1. Continuously changing economic and social conditions (such as increasing population, rapid urbanization, and industrialization).
2. Adverse environmental circumstances stemming either from ecologically fragile environments, i.e. from natural sources of ecological pollution, or man-made perturbations, especially the increasing environmental disruption from the discharge of effluents, the fouling of the air, the misuse of the land, and the despoliation of the water supply.
3. The strong presence of institutional constraints, result of long historical and cul-

tural practices embodied in laws and doctrines and of traditions reflecting the norms and practices of a given society and community.

Irrigation is practiced on about ten per cent of the total crop land in the United States, yet it produces approximately 25 per cent of the total value of all crop production. As in other regions of the country, irrigation contributes to strengthening many facets of the region's economy in that it creates employment opportunities and provides for a diversified variety of choice commodites. The nation has abundant water resources, but the distribution and timing of the water resources differ in the various regions of the country, from season to season, and from year to year. In various studies it has been repeatedly indicated that water would play a major role for the life and development of the nation. An essential point, however, made throughout a number of diversified studies is the central hypothesis and projection that as the nation grows, the limitation of water and related land resources available to competing regions becomes more important from a national point of view. The survival of the country and the meeting of major national goals will be very much dependent on efforts of comprehensive planning and regional development, as well as integrated policies of proper resource development. At the same time, balanced population and balanced economic growth become essential ingredients for a successful equation of future survival.

Perhaps it is easier to talk about the West demographically since analysis follows established lines of State boundaries. It becomes, however, much more complicated to talk about the West from a water development point of view. The Mountain and Pacific divisions are comprised of a number of regions formed by natural water runoff districts not necessarily coinciding with present administrative boundaries. It would be a fair generalization, however, to say that perhaps with the exxception of the Columbia-North Pacific region and some parts of the California and Missouri regions, the area of what is known as the Mountain and Pacific States (that is the States west of and including Montana, Wyoming, Colorado, and New Mexico) is expected to have severe water shortages by the year 2020.

The Western United States has also been steadily moving from an economy dominated by agriculture and the resource producing industries of forestry and mining, to an economy increasingly shaped by urban growth, manufacturing, and service and recreational industries. Although the quantity of the water being used by agriculture still seems to increase, more and more urban oriented considerations will be influencing the nature of water development in the coming years in this part of the nation.

The anticipated water shortages in the West are not only a result of an expected reduction in the overall supply of water, but also a consequence of the following national and regional trends.

1. Increasing population, especially the continuous internal migration to western states. Indeed while the population increased by about 14 per cent during the last decade, 1960-1970, most of the states in the west increased substantially above the national average. Table 1 shows the population changes in the Western United States during the last three decades, where, with the exception of Wyoming and New Mexico, most of the States have been experiencing recently high rates of population growth.

2. Another important regional trend is the increasing urbanization and metropolitanization and the increased demand for municipal services with a resultant conflict between farm and non-farm water usage. As the urban centers in the West continue to grow, the most pronounced picture of population movement in the Western United States is the increased concentration of population around metropolitan cores. The 1970 census has already indicated that the fastest growing metropolitan areas and central cities in the nation are located in the western regions. Between 1960 and 1970 the metropolitan population of the Pacific division increased by 4.8 million or 27 per cent while the metropolitan population of the Mountain division grew by 1.2 million or 34 per cent. As a matter of fact, the proportion of the Mountain division population living in metropolitan areas rose from 51 per cent in 1960 to 57 per cent in 1970 (although this percentage is still among the lowest in the nation). In contrast, the population of the Pacific division is more

TABLE 1

Population changes in the Mountain and Pacific states, 1950-1970

Region	Years 1950	1960	1970	Per Cent Change 1950-1960	Per Cent Change 1960-1970
Mountain	5,074,998	6,855,060	8,283,585	35.1	20.8
Montana	591,024	674,767	694,409	14.2	2.9
Idaho	588,637	667,191	713,008	13.3	6.9
Wyoming	290,529	330,066	332,416	13.6	.7
Colorado	1,325,089	1,753,947	2,207,259	32.4	25.8
New Mexico	681,187	951,023	1,016,000	39.6	6.8
Arizona	749,587	1,302,161	1,772,482	73.7	36.1
Utah	688,862	890,627	1,059,273	29.3	18.9
Nevada	160,083	285,278	488,738	78.2	71.3
Pacific	15,114,964	21,198,044	26,525,774	40.2	25.1
Washington	2,378,963	2,853,214	3,409,169	19.9	19.5
Oregon	1,521,341	1,768,687	2,091,385	16.3	18.2
California	10,586,223	15,717,204	19,953,134	48.5	27.0

highly concentrated in metropolitan areas than elsewhere in the nation, having surpassed the Middle Atlantic division during the last decade.

With the exception of Montana, every state in the West (excluding Alaska and Wyoming which have no standard metropolitan statistical areas) had metropolitan increases of 20 per cent or more. States with the fastest growing metropolitan areas in the nation are Nevada, Arizona, and Colorado, the last with a metropolitan growth rate of 33 per cent, placing the State in fourth place nationally. Thus, by late 1960, we have in the region not only major metropolitan concentrations, but the beginnings of the emergence of megalopolitan concentrations such as the Front Range megalopolis in Colorado (encompassing almost 80 per cent of the total population of the State), the Wasatch Front megalopolis in Utah, and other megalopolitan formations such as the Sante Fe-Albuquerque emerging megalopolis, the Phoenix-Tucson conurbation, and of course the vast strip cities in California, particularly the San megalopolis between San Francisco and San Diego. According to the 1970 population count, neatly 24 million reside in four large urban regions—the California, Puget Sound, Metropolitan Arizona, and Colorado urban complexes.

Similarly, there seems to be general agreement in various studies and projections that the greatest percentages of all future population growth will be in the western third of the nation. It is expected that the West will increase its present national share of population from 17 per cent to 22 per cent by the year 2000. Thus, in most western states, three interrelated trends will be crucial in the solution of emerging problems of water supply and use: flight from the countryside and abandonment of small towns, increased metropolitanization and urban sprawl, and total population growth from both natural increases and continuous inmigration.

3. Increasing industrialization in the West which not only effects the total volume of water use, but also the quality of water supply. Major industrial concerns have moved, for example, in formerly sparsely industrialized areas of the Mountain states such as IBM and Kodak in Colorado, and Litton and Sperry Rand in Utah. Needless to say, one can only indicate the continuous growth of major industrial concerns in the Pacific States, especially California.

4. Another major trend in the region, as well as in the rest of the nation, is the increasing concern with ecological perturbations and ecological mismanagement and the consequently increased requirements and costs for pollution control which will affect both agricultural and non-agricultural uses. This is particularly

important in the case of the western states, especially the Mountain division, where a fragile ecological environment and limitation of resources compound problems of pollution. By the year 2000, it is estimated that the amount of water flow needed for pollution abatement in the West will be approximately 2/3 of all consumptive uses. In other words, while in the past the uses to which water could be put, essentially predetermined the character of the development. Now, and increasingly more in the future, water resources will be employed as a controlling commodity for shaping future patterns of population distribution and industrial location in the West.

Both the number of inhabitants and the spatial dimensions of the future large urban masses in the country are truly impressive. In view of the continuous trends of growth and the problems of urban sprawl and metropolitan decay, a national growth policy has been also proposed, advocating dispersal of the population away from the heavily congested urban regions. The West, relatively sparsely populated and despite its present rapid growth rates offers many opportunities for meeting proposed national policy (such as, e.g. new towns of various sizes). Resources, however, and the relatively fragile ecological environment of many states are restrictive conditions as to the maximum volume of future inhabitants, the choice of future locations, and the flexibility in the use of such limited commodities as water.

From the above four trends, it becomes apparent that new, different, and expanded demands for water will be generated in the Western United States. However, the urgency for a comprehensive water development policy depends not only on past and present trends of population increase, urbanization, industrialization, and ecological awareness, but also on other factors complicating the physical and technological aspects of water resources planning and use. A major problem is the numerous governmental jurisdictions, each with specific responsibilities for water conservation and management. Contrasted to the usually unified government unit managing water supplies in most of the nations in the world, the American federal system divides power between national (Federal government) and the States. The last delegate powers to several types of local authorities, including counties, cities, districts, and special administrative units. Thus, upon the numerous river basins of the Western United States and in addition to the national government represented by 17 states, there are to be found over 14,000 units of local government, all with various responsibilities for determining the allocations of water for specific uses. At the same time, segments of private enterprise vie with publicly owned and operated enterprises, such as, for example, in the case of hydroelectric power generation.

When we look at the problem of water management from a macropoint of view, we have also to acknowledge the larger difficulty where each State is obligated under either a compact, a court decree, or a judicial allocation to apportion the water of the interstate stream between States. Two problems are immediately associated with this fact, one of quantity and the other of quality. Thus, although liability for water distribution rests with the particular State, there is no effective or efficient mechanism for proper transfer of this obligation to the people using the water. At the same time, through the use (or misuse) of his water rights, the individual holder is effecting the quality of the stream, either through misapplication (resulting in salt concentration), or by taking the water out of the system and thus maintaining (and in some cases increasing) natural salt pick-up. As water supplies become more fully utilized, the importance of irrigation return flow quality will be of even greater significance in the over-all water management and development in a green basin.

What we have, then, in the West is a complicated system of demographic, administrative, and natural water districts which, in addition to natural overlaps, create a multitude of problems in jurisdiction and use. At the same time, given the open character of the water systems, we have major ties of every kind of a major basin with surrounding water systems. For example, the Colorado Basin is not a self-contained system but has many ties with surrounding areas, such as the provision of water from the Colorado to the Great Basin through the Central Utah Project, water from the Colorado Basin to the Missouri basin through,

for example, the Denver water withdrawal system, the Fryingpan-Arkansas transfer of water, the San-Juan Chuma transfer of water to he Rio Grande basin, the transfer of water to the Central Arizona project, and finally the major transfer of water from the Colorado River to the Southern California project (MWD). Figure 1 exemplifies the major river basins in the Western United States, which show the overlapping character of physical and administrative units as exemplified in State boundaries. When we think of problems of water management, we have to keep in mind the existence of a myriad of systems and subsystems, each only relatively autonomous, and open since they have a wide variety of linkages on different levels. In other words, a specific irrigation company is usually part of a federation of irrigation systems within a subsystem of a given basin and part of larger inter-basin exchanges.

Figure 1: River Basins of the Western States

The previous general discussion has attempted to show the overall trends affecting water use in the West. This part of the country will also continue to have continuous (although not highly increasing) water demands for irrigated agriculture. As Table 2 indicates, the western region of the United States will experience moderate increase in agricultural irrigation between 1980 to 2020. Various other studies have shown similar trends in the slow rate of increase in irrigation water use. A most interesting estimate of water use and projected requirements by region is that included in the composite Table 3, based on projections of the Water Council. As contrasted to other regions of the nation, most of the western regions present us with stationary trends of projected irrigated land use.

Irrigation, just as other of man's activities, can have detrimental effects on the environment. As indicated before, although it has long

TABLE 2

Projected estimates of agricultural irrigation in the Western Regions of the United States, 1980-2020 (thousands of acres)

Region	*1980*	*2000*	*2020*
Souris — Red — Rainy	90	230	250
Missouri Basin	8,050	8,950	9,600
Arkansas — White — Red	5,600	6,400	6,690
Texas Gulf	6,510	7,350	7,770
Rio Grande	2,050	2,180	2,200
Upper Colorado	1,900	2,150	2,250
Lower Colorado	1,820	2,190	2,400
Great Basin	2,340	2,510	2,570
Columbia — North Pacific	7,350	7,810	8,490
California	9,050	9,600	11,540
TOTAL — WESTERN REGIONS	44,760	49,370	53,760
MAINLAND UNITED STATES	49,990	56,910	62,890

TABLE 3

Regional projections of population and irrigated land in the conterminous United States, 1960-2020

Region	Population				Thousands of Acres				
	1960	*1980*	*2000*	*2020*	*1960*	*1965*	*1980*	*2000*	*2020*
North Atlantic	43,896	56,693	74,993	101,726	240	310	380	550	700
South Atlantic-Gulf	19,727	29,099	42,602	61,438	850	1,500	1,800	2,750	3,750
Great Lakes	25,474	33,171	43,293	57,640	100	140	230	350	470
Ohio	18,793	23,498	30,742	41,241	35	55	90	180	260
Tennessee	2,979	4,118	5,643	7,785	15	20	30	40	50
Upper Mississippi	11,759	15,180	20,004	26,766	80	140	210	390	550
Lower Mississippi	4,619	5,871	7,815	10,587	700	900	2,100	3,050	4,150
Souris-Red-Rainy	652	791	1,023	1,368	10	15	90	240	250
Missouri	7,845	10,337	14,260	20,079	6,600	7,400	8,050	9,000	9,600
Arkansas-White-Red	7,122	8,972	11,952	16,055	3,100	3,800	5,600	6,400	6,850
Texas Gulf	8,109	12,491	18,230	25,901	5,100	5,500	5,500	5,500	5,500
Rio Grande	1,604	2,649	4,173	6,063	1,950	2,000	2,050	2,050	2,050
Upper Colorado	317	454	700	1,025	1,370	1,440	1,800	2,000	2,000
Lower Colorado	480	3,038	4,768	7,194	1,520	1,660	1,750	1,800	1,800
Great Basin	970	1,790	2,822	4,285	1,700	1,860	1,950	2,000	2,000
Columbia-North Pacific	5,359	7,581	10,463	14,444	5,450	6,250	7,700	9,500	11,200
California	15,584	28,167	43,317	64,003	8,420	8,850	10,150	10,750	11,100
Total. . .	176,289	243,900	336,800	467,600	37,240	41,840	49,480	56,550	62,280

been recognized that the quality of water draining from irrigated areas has consistently been degraded, it is only recently that attention has been given to the possibility of controlling or alleviating the degraded quality of our water resources. This interest has been accentuated not only by recent general concern with environmental mismanagement, but also by increasing federal legislation addressing itself to the establishment of a national policy for the prevention, control, and abatement of water pollution.

The water quality problems associated with irrigation return flow are of particular concern because irrigated agriculture, especially in the West, is the largest consumer of public water supplies, and it is likely to be so in the foreseeable future. As a matter of fact in federal statements questions have been raised regarding the need for the various forms of federal assistance in relation to the outlook for national food and fiber requirements. A number of authorities, private as well as federal, have recently raised serious questions as to the permanence of economically feasible irrigation agriculture in the West in view of the rapidly increasing demands on this fixed resource.

Perhaps we need to elaborate a little bit on the problems of water quality associated with irrigation in the Western United States. One of the things we need to bring forward is an essential question and a fundamental reassessment which begins to emerge concerning the need for future water projects in the seventeen states west of the 100th meridian. Indeed, the constant hunt for water is coming under increased criticism, especially for all these big projects designed to bring more of it to arid lands. A question that has been repeatedly raised runs as follows: "Should the government pay farmers not to till the soil in States with high rainfall while it subsidizes farm irrigation in States with low rainfall?"

Thus, it appears that there are two interrelated problems: first, the question of water supply which is associated also with the present wasteful use of limited water; and, second, the economic impact of increased natural, as well as man-made pollution. According to EPA, BLM, and CRBC estimates, man in his works is al-

ready significantly increasing the salt load in the Colorado River's natural salinity. As a general rule, in salinity concentrations above 500 mg/1, the value of water begins to diminish not only because of increased costs in water softening, corrosion, etc., but also because of the need for greater amounts of leaching water and the damages incurred from diminished crop yields or the inability to grow certain high-value crops. it is now estimated that the bill for this salt reaches $16 million a year and it is expected to reach $28 million by 1980 and $51 million by the year 2010, unless the salt loads are reduced substantially. At the same time, it should be noticed that the major efforts concerning return flow quality problems are directed at control of the source, rather than treatment and reclamation of degraded water.

The natural problems of salinity are accentuated by the larger trends of growth described above. So as man has been and will be taking water out of the river and its tributaries, as well as daming the streams and polluting existing water supplies, water used for irrigation will not only be picking the salts in the land, but will be increasing the salt levels because of the above conditions. The vast natural evaporation, municipal use, and the malpractices in the use of water based on the convenience of the irrigator and protection of his water right, are not only diminishing water supplies and increasing natural water salinity, but they are also excelerating problems of man-created pollution in the water systems of the West. Many federal studies have been pointing out that in order to maintain salinity levels (700 parts per million of dissolved solids is increasingly used as a possible standard), water use will probably have to be curtailed and steps taken to remove the salts.

Given the natural problems of water salinity, the increasing demands for water and the parallel trends of population growth, urbanization, and industrialization and increasing water quality requirements, we may have also increasing conflicts in water use. On the one hand, water quality is assuming greater importance due to the pressures of population growth, municipal expansion and competition among a wide variety of uses of this limited resource. On the other hand, with each water use there are also associated quality considerations pertaining to both the water extracted from and that returned to the source. A simple diagram (Figure 2) summarizes in a graphic way the problematic situation giving rise to a water management system, where a configuration of structures and procedures transforms the water resources into water-related products and services, and where the desired outputs have both use, as well as quantity and quality limitations.

From this simple diagram describing the essential parameters of a water management system, we would like to generate a discussion on the social aspects involved in water quality management projects. Many other individuals have been addressing themselves to the natural and technical dimensions of the problem at hand. It has been contended, however, that we have been approaching the need for water quality management with little preparation and knowledge of either policy considerations or technology for improving the quality of irrigation return flow. Thus, it becomes apparent that in order to deal effectively with problems of water quality management, consideration also has to be given to the following major questions:

1. What should be the future of water development projects for new irrigation in the Western United States?

2. What are the larger considerations for an understanding for agriculture in a changing society?

3. How do we account for the relationship between man, technology, society, and environment.

4. How can we make some tentative recommendations concerning the social aspects of water quality management especially in the Western United States?

The last point brings again forward the central thesis that in order to speak of the social environment of the Western United States, one should have to consider a complex combination of normative resources, community environments, cultural traditions, water management systems, sources of social conflict, and their interconnection with limited physical resources.

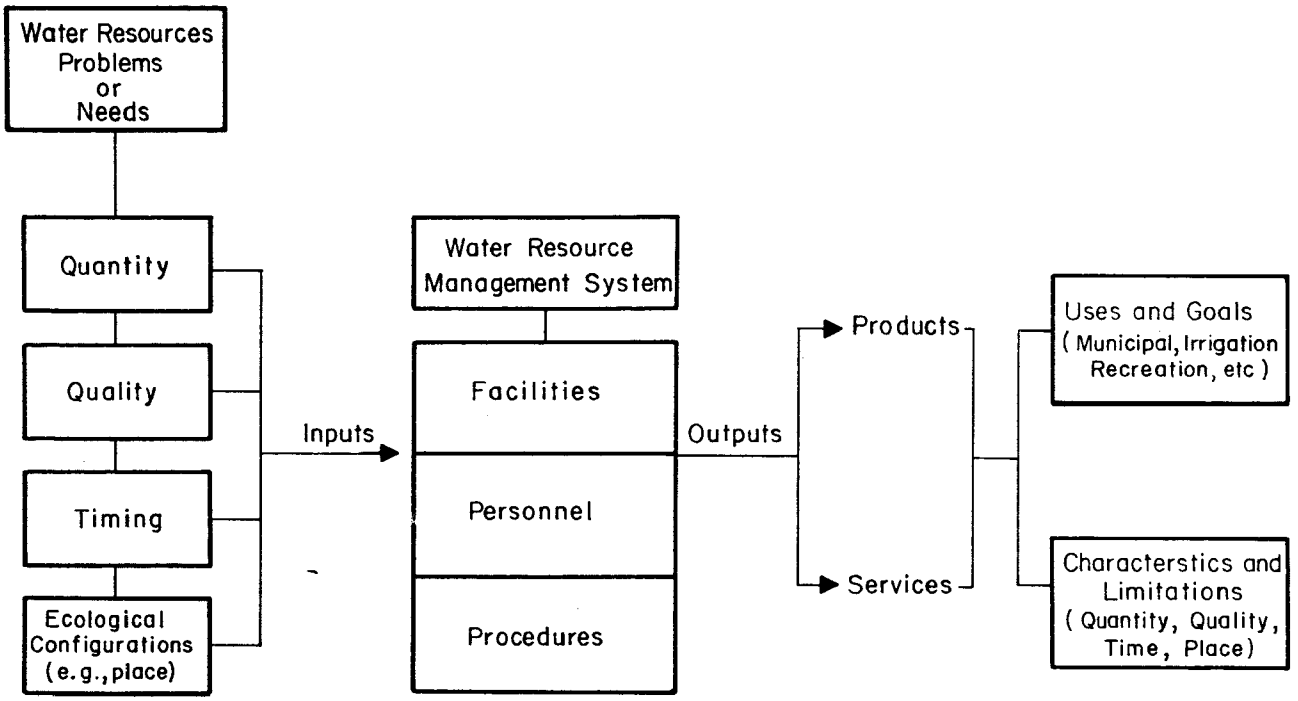

Figure 2: A Simplified Version of Water Resources Problems and of Water Management

Towards A Systematic Viewpoint of Man-Made And Natural Environments

Sociologists traditionally have always included the environment in their theoretical frameworks, but the interconnection between physical and social environments has not always been clearly stated. In order to be able to examine any kind of a physical system, it becomes imperative to provide a much broader view of natural resources, and a more careful analysis and delineation of individual and aggregate levels involved in the presentation of a system. This is particularly true in irrigated agriculture which has to be examined within a complex socio-technical framework that is operating with varying degrees of success in relationship to an encompassing natural environment.

Increasingly in current years, many of the basic decisions related to water development are made not only with technical considerations in mind, but at the same time increasingly call for a better knowledge of the political, legal, and social economic institutions which control the supply and allocation of water. Yet, in any water development project, we have a number of unknown processes providing us with complex interactions between physical, economic, political and social factors. This complex whole does not permit accurate prediction and measurement of the consequences of any proposed water development action, or even a very accurate argumentation either in favor or against large-scale water policies. The above simply indicate that the limited water supply, the increasing population, the problems of water quality, and the multiplicity of uses call for new integrated forms of coordination and understanding between various disciplines affecting and being affected by a given water development project.

Thus, it has become apparent that the problems of water quality are very much interconnected in an intricate pattern with not only problems of overall supply, but are part of a general integrated policy of regional and national welfare. A policy of improved water management, in terms of both quantity and quality, requires a coordinated effort towards an efficient and effective maximization of limited natural resources. Therefore, the problem of water quality management is not only one involving the very careful considerations of physical potentialities, but also a clear and thorough understanding of problems of political, economic, legal, and social feasibility. As a matter

of fact, from the sociological point of view part of this problem involves also a delineation of the organizational capability of present water management systems for new alternatives and new organizational forms, an understanding and utilization of a social climate of receptivity towards new cultural practices and towards changing social and economic circumstances.

As it has been repeatedly emphasized before, because of large national trends and new or expanded demands while the overall supply and quality of water are vital in any future planning of resource utilization, equally important from the sociological point of view are the following major considerations:

1. Organizational innovations applied to increased efficiency in the distribution of water.
2. New cultural practices and attitudes towards innovative forms of water use and an understanding of the demands for efficient use.
3. An understanding of the broader community culture and of the institutional structures involved in obtaining water supplies, the forms of distribution, and the meeting of larger society goals.
4. The recognition, at the same time, that as pressures for existing supplies increase, there is also stronger concern for proper social control against water quality deterioration.

To be able to develop a more systematic framework for a discussion of social aspects of water quality management, we have to see an irrigation system within its larger context. Figure 3 tries to exemplify the relationship between nature, society, and man, and the central role of technological developments. This diagram simply indicates the close interconnection of the major components of the proposed system which operate within a biosphere. Thus, each one of these component parts—man, society, nature, and technology—affect, and in their turn are affected by each other, and a change in any of these factors will have consequences and alternatives for the others. In the case of water quality management, technical breakthroughs in salinity control will affect its component part of the biosphere, and so will also structural changes in society (e.g. ubanization), new cultural practices, ecological shifts, etc.

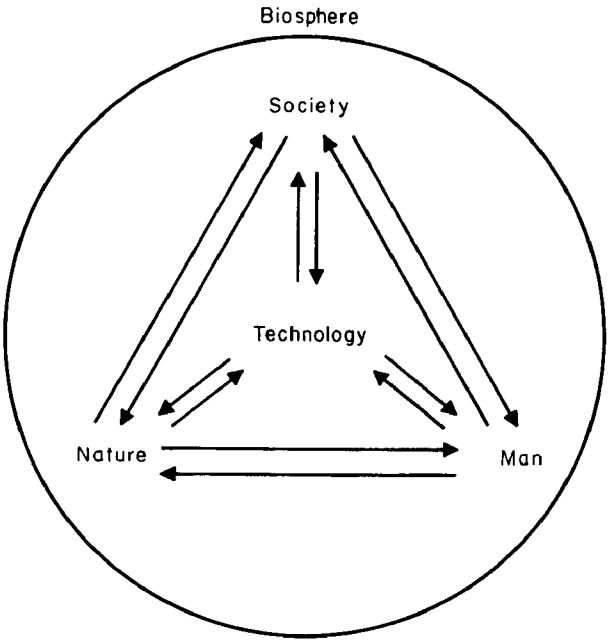

Figure 3: Relationship Man, Society, Nature, and Technology

Such general remarks and impressionistic observations help us introduce a systems analysis point of view. Water management is perceived as a system operating in a given environment where inputs (physical and social) processed through the "organization" result in outputs or goals established for the functioning of the system. The systems approach makes it possible to identify not only component parts, but also various conditions which enable the parts of an irrigation system to function "effectively" in relation to each other and "efficiently" towards the achievement of desired goals.

The most important element is to describe the kinds of environments in which a given water management system operates. To start with, there are two major environments in which systems or subsystems operate. First, the *external* environment which is both natural and man-made, and second, the *internal* environment which encompasses all subsystems operating primarily inside the boundaries of the external environment. Simply, a particular system implies a collection of people, devices, and procedures intended to perform some function. A systems model is a working model of a social model which is capable of achieving a goal and involves the systematic exploration, analysis and evaluation of all the possible consequences

of proposed alternatives to an on-going system. More specifically, an irrigation system may be designed in such a way as to be able to include a variety of environments and inputs and be defined as the application of water by human agency to assist the growth of crops and grass. Figure 4 is a simplified version of an irrigation system designed to achieve maximum agricultural productivity.

Figure 4 indicates that four major environments, i.e., the physical environment with particular ecological constraints, the existing socio-demographic conditions and spatial arrangements, the economic potentialities, and the normative milieu (which includes not only norms, values and institutions, but also legal constraints and cultural resources) provide the necessary inputs for the operating of a system or organization. In addition, there are additional inputs into an irrigation subsystem, arising from constraints and/or facilitators of the larger system or external environment, such as the state of technology and technical innovations, the larger political network and the linkages with other administrative units, and the constraints from larger resource policies affecting the operation of the irrigation subsystem. Perhaps, from the sociological point of view, the most important inputs are those patterns of normative behavior which influence water use. The most crystallized part of the normative environment, i.e. the legal norms and the legal interpretation of institutionalized arrangements are among the crucial elements for the successful operation of an irrigation system.

The inputs from a variety of environments are processed through structures and procedures which attempt to maximize desired goals. This organizational system varying in size, scope, integration, and complexity from region to region, and from basin to basin includes both physical facilities developed for meeting the need of increased productivity, etc., and the intangible aspects of organizational infrastructure, such as rules of operation, pattern of leadership and command, efforts for control, integration, information, and communication and ways of interacting with other organizational environments.

The desired goals or objectives in an irrigation system denote the output part and revolve around a variety of goods and services

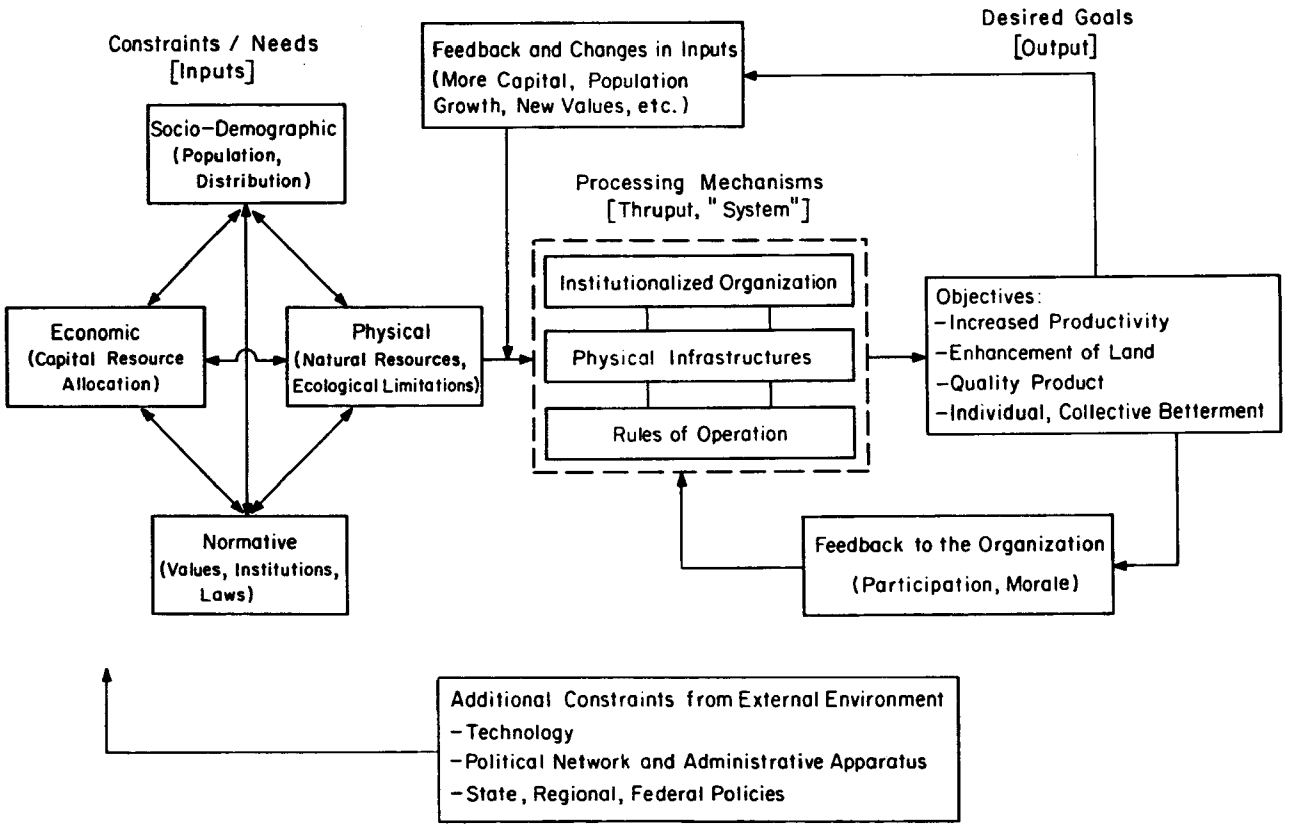

Figure 4: A Simplified Version of a Local Irrigation System

for individuals, communities, and regions. Recently, in addition to such obvious objectives as increased productivity, wealth, land enhancement, security, etc., increased mention is made of such qualitative goals as enhancement of quality of life, esthetic satisfaction, regional balance and others, which provide us with infinitely more difficult problems of evaluating the performance and effectiveness of an irrigation system.

System or organization and inputs from diversified environment are linked with the output of an irrigation system, through two feedback loops. One, provides feedback to the "organization" or processing mechanisms through increased participation of individuals organizational morale and direct interaction between, e.g. users and/or officials and members of the organizational units. The other feedback loop is understood in terms of additional inputs through increased or achieved objectives, such as e.g. more capital invested, increased population, and changed attitudes or norms vis-a-vis any of the four environments (and other external constraints) which provided the initial input. Ideally, feedback processes could serve as corrective mechanism, monitoring devices, and additional inputs which could increase the organizational effectiveness and, thus the achievement of desired and expanding objectives.

While Figure 4 shows the overall structure of an irrigation system and the more or less static consideration in terms of the constraints of the natural and socio-cultural environments, Figure 5 attempts to provide an overview of the dynamic aspects in the operation of a given irrigation system. An irrigation system's functions can be broken into the following major areas, each of which requires a vast array of not only organizational structures, but also complex rules and procedures and critical considerations of decision-making and policy guidelines:

1. Water supply and water source considerations, including new or potential sources of supply.

2. Water control aspects and characteristics of diversion, storage, reservoirs, and wells, and the assorted institutional forms of regulation.

3. Water distribution systems, the means of transmission and patterns of water flow.

4. Water utilization, the system of irrigation and crop operations, (including crop and leach-

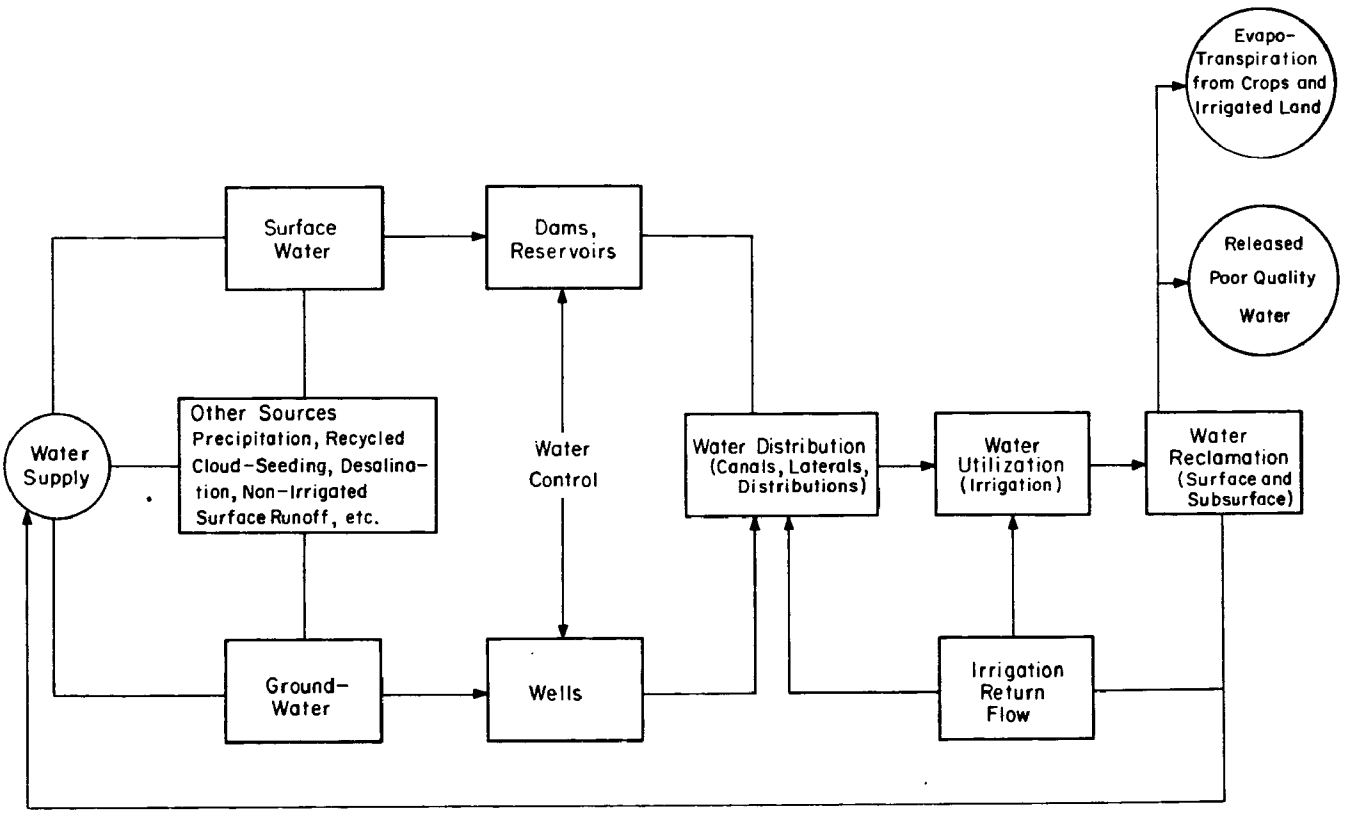

Figure 5: Irrigation Water System Functions and Dynamic Processes

ing requirements), as well as cultural practices and scheduling programs.

5. Water reclamation and aspects of drainage, including field outlets, release of poor water, and irrigation return flow.

Both figures 4 and 5 try to emphasize the multiplicity of levels of analysis and the multiplicity of functions in an irrigation system. Most important, at each level and for each subsystem component part and function, problems of institutional order arise, difficulties of organizational arrangements, and need for specific understanding of the normative rules involved at each stage or phase of a dynamically operating irrigation system.

Water Quality Control: Preliminary Considerations

The general argument and preoccupation with the systems approach is part of an effort of integrating physical and non-physical dimensions in irrigation systems. Such an integration implies that any change in either physical or social dimensions of our system will have impacts on each other. If we perceive, then, that the sociological examination of a water management system or an irrigation system involves a careful delineation of inputs, organization, and output, we may be able then to examine the problem of water quality management as one affecting all parts of the system. If the problem under consideration is, let us say, increased salinity of a river as a result of both natural and man-made pollutions it will be easier to examine its effects, and consequences as a result of three types of changes in an irrigation system:

1. Changes in the external environment which lead to changes in inputs, such as changes in the total number of people, changes in the economy, changes in technology, etc.

2. Changes in organizational structures and procedures because of changes in size, capacities, and technology, different roles or organizational power, etc.

3. Changes in output or what has been described as "goal alterations", which result from goal displacement, new targets of society, and new expressed or latent policies of federal, state, or local authorities.

It has been repeatedly stated that the practice of agriculture may have detrimental effects on the environment. Presently, the major irrigation return flow quality problem areas in the West are the San Joaquin Valley, the Colorado River Basin, and the Rio Grande River Basin. In addition to these areas, many other areas in such States as Nevada, California, and Utah have serious problems and are affected by irrigation return flow.

The research concerning such areas and the suggestions made on potential solutions for controlling irrigation return flow, seem to emhasize that a basic attack in minimizing quality problems is the improvement of water management practices on the affected crop lands. Physical suggestions to the solution of this problem and improved practices that can be used on the farm include a diversified array of technological solutions. At the same time, there is wide recognition that there are various institutional methods which can be used to control irrigation return flow quality.

If we assume, for the time being, that there are solutions to the technical problems imposed by the return flow hydrologic cycle, we need to see from the social point of view what is the so-called institutional problem in improving water quality management. Essentially, the key problem seems to be a simple one, that is, how to minimize water passing below the root zone or how to account for deep percolation losses. This key problem, and the fact that more salts are dissolved in the water, is not equally prevalent in every geographical area in the West. Not only every area is differentially affected from quality problems arising from irrigation return flows, but also the historical establishment of an irrigation project has something to do with the overall problem of salinity. In other words, certain areas of the West not only had less salt to start with, but over time their salts were washed out. The areas of concern today are then those areas of high natural salts whose problems of high salinity are accentuated by irrigation practices which allow the additional solution of salts in the deep percolating water. It seems that a dilemma appears in all these areas of concern, that is, that although some water is needed to maintain agricultural productivity (leaching requirements) people quite

often over-irrigate and, therefore, permit more deep percolation losses. Essentially, then, the problem of water quality management is one of exceeding a satisfactory level of leaching requirements.

The question of how these leaching requirements are to be met is answered by proper application efficiency which involves a two-fold consideration, i.e., leaching requirements and crop requirements. To be able then to have proper application efficiency we need essentially two major things.

1. Find the exact technical specifications for application efficiency. This is a technological problem to which increased concern and research is addressing itself presently.

2. Answer the question of how to implement technology, which in turn is based upon three further considerations: a) the implementation of technology in accordance with existing water rights; b) implementation of technology through organizational innovations, i.e., with improvement in size of the units that are capable presently, and increasingly so in the future, to meet both the economic and organizational demands of expanded efficiency; c) implementation of technology in accordance with changing attitudes of people, i.e., not only changing attitudes in relation to irrigation practices, but also changing attitudes with general patterns of water use in a given region.

It becomes apparent, therefore, that the western salinity problem is very closely tied to the major considerations of population, urbanization, industrialization, and ecological trends mentioned at the beginning of the paper. The belated concern with increasd salinity in the Colorado River has come about as a result of the fact that as we take more water from the basin, we leave less water for application efficiency. The less the water, and with the volume of salts remaining more or less the same, any withdrawal from a given river basin is bound to raise the concentrations of salts. Thus, the agricultural problems have become the focus not only because of outright agricultural damages, but also because the problem has become a larger one involving a more complex equation of a multiplicity of water uses. If salinity criteria are established, their implementation would conflict with existing water rights, interstate compacts, even with international agreements concerning the division and allocation of any given basin's water resources. In addition, long-established water rights with no consideration of improvement in the salinity level, may preclude any future development of irrigated land and impose restrictions which are totally unaccepted in present practices. All in all, however, independent of the establishment of any salinity criteria, it is again concerted public policy, comprehensive planning and larger social considerations that will ultimately determine new water uses, rather than piecemeal restrictions or efforts for post hoc enforcement in both the quality and quantity aspects of irrigated agriculture.

As it has been emphasized above, a crucial problem in any water management system are the types of incentives and the structure of the organizational arrangement that may permit irrigators to control irrigation return flow. Incentives for efficient management usually come in the form of economic incentives, either negative or positive. At the same time, the larger law regulations contribute substantially to both the creation and the solution of irrigation return flow quality problems. Indeed, in many instances, there is no incentive to conserve water in most of the irrigated valleys in the West. A key problem is that most irrigators feel that they must use their full water right because they are afraid of losing any portion of the unused right. Despite repeated observations and findings that such attitudes of excessive use of water right frequently contribute to local drainage problems, the practice persists because it is rooted in deep seated personal fears as to water use and on the notion that the exercise of the right means the preservation of the right. A paradox then seems to emerge, i.e., that efficient farmers who through improved technological practices save water, are not able at the same time to use the conserved or saved water to irrigate additional land or to supplement their water supply for lands having an inadequate water right. A farmer who has used inefficient and many times flooding techniques has a built-in advantage and, thus, any incentive from the legal point of view is diminished by the realities of the persistent attitudes in the use of

present water rights. This simply compounds any effort for improving his water management practices.

It should be emphasized that although the law *per se* may be satisfactory, the difficulties arise mostly from its interpretation. Provision, therefore, should be made in the law, as well as in everyday practice, of building incentives, both economic and legal that would make possible water saved by a given farmer to be sold or rented to a farmer having an inadequate water supply. Such an attempt points also to the fact that water supply should be redistributed within an irrigated valley in an efficient way to meet total water agricultural demands rather than be based on capricious individual farmer requirements. The distribution of existing water supplies has to be met not only in tighter regulatory procedures, but also in a more efficient organizational structure that would permit better monitoring and budgeting of available water.

At the same time, safeguards need to be built in any interpretation of the effort towards water saving, so that not only plans for a comprehensive water resources development for a given basin can be made, but also inordinately high prices could be avoided.

Improving irrigation management implies not only technological innovations and better interpretation of water law, but also other organizational improvements. Such organizational improvements include, for example, better irrigation scheduling which is very closely associated with the present negative aspects of western water laws. When we combine better information regarding soil moisture management in the root zone of the crops and more sersitive equations concerning application efficiency criteria, the farmer may still wish to use his full water right. It is assumed, at this point, that various positive incentives and resulting changing attitudes will allow saving of water, and transfer of saved water to other uses of a comprehensive water resource development plan of an irrigation basin.

A major problem in the overall management efforts is the lack of single management units in most of the irrigated valleys of the West. Most of the valleys in the western United States are characterized by the existence of quite a number of fragmented irrigation companies and districts, with each company responsible for water delivery to only a part of the valley. In most cases, separate institutions exist to handle the water drainage system. In order to develop not only effective irrigation return flow quality control programs, but also to be able to improve the overall efficiency of a water system in a given irrigated valley, it is imperative that the entire irrigated system should be coordinated on an integrated basis. We need to move from private, single company oriented management units to what we may describe as primarily valley-wide alternatives. This brings forward a very difficult, but challenging water management problem, that is, an attempt towards consolidating separate small irrigation companies into single entities which would have advantages of size, economies of scale, and potential for comprehensive valley-wide development. Water quality degradation will be reduced if attempts are made to face the problem not only as an integrated approach of various units within a valley, but also as a much larger effort to integrate the particular basin with other surrounding systems. We are speaking, therefore, here not only for comprehensive systems on a small scale within a given valley, but for comprehensive larger entities encompassing a number of basins, a collection of systems, and hopefully the larger region of natural water flow. In other words, we are speaking for inter-valley coordination, as well as inter-basin and inter-region coordination.

Many other suggestions have been offered concerning the solution of problems of irrigation return flow quality control. Essentially, most of them can be summarized around a cluster of individual and community attitudes which seem to have consequences for the quality of a given water system supply. There is agreement that there is a host of social practices, traditional ways of irrigating and using the water, as well as modern practices which directly degrade the quality of a given water supply system. The immediate solution and the attack against such practices can be easily perceived as a simple problem of social control. This means that perhaps one of the immediate attacks to this problem is to require that anyone degrading the quality of water should pay the cost

of treating this water. However, this approach treats the problem of the degradation of the quality of water only from a symptoms point of view rather than addressing itself to the essential cause. It is not only difficult to assess penalties, but also to provide a very complex and expanded system of policing and mechanisms of law enforcement. The attack to the problem would be to try to reach the roots or the causes of the water quality degradation, that is, the kinds of social practices and the types of attitudes which would improve water use before degradation of water takes place. From the social point of view, in changing practices, and provided that there are also technological solutions to both natural and man-made pollution of water, we should be concerned with the following major areas:

1. Priority of use (and the interpretation of legal doctrine).
2. Geographic area (and the increasing scope of planning).
3. Population affected.
4. Political units involved.
5. Disciplinary scope (and the attempt towards a multidisciplinary synthesis).

As it was pointed out above to bring about changes in the organizational behavior of all types of units involved in water management, as well as effective response from individual irrigators, three major categories of policy decisions and social action must be made: first, strong incentives for efficient or new uses (economic benefits, redefinition of the doctrine of beneficial use, etc.); second, structural changes (such as new organizational arrangements, creation of inter- and intro-state agencies, appelate bodies, water brokerage—either private or public, etc.); and, third, "regulatory counter-incentives" (such as stricter enforcement, pricing policies, etc.). More than anything else, however, all the above changes or attempts for modification must be guided by a pervasive spirit of social consciousness and a new world outlook of individuals and collectivities away from their small closed system of their particular community, to the larger and much more complex regional scene.

To be able to give answers to the above major areas of concern, we need to develop an assessment methodology which would enable us to identify in a systematic way potential causes and corresponding effects, a description of their characteristics, and possible consequences in the overall water system. The following diagram of Figure 6 attempts to show the steps involved in a systematic methodology utilizing a multidisciplinary model of assessment and of alternative plans of evaluation.

In trying to determine effective water management, we need to keep in mind that alternatives offered should be evaluated under three different conditions of "effectiveness." Traditionally, the most widely used term has been that of *efficiency* which attempted to relate in simple, economic benefit-cost analysis the relationship between resources (input) and proposed goals or attempted targets (output). An efficient system has been an easy one, that with minimal cost, and that cost has always been understood in terms of dollar values.

The term *effectiveness* has been used mostly in terms of organizational performance or the meeting or purely organizational goals, that is, the relationship between a given organization (thruput) and perceived goals (output). It has been also used in the context of the overall measure of achievement for a system, derived from its subsystem's performance or related to its interactions with other systems.

And last, but not least, the term *efficacy* is used, which attempts today to incorporate the meeting of social goals and a much more comprehensive relationship between input, thruput, and output. Efficacy, in other words, attempts to move beyond purely economic considerations, or criteria of organizational effectiveness, and tries to answer the question of how a particular system can efficiently, effectively, and guided by principles of social awareness, meet goals of a given society. The term of efficacy brings forward an increasing awareness of a whole number of intangible benefits to be accrued from a given water system that can not be directly measured by existing economic or other quantitative criteria. Qualitative criteria and the consideration of social goals transcending purely utilitarian criteria provide us with the very difficult task of trying to strike a balance of fulfilling water use goals in expedient, technologically and economically feasible ways, to

larger questions of social policies and attempts of environmental balance. This implies that any water management system, as well as any attempt for comprehensive water use development would be also dependent on subjective models which are much more difficult to construct, yet they contain long-range policies for a *social* use of natural resources.

These kinds of considerations probably provide the answer to a point raised earlier. As it will be recalled, many questions have been expressed as to the advisability of continuous water use development in the arid West under the adverse or fragile ecological conditions of the territory. It would have been easier to have water systems responding only to technological imperatives. However, the valleys of the West and the irrigation systems are not abstract simulation models responding to the whims of any experimentor. They include individuals and communities that have developed a pattern of life and whose welfare and future may even depend on inefficient water systems. Even a marginal or not particularly efficient agriculture fulfills the purpose of being a supportive social system for a number of individuals and part of the ongoing life of a number of Americans. It is not easy to dictate a social policy that would be based solely on criteria of efficiency and effectiveness without considering at the same time the so-called "human factor." And in many respects the human factor involves questions of inefficiency (and ineffectiveness) because the social costs of dislocation and disruption may be so high—when examined under criteria of efficacy—that they may dictate a policy of continuing present practices with little technological intervention.

The above discussion, however, does not mean that there is very little to be done with the irrigated valleys of the West or with any presently declared inefficient or ineffective water management system. It only points out that the problem of water quality management control is a complex one that requires considerations beyond accepted technical, economic, or even political constraints. Our effort for improving water quality management implies, therefore, a manyfold attack and a series of efforts aimed at improving project irrigation efficiency and effectiveness, under the larger rubric of efficacy and the achievement of larger social goals.

An artificial distinction between technical and non-technical propositions concerning water quality control may serve as the basis for summary and tentative conclusions.

A) *Technical Recommendations*

1. Water measurement.

Research has shown that where water measurement is not practiced throughout a given water system, irrigation efficiencies are generally very low.

2. Modification of delivery schedule.

It has become apparent that the modification of present delivery schedules, especially where the continuous flow method is found to be inefficient, are necessary conditions for an efficient system. It should be recognized, however, that the major obstacle to overcome such a difficulty are the long-established local customs of water delivery and use.

3. Treatment.

Concern is expressed and recommendations have made that studies are needed to evaluate methods of reduction of salt or nitrate in various soils and that they are apparently technical solutions to such an attempt.

4. Water charge schedule.

Studies again have shown that when excess water charges have been levied, water use has remained reasonably low without reduction in crop yields. The water charge also should be used for all irrigation districts, not only against those using excessive water, thus making the farmer cognizant of the need for good irrigation practices.

5. Modernization of project facilities.

Many of the irrigation valleys are characterized by nearly obsolete or worn out structures since a number of the projects constructed date back to the early 1900's. This is particularly true of turnouts, canal linings, and other structures. A program for replacement and modernization is needed in order to increase efficiency.

B) *Non-technical recommendations.*

1. Improvement in operational practices.

Organizational innovations need to be introduced in many irrigation systems to be able to increase water deliveries in an efficient manner. If we are aiming towards efficient water use and proper water scheduling, as well as an efficient delivery schedule, we must have reason-

able assurance that water can be obtained when it is needed or when one is entitled to receive it. Streamlining of companies innovative administrative procedures, trained personnel, and overall organizational effectiveness are parts of the guarantee for improvement in operational practices.

2. Consolidation of irrigation companies and districts.

From previous discussion, it has become apparent that it is difficult to accomplish the task of an efficient water management system, which will be capable of providing an efficient water delivery system as well as minimizing degradation of the quality of the water supply, unless there exists the proper operational unit which may allow the employment of better qualified personnel, streamlined procedures, and the administrative facilities for a better management. Consolidation of irrigation companies and districts becomes a necessary condition for a better management, reflected not only in lower operating costs per unit area, but in more efficient regulation and control of the water supply, avoidance of duplication, and provision for increased capital availability for better irrigation projects. At the same time, the coordination and combination of small irrigation districts may permit exchanges or regulations of water between districts, and if practiced at a larger scale, permit better regulation between basins and interregional arrangements. The elimination of overlapping personnel and facilities are parts of the guarantee for a new operational structure that will be able to respond to the changing needs of agriculture.

3. Institutional changes.

The major institutional change required in the West is the interpretation of the western water laws, which will provide incentives for efficient water use. This is particularly true for States having major quality problems resulting from irrigation return flow. There, not only studies should be undertaken to delineate the changes required in water law interpretation, but also procedures must be devised so that such interpretations could be incorporated in water law structures and mechanisms that could be implemented. The interpretation of western law must always be followed by the kinds of administrative and procedural structures which will permit regulation and control and effective interpretation of a limited resource and of the individual water right.

4. Social Control and regulation.

The above recommendations need to be incorporated into control measures which will make feasible the improvement of downstream water quality. Coordinating committees representing local, state, and federal interests may be developed, that would attempt to show only the particular benefits to be gained from a concerted policy. Larger mechanisms, such as appelate administrative bodies, could also help resolve potential social conflicts. These social conflicts may arise for two reasons: either because the *scarcity* of water leads to conflicts of interests between individuals and groups; or, because *efficient use* of water requires organized, coordinated, cooperative, even comprehensive action on the part of all persons or organizations sharing the resources of a given system.

5. Comprehensive planning and social policy.

It becomes apparent that the problem of water quality return flow is only part of a larger developing complex resource utilization scene in the western United States. Already framework studies attempt to provide a systematic examination of the requirements for comprehensive planning in various basins. What is also needed is an understanding of the emerging new trends which will affect not only agricultural practices, but will determine the question of a valuable environment in the Western United States. Agriculture needs to be examined in the context of major population trends, the increasing centrifugal forces of urbanization, metropolitanization and suburbanization. At the same time, there should be cognizance of the fact that increased industrialization and the multiplicity of uses of the water in the West will also contribute to the growing problem of return flow quality control. This is also to be understood in the context of water as a precious recreational use in the West, whose increasing role will also affect attempts for control and improvement.

6. Education programs.

All the above, technical and non-technical proposed solutions for improved water man-

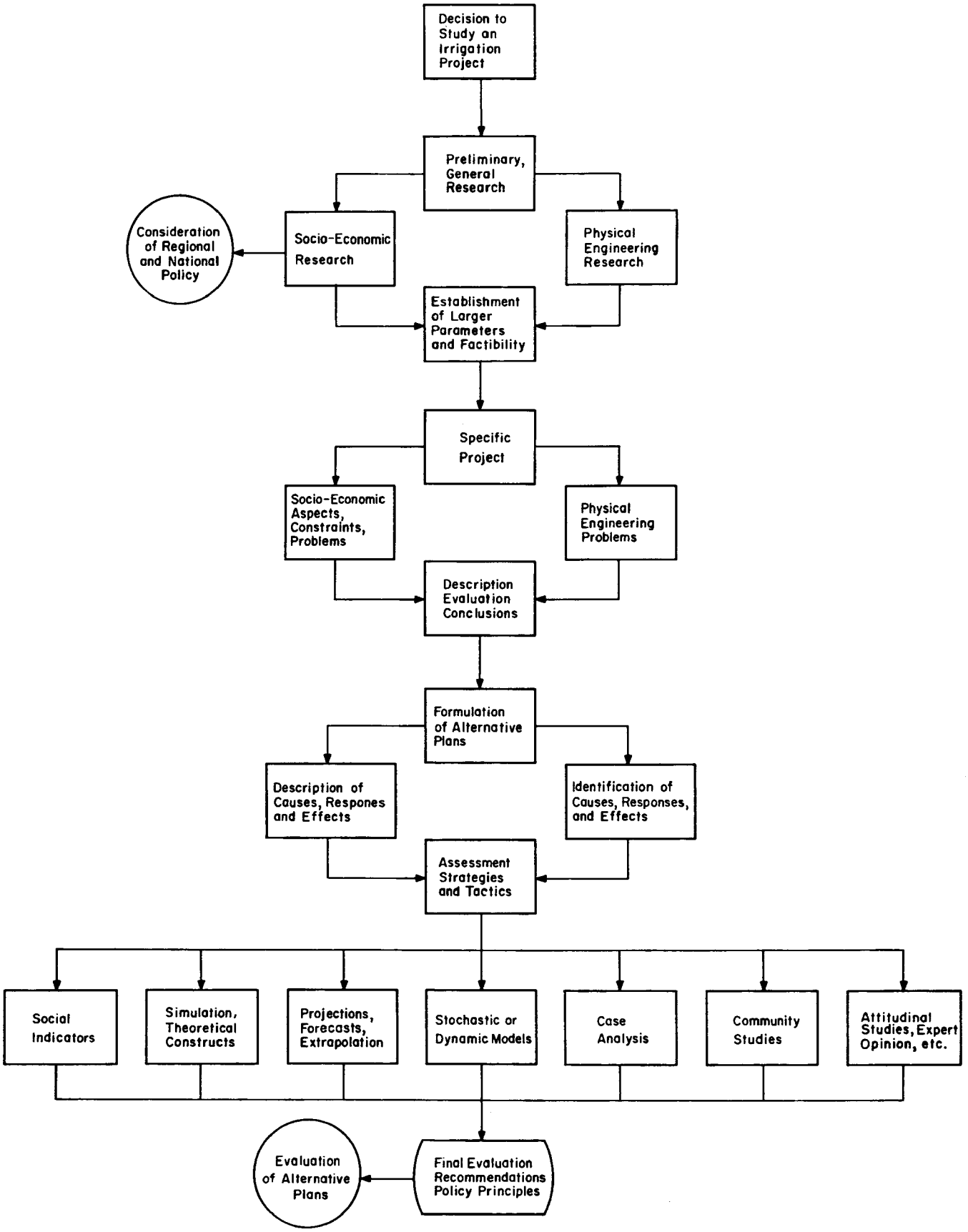

Figure 6: Research Strategy and Assessment Methodology in the Implementation of Irrigation Systems

agement, depend very much on strong educational programs and informational inputs attempting to reach all those responsible for the operation and use of a given system. Everybody involved, from the single user, the communities, the board of directors, the local, state, and federal authorities need to incorporate into their way of thinking the idea of social responsibility and wise use of every type of natural resource. This is part of a larger biospheric commitment in the use of resources as part of a limited commodity which needs to be wisely extracted and also wisely used. Training programs should be incorporated into all research and development activities, making it possible for all people to participate early in the formulation of larger policies and to, thus, be able to understand the consequences of present practices and future trends.

It has been found in many studies that when individuals have the chance to participate early in the formulation, administration, and actual running of a project they are much more able to understand the implications of certain actions and much more able to respond to the challenge of change. The challenge of change indeed is the one that will ultimately determine all efforts for water quality control. The management of a system is only a small part of a larger effort to develop comprehensive policies, proper administrative mechanisms, and mobilization of individuals who will be able to respond to the continuous challenge of growth, to the natural limitations of the region, and to the challenge of continuously improving the environment for the common welfare.

No research and no technological solution will be able to compensate the damage done to an area and to our total environment by people who have very little appreciation of the larger picture and by individuals who cannot perceive their role in the context of an integrated social system. The social awareness of problems and an intelligent citizen approach is part of a much larger challenge for both hard and soft science practitioners who are increasingly asked to answer questions of future survival in an environment characterized, not by the quest of continuous growth, but by questions of quality and the search for a way of life and a community of people who recognize natural limitations and the fragility of our planet.

BIBLIOGRAPHICAL COMMENTS

Generally, the literature on sociological aspects of water management, or on problems of water quality control is very limited. Rather than provide any specific literature, we would like to cite the works most useful in the above argumentation.

A number of general works are important in providing general information on water resources and population trends. These include, *The Nation's Water Resources* prepared by the Water Resources Council in 1968; Robert M. Hagan, *et. al., Irrigation of Agricultural Lands,* Madison, Wisconsin, American Society of Agronomy, 1967; Gilber F. White, *Strategies of American Water Management,* Ann Arbor, University of Michigan Press, 1969; Otto Ekstein, *Water Resource Development,* Boston, Harvard University Press, 1958; various current reports of the Census Bureau, including available returns of the 1970 enumeration; and, finally, for some major theoretical dimensions and the role of water in society, A. Wiener's, *The Role of Water in Development,* New York, McGraw-Hill, 1972.

For the social dimensions in the use of natural resources, there are a number of select articles and special papers that are of use. Among them, B. H. Bylund, *"The Human Factor and Changes in Water Usage Patterns," Water Resources Research,* 2 (1966): 365-369; Arit K. Biswas, "Socio-Economic Considerations in Water Resources Planning," Paper presented at the National Water Resources Engineering meeting of ASCE, Atlanta, 1972, Samuel Baxter, "Effects of Urbanization," *Water Resources Bulletin,* 4 (1968): 51-56; the present author's "Social Processes in Water Management Systems" in *Treatice on Urban Water Systems,* Fort Collins, Colorado, State University, 1971, pp. 722-739; R. K. Linsley, "Some Socioeconomic Aspects of Water Development," in *Water Resources Use and Management,* Melbourne, Melbourne University Press, 1964, pp. 429-437; Kenneth Wilkinson and L. W. Cole, *Sociological Factors in Watershed Development,* Mississippi State University, Social Science Research Center, Preliminary Report 20, 1967; and Evan Vlachos, "Urban Growth and Natural Resources," in *Urban Demands on Natural Resources,* Denver, University of

Denver Press, 1970, pp. 259-276. I have also greatly benefited from an unpublished manuscript of Garth Jones, "A Conceptual Framework for the Evaluation of Irrigation Systems." And for a perceptive analysis of regional trends, socio-economic conditions and natural resources, one should see Ernest A. Engelbert, "Regional Planning for Water Development in the Western United States; The Relevance of American Experience for Other Nations," in *International Conference on Water for Peace,* Washington, D.C., 1968, Vol. VI, pp. 256-268.

In thinking about problems of water resource management, the following works were informational: *Social and Ecological Aspects of Irrigation and Drainage,* New York, ASCE, 1970; U. P. Gibson, "Integrating Water Quality Management into Total Water Resources Management," *"Critical Reviews in Environmental Control,* 2 (1971): 1-55; and Irving K. Fox and L. E. Craine, "Organization Arrangements for Water Development," *Natural Resources Journal,* 2 (1962): 1-44.

For a more general discussion of the systems approach in social sciences, the list of works is lengthy but of great benefit can be the discussions in Walter Buckley, *Sociology and Modern Systems Theory,* Englewood Cliffs, Prentice-Hall, 1967; Joseph H. Monane, *A Sociology of Human Systems,* New York, Appleton-Century-Crofts, 1967; and, the descriptive but insightful little volume by C. West Churchman, *The Systems Approach,* New York, Delta Books, 1968.

A very difficult problem in the present exposition has been the locating of pertinent works of problems of irrigation return flow, salinity, etc. Most beneficial for a first understanding of such problems were the works of James P. Law, Jr. and Jack L. Witherow (eds.), *Water Quality Management Problems in Arid Regions,* Ada Oklahoma, 1970; the Report of Gaylord V. Skogerboe and James P. Law, Jr., submitted in November 1971 to the Office of Research and Monitoring Environmental Protection Agency, under the title, "Research Needs for Irrigation Return Flow Quality Control;" and Lloyd V. Wilcox, "Salinity Caused by Irrigation," *Journal of the American Water Works Association,* 54 (1962): 217-222.

Finally, in trying to develop alternatives for evaluation and aspects of technology assessment, in addition to a number of general sociological works (such as on social indicators), a few specialized works were helpful in the clarification of the argument. These include: William K. Johnson, "Assessing Social Consequences of Water Deficiencies," Journal of the Irrigation and Drainage Division, ASCE, 4 (1971): 547-557; V. Vemuri and N. Vemuri, "On the Systems Approach in Hydrology, *"Bulletin of the International Association of Scientific Hydrology,* 15, 6 (1970): 17-38; and the unpublished paper of A. Bruce Bishop, "An Approach to Evaluating Environmental, Social, and Economic Factors in Water Resources Planning," (mimeographed, no date).

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