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EVALUATION OF SALINITY CREATED BY IRRIGATION RETURN FLOWS

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Water Program Operations
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EVALUATION OF SALINITY

CREATED BY IRRIGATION RETURN FLOWS

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Office of Water Program Operations

Environmental Protection Agency

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Cover Photograph: Irrigated lettuce in the Palo Verde Valley, California. Water for the Palo Verde Project is diverted from the Colorado River. Photo courtesy Bureau of Reclamation, U.S. Dept. of the Interior.

ILLUSTRATIONS

ACKNOWLEDGEMENTS

The information presented in this report has been drawn from various sources. The references cited represent a worthwhile and useful assemblage of publications on the subject of irrigation return flow but is not intended to be all-inclusive. The Soil Conservation Service, USDA, and the Bureau of Reclamation, USDI, have made a valuable contribution in the form of both technical advice and photographs of various aspects of problems associated with irrigated agriculture and methods related to their solution.

Technical advice, comment, review and editing were provided by personnel of the Non-Point Source Control Branch, Office of Water Program Operations, and by personnel of other elements of the Environmental Protection Agency.

INTRODUCTION

Irrigated agriculture has been practiced in arid and semi-arid regions of the world since the beginning of man's civilized history. Supplementary irrigation during the growing season is becoming increasingly commonplace in humid regions.

The earliest known records of man's attempt to raise crops using artificial application of water are found in the Middle East and North Africa. The remains of wells, underground collection systems, dams, reservoirs, terraced irrigation works, catchment basins, aqueducts and conveyance channels in the Middle East all indicate that the land once supported a large population with an advanced knowledge of irrigated agriculture. Today, this once verdant land is largely barren and non-productive as a result of salinity buildup in once-fertile valleys, salt marsh development, denudation of topsoil by aeolian and fluvial erosion, sand dune encroachment, and general deterioration.

Of the world's nations, China irrigates an estimated 182,855,000 acres (74,001,400 hectares), India 93,000,000 acres(37,637,100 hectares) and the United States approximately 44,000,000 acres (17,807,000 hectares). Irrigated agriculture is practiced on about 10 percent of the cropped land of the United States and yields about 25 percent of the total national crop value.

The Problem

Irrigation is not without dilemmas. Serious problems of salinization and water-logging of land commonly result from inferior or inefficient irrigation practices. The problem of excessive salinization is not necessarily confined to soil. Increases in salinity of waters receiving irrigation return flows have been occurring at an alarming rate in the United States during the past two decades. Water pollution resulting from irrigated agriculture originates from both non-point, or diffuse, and point sources. The impact of agricultural irrigation wastes, including salinity, sedimentation, pesticides and nutrient runoff and organic debris, on water quality degradation has only been recognized fully in recent years. This was due to the gradual development of the problem. Significant increases in irrigated acreage since the termination of World War II, along with increases in the use of pesticides and fertilizers have focused attention on water quality deterioration associated with irrigation practices.

This report is devoted primarily to an objective presentation of the nature and extent of water quality deterioration created by the introduction of salinity into the aquatic environment by irrigation return flows. While it deals primarily with salinity, or total solids, it recognizes that sedimentation, nutrients, pesticides, organic debris, and heavy metals, among others, contribute significantly to the problem of water quality degradation throughout the nation. Water uses affected are municipal, industrial, commercial, downstream agricultural and recreational, all of whom receive water of ever-diminishing quality. Deep percolation of irrigation returns is causing increasingly significant pollution of the ground water environment in many parts of the nation.

SUMMARY AND CONCLUSIONS

1. Irrigation, the artificial application of water to the land, can result in serious water pollution problems in the aquatic environment wherever it is practiced.

2. Numerous water quality changes may take place during irrigation. The magnitude and nature of these changes are functions of mineralization, evaporation, transpiration, ion exchange, solution, leaching and biochemical action.

3. Surface runoff water from irrigated lands may be expected to contain a mineral composition similar to that of the applied water, with a significant increase in pesticides, fertilizers, organic debris, soil particles, colloids, heavy metals and other pollutants derived from accidental or purposeful placement onto the land.

4. Irrigation water which has moved through the soil (deep percolation) may become burdened with excessive dissolved solids, and possibly a change in ionic composition. The water may also acquire soluble fractions of fertilizers such as nitrates. A reduction in insoluble nutrients, degradable pesticides, oxidizable organics, pathogenic organisms and bacteria can be expected.

5. Degradation of water quality can be costly to the consumer. Adverse economic effects on municipal, industrial and commerical users often necessitates increased and expensive treatment. Agriculture frequently experiences impaired crop yields and greater water use requirements. Deep percolation, often required to leach salts below the plant root zone, may introduce toxic levels of nitrates into the aquifer.

6. Improved and modernized on-the-farm water management practices represent the most feasible approach to the abatement or elimination of water quality degradation caused by irrigation return flows. An acceptable control program includes the application of recognized technology at the pollution source. This is in harmony with the time-honored concept that pollution be abated at the source rather than by applying treatment to the contaminated waters.

7. Demonstration and pilot control projects designed to improve on-farm irrigation efficiency should be afforded high priority in the overall effort to abate pollution created by irrigation returns.

8. Legal and institutional factors combine to constrain more efficient water practices, particularly in the Western

United States. The concepts and rules of the prior appropriation doctrine, in which water quality is not considered, are major deterrents to the implementation of a sound water management technology. A possible solution may lie in the reinterpretation of the doctrine.

9. A piecemeal approach to the water quality degradation problem caused by irrigation return flows will be ineffective. Only a basin-wide total control program will produce acceptable and lasting results.

10. There is a need for additional documentation of pollution caused by irrigated agriculture throughout the nation. Records currently available too often involve only those areas where salinity is already acute. Frequently, the modifying or diluting effects of ample water supplies mask continuing increases in salinity. Well-planned monitoring and surveillance programs will direct immediate attention to seemingly inconspicuous problem areas and allow corrective measures to be applied.

11. The best available irrigation and drainage management methods, aimed at assuring a minimum generation of wastes, should be incorporated into the initial planning and development of all future irrigation projects.

GENERAL

Irrigation is the artificial application of water to land to supply and maintain optimum soil moisture necessary for plant growth. In arid and semi-arid regions of the world, irrigation accounts for almost all of the life - supporting water for agriculture whereas in sub-humid and some humid areas irrigation is supplementary and principally used to maintain soil moisture during periods of drouth.

The practice of irrigation was known to the peoples of ancient Egypt and Asia Minor. Irrigation systems in that part of the world are evident today. This beginning was in arid and semi-arid lands similar to those in many parts of the Western United States. Increases in population created concentrations in cities and villages and a reduction in the nomadic way of life. This created increased crop demands and irrigated agriculture was the method that could assure a continuous food supply on a reasonably reliable basis. Irrigation was, and is, a science of survival. Successfully practiced, it enabled man to survive drouths, support larger populations, and expand territorially and culturally.

There are approximately 44,000,000 acres (17,807,000 hectares) of irrigated land in the United States. About 90 percent is in the seventeen western conterminous states*. The balance lies in humid and semi-humid states where there is a need for supplemental irrigation during periods of drouth. Florida, for example, ranks tenth in the national inventory with 1,490,000 irrigated acres (603,000 hectares). The importance of irrigated agriculture to the national economy is apparent when it is realized that irrigation is practiced on about 10 percent of the nation's cropland and generates approximately 25 percent of the total crop value.

Irrigated agriculture accounts for about 35 percent of the total water withdrawn in the nation for off-channel uses and approximately 85 percent of the total national water consumption. The national annual irrigation water requirement, projected to 1980, is placed at 140,000,000 acre-feet(172,688,600,000 cubic meters) (1). This water will be supplied from both surface and ground water sources.

The application of water to cropland under controlled conditions has many advantages. It enables the equitable distribution of water-soluble fertilizers, liquefied animal

*Those conterminous states located west of the eastern boundaries of North Dakota, South Dakota, Nebraska, Kansas, Oklahoma and Texas wastes, and pesticides. Crop cooling to ensure continued growth, and frost protection are additional benefits (Figure 1). Partial control of date of maturity and subsequent early harvest of crops such as fruits, vegetables and flowers may also be achieved through irrigation (2).

Irrigation Return Flow

Of the total water applied during irrigation, as much as 65 percent may be used consumptively. This use includes loss by direct evaporation from the soil plus transpiration from plants. Consumptively-used water is that discharged into the atmosphere as vapor and is no longer available for reuse within or by the existing system. The balance of the applied water, or about 35 percent, is termed irrigation return flow and finds its way back into the surface or subsurface hydrosystem. Irrigation return flow then, is the water diverted for irrigation which returns to the surface stream or to the subsurface ground water environment (3).

The practice of irrigation necessarily degrades the quality of applied water to some degree inasmuch as the water is used consumptively. Evaporation and transpiration alone may concentrate dissolved minerals in the applied water as much as 300 percent. In addition to an increase in salinity, the applied water may acquire sediments,

FIGURE 1. Freeze protection afforded citrus nursery as a result of overnight irrigation in Florida. Temperature was approximately 27 degrees farenheit for 8 hours. Photo Courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

pesticides, fertilizers, organic debris, heavy metals, trace minerals, farm oils and greases, bacteria (including pathogenic organisms), nematodes and other forms of pollution. Salinity, a major water pollutant, and its effect on the aquatic environment, is addressed in this report.

Salinity increases associated with return flows may be brought about by both consumptive and non-consumptive uses of applied water. The principal constituents comprising return flow salinity are the water-soluble compounds of calcium, magnesium, sodium and potassium. Minor amounts of iron, aluminum, manganese and other cations may also be involved. The dominant anions in the compounds are carbonates, bicarbonates, sulfates, and chlorides. Any combination of these cations, and anions form the salts or "salinity" of irrigation return flows.

A basic process by which irrigation return flow elevates the salinity of a hydrologic system with which it is in contact is termed salt loading. This process increases the total salt burden of the receiving waters by adding salts. A second process is concentration, in which the salinity of a water body or hydrologic system is increased by evaporation. Evaporation merely reduces the amount of water but does not reduce the total quantity of dissolved salt. Return flows may be aggravated by non-associated sources of pollution as natural salt flows, mining, and oil field operations. Additional sources including municipal, commercial and industrial waste discharges, together with runoff from urban, construction, highway and agricultural sources may augment return flow salinity.

Origin of Return Flow

Return flows originate from both surface and subsurface sources. Surface sources include bypass water, tailwater (wastewater), and the incidental source, precipitation. Bypass water is that diverted for irrigation but returned to the source without having been applied to the land. Tailwater is the excess remaining after an irrigation and is hopefully retained in ditches or in ponds. The subsurface source is water which has percolated through the soil profile. This water finds its way either to the zone of ground water saturation or to the stream through artificial drains or by shallow diffuse seepage (non-point sources) along the stream bank.

Excessive application of irrigation water often results in tailwater losses as shown in Figures 2 and 3. If movement of the runoff is excessive, serious erosion may occur and valuable topsoil lost (Figures 4-7)

Runoff may have high turbidity imparted by sediment. Eroded soil particles may transport adsorbed contaminants such as pesticides, fertilizers, and organic material. Tailwater is exposed to other pollutants and may contain non-adsorbed pesticides that were applied directly to the soil or washed from the plant by rainfall or sprinkler irrigation. Soluble fertilizers, soil amendments, animal wastes and organic constituents may also be found among tailwater pollutants. Evaporation accounts for further concentration of dissolved contituents. Finally, excessive application may cause a significant rise in temperature resulting from storage in pools, canals, laterals and ditches (4).

Bypass water ordinarily acquires relatively little additional contaminant inasmuch as it represents water routed through conveyance canals and ditches and which is returned directly to the stream without having been applied to the land. It too, is subject to concentration through evaporation and may be consumptively used.

FIGURE 2. Destructive effect created by excessive amount of tailwater being lost from field having too steep a grade for efficient irrigation. Hudspeth County, Texas. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 3. Execessive amount of tailwater being lost from irrigated field. Note water flowing across highway. Hudspeth County, Texas. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 4. Considerable erosion caused by excessive irrigation on light sandy soil. Gully depths are greater than two feet. Near Caldwell, Idaho. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

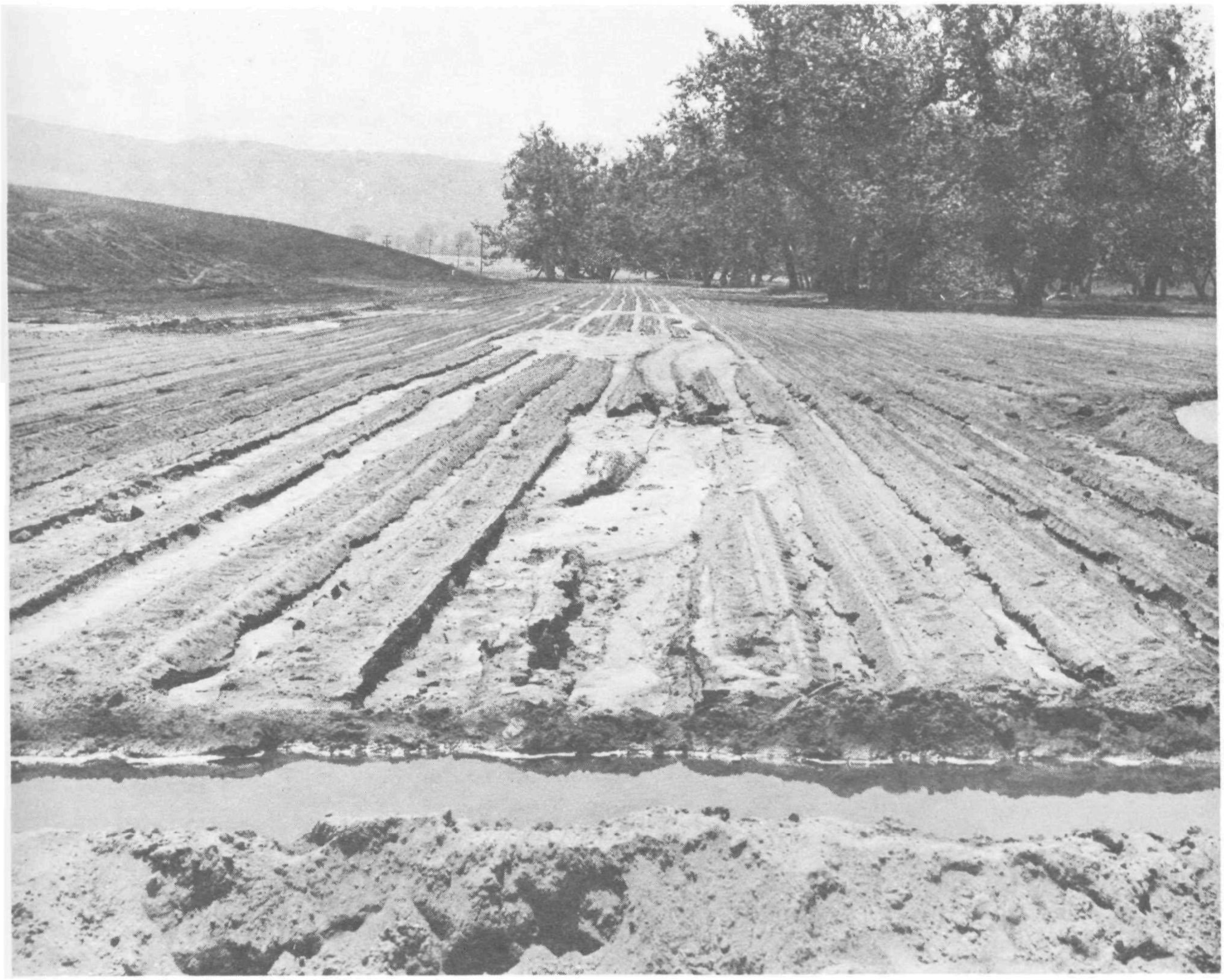

FIGURE 5. Erosion caused by excessive irrigation. San Diego County, California. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

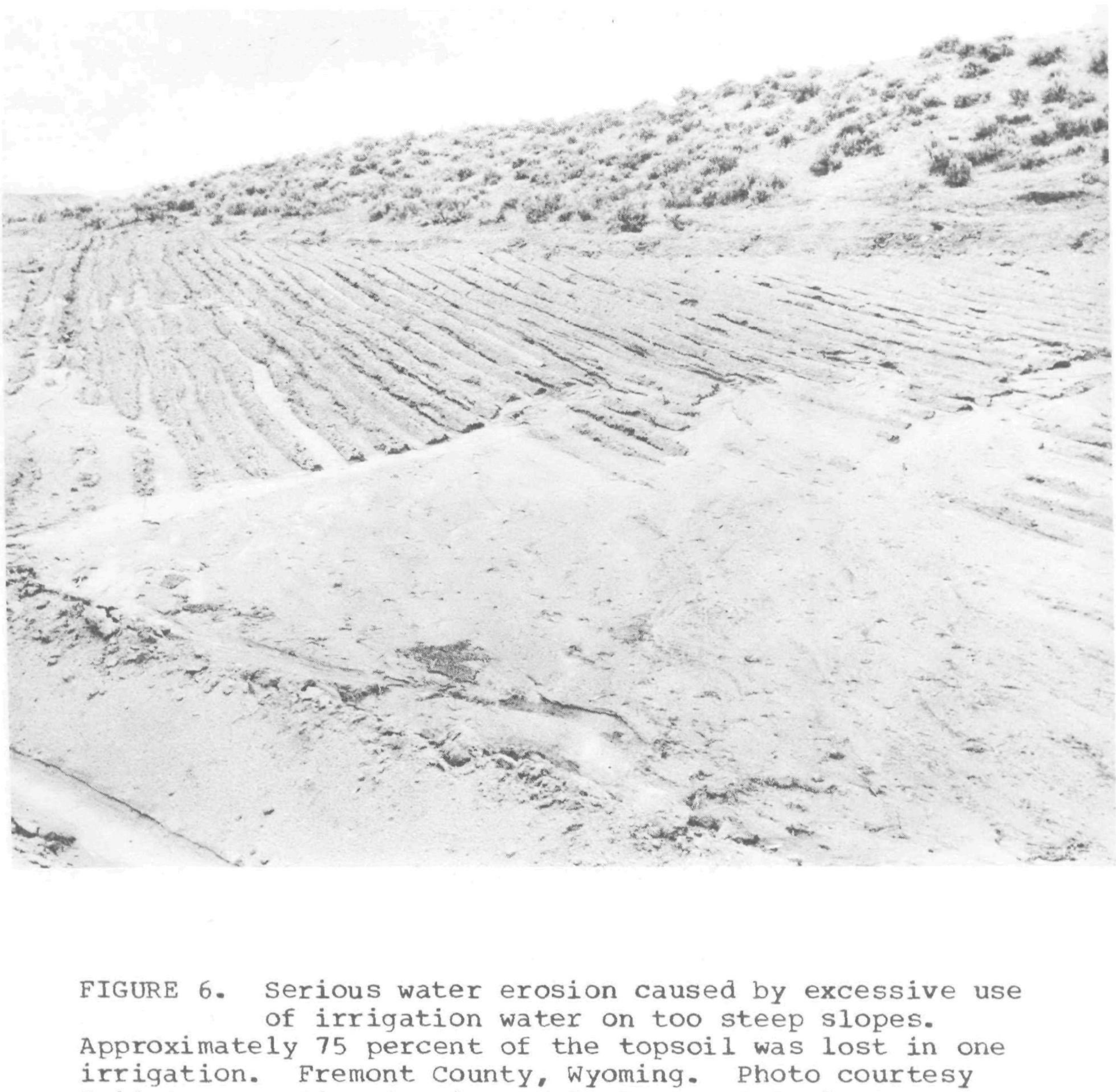

FIGURE 6. Serious water erosion caused by excessive use of irrigation water on too steep slopes. Approximately 75 percent of the topsoil was lost in one irrigation. Fremont County, Wyoming. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 7. Irrigation waste water erosion on a cultivated field. Morrill County, Nebraska.
Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

The applied water which percolates into the subsurface plays the major role in the life-sustaining drama of the irrigation event. Normally, it is also the greatest contributor to pollution in return flows. A part of the water is stored in the root zone where it is used comsumptively by crops. The plant uses the pure-water fraction of root-zone moisture and the remainder is left with an elevated mineral (salt) and soluble nutrient concentration. That water not retained in the root zone may continue to percolate downward, continuously acting as a mineral solvent or leaching agent. It may then move laterally to seepage areas, be collected by artificial drains, or ultimately find its way into the ground water system. The percolating fraction of applied water increases the concentration of salinity in the return flow. This increase is inevitable and is an inherent part of the irrigation scheme that must be recognized by agriculturist, hydrologist, engineer and environmentalist alike. The concentration of mineral salts in irrigation return flow from both leaching and evapotranspiration may range from three to ten times that of the applied water.

Salt Accumulation in the Soil

The introduction of irrigation into the field of agriculture on a large scale has had the effect of diverting salt to the soil. This is salt that, in previous years, had been dedicated by nature to the oceans. Through irrigation, salt is being intercepted enroute to its time-honored destination, placed upon and through the soil mantle, concentrated by evapotranspiration and leaching, and returned to the stream. This series of events may take place many times in a single river basin or stream prior to discharge. Each use results in increased concentration and the cumulative effect is the magnification of a normal salt content several times that expected under non-irrigating waterway conditions (5).

Accumulations of salt in irrigated soil must be avoided inasmuch as the land would soon become too saline to support plant life. If normal rainfall cannot flush the salt from the root zone, excess water must be applied during regular seasonal irrigations to prevent buildup. The excess represents the "leaching requirement" necessary to prevent salt accumulation above a prescribed level. Failure to maintain the level can become a limiting factor to further agricultural development in a given area. The increased application of water to achieve a proper leaching requirement could result in waterlogging the land. The imbalance, if it occurs can be corrected by providing adequate drainage. Returns collected in drainage systems may be highly saline.

PROBLEMS ASSOCIATED WITH EXCESSIVE SALINITY

The degradation of water quality caused by increased salinity may have far-reaching, accumulative effects on subsequent beneficial use. The use to which water is put determines the level of quality required. A particular quality may have a detrimental effect on a specific use. High quality water is required for municipal use and for many industrial purposes. The effects of moderate increases in salinity on the well-being of adult aquatic animals may be minimal. However, spawning of certain fish species may be impaired by salinities in the range of 500 milligrams per liter, or even less. Ascertaining water quality requirements for aquatic life may be difficult inasmuch as different species vary widely in their tolerence to salinity and other dissolved substances during various life stages. For other uses salinity levels can be moderately high and not be particularly detrimental. Among these are water skiing, swimming, boating and hydroelectric power generation and some commerical applications.

Water is ordinarily categorized in terms of its suitability for municipal, industrial, agricultural, and recreational uses. Some specialized industrial uses such as pharmaceutical, food processing, textile manufacturing, and laundering are often particularly sensitive to specific dissolved elements in very low concentrations. The projected industrial growth and expansion of any area or municipality may be limited by the quality of the available water supply. Industries critically examine additional costs involved in treatment necessary to upgrade water quality at prospective plantsites. These secondary costs may be an important factor in determining the establishment of highly desirable industries in areas that are otherwise ideally situated with repsect to terrain, fuel, labor, climate and accessibility.

Effect on Domestic Use

The use of water that is of direct personal concern to the domestic consumer includes drinking, food preparation, laundering and personal hygiene among the most important. Water high in dissolved solids may damage ornamental shrubs, trees and lawns. It can also be detrimental to water-using home appliances. Water high in calcium and magnesium salts, termed "hard", can cause scaling in hot-water heaters, pipes, boilers, air-conditioning equipment and significantly shorten their life. The salts of calcium and magnesium, unless eliminated by softening, leaves scums, crusts, curds and rings on household utensils and fixtures They also cause yellowing of fabrics and toughen vegetables during cooking. Hard water requires excessive amounts of soap and detergent, adding appreciably to household expense. If the water contains excessive chlorides and sulfates, corrosion may replace scaling as the undersirable mechanism. Salts of these ions are more difficult and more expensive to control.

The U.S. Department of Health, Education and Welfare, Public Health Service, has published standards applicable to drinking water and water supply systems used by public carriers and other subject to Federal quarantine regulations. The recommended upper limit of total dissolved solids is placed at 500 parts per million (6). The National Technical Advisory Subcommittee on Public Water Supplies in its report to the Secretary of the Interior, has expanded upon the Public Health Service's Regulations with respect to drinking water standards. The Subcommittee prepared an in-depth review and reported its findings and recommendations regarding water quality for Recreation and Aesthetics; Public Water Supplies; Fish, Other Aquatic Life and Wildlife; Agricultural uses including Farmstead Water Supplies, Livestock and Irrigation; and Industry (7).

A severe municipal water salinity problem caused by irrigation return flows recently occurred in the Lower Colorado River. Saline water in an aquifer underlying the Wellton-Mohawk Irrigation District near Yuma, Arizona is drained by a series of large-capacity wells drilled to control the water table (8). The discharged effluent greatly increased the salinity of the Colorado River at Yuma. The company that supplied domestic water to the city had to abandon its intake structures in the river and obtain potable water by diversion at Imperial Dam, approximately 15 miles upstream. Downstream users in Mexico, however, had no alternative source of supply and the salinity of the Colorado River flowing into Mexico is the subject of international negotiations (9).

Effect on Agriculture

Salinity created by irrigation generates additional problems for the downstream user. Saline water may increase the salinity of the root zone environment of the soil. Elevation of soil salinity may inhibit seed germination, reduce crop yields and prevent the growing of crops having low salt tolerances. In extreme instances, salt buildup may even cause the removal of land from agricultural production (Figure 8). Production of vegetable crops having low salt

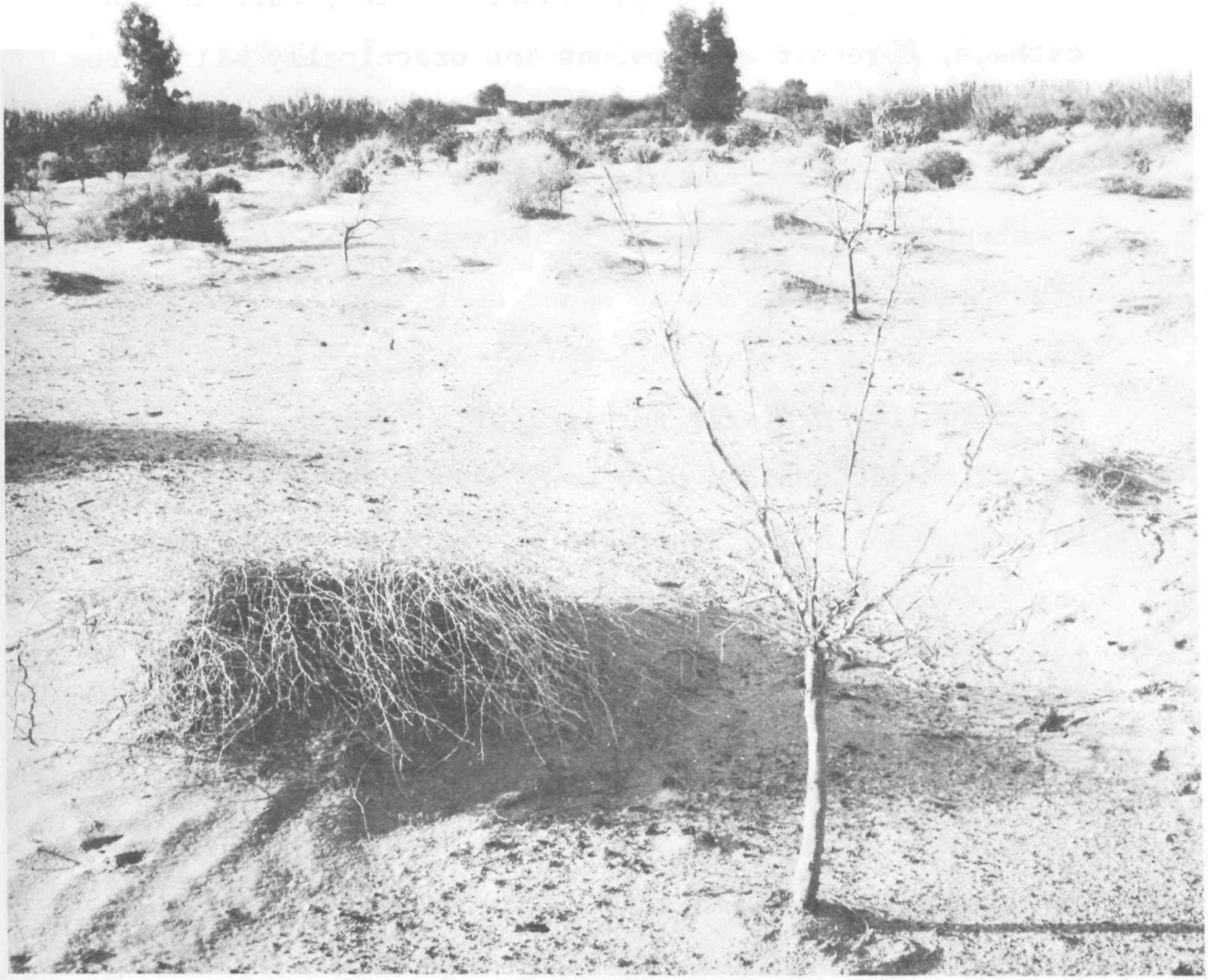

FIGURE 8. Citrus grove abandoned as a result of build up of salt in the soil.
Coachella Valley, California. Photo courtesy Bureau of Reclamation, U.S. Department of the Interior.

tolerances such as celery, beans, lettuce, carrots and cabbage, together with melons and practically all citrus fruits could be greatly reduced by soil salinity buildup (Figure 9). These are high-value crops which contribute substantially to the economic well-being of the grower. Other money crops such as sugar beets and flax have suffered damage from excessive soil-salinity (Figures 10 and 11). Water quality criteria for irrigation and general agricultural purposes have been developed by the Federal Salinity Laboratory Staff (10). These cover a wide range and are closely interrelated with soil texture, infiltration rate, drainage, climate and crop salt tolerance.

As the salinity of applied water increases, a larger quantity is ordinarily needed to prevent salt buildup in the root zone. In some soils continued irrigations using limited amounts of water -- only that necessary to maintain field capacity -- will invarably induce salt concentration. The buildup can progress to the stage where it adversely affects the surface and greatly inhibits plant growth, creates large "kill" areas and may ultimately result in the abandonment of much land (Figure 12).

Many soils in their natural (virgin) environment are highly mineralized and may be either sodic or saline. Sodic

FIGURE 9. Salt damage to carrot crop, Coachella Valley California. Photo courtesy Bureau of Reclamation, U.S. Dept. of the Interior.

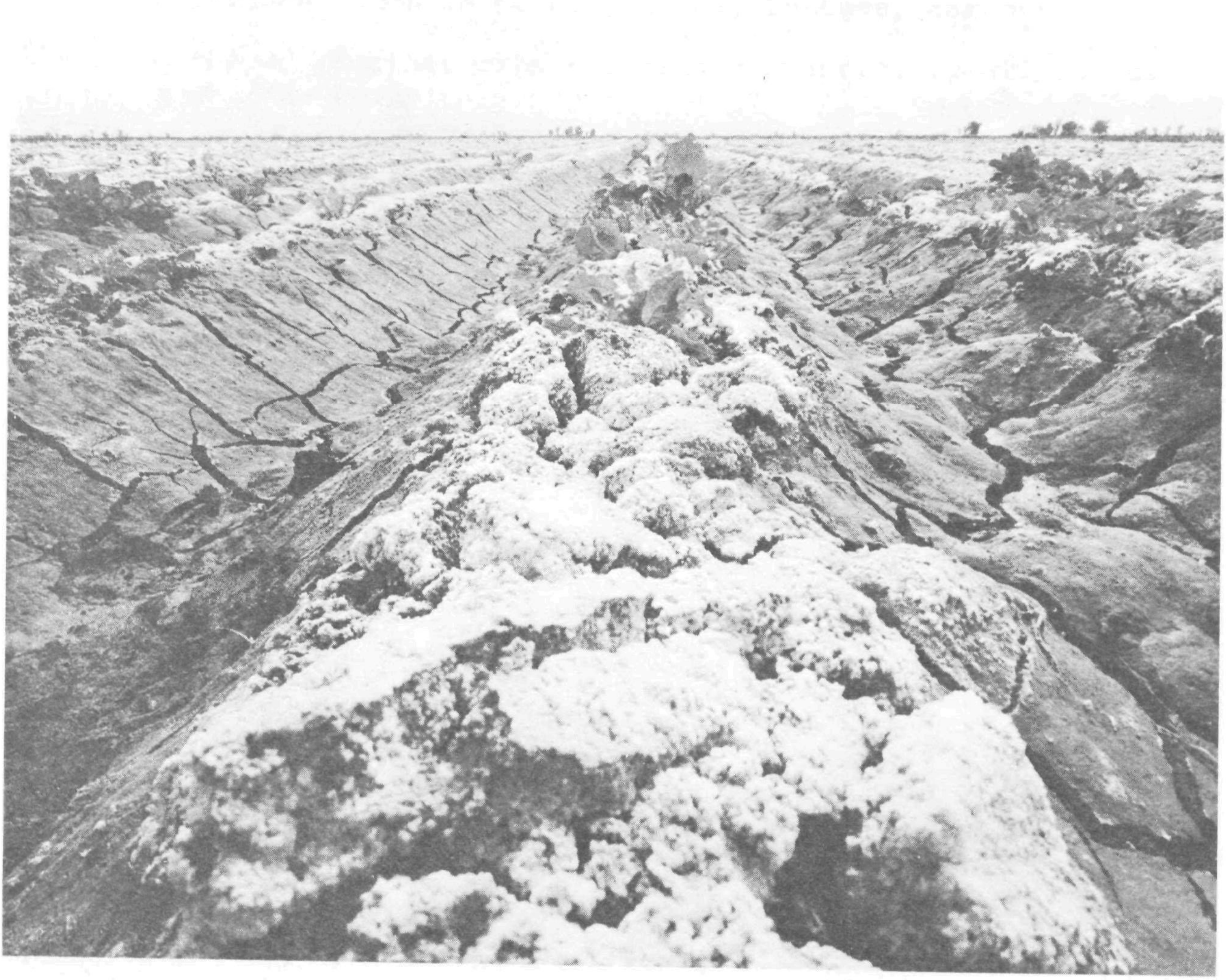

FIGURE 10. Sugar beets growing sparsely along salt-encrusted ridges between irrigation furrows. Irrigation water containing salts rose to the ridge surface through capillary action and evaporated, leaving the solids behind. Photo courtesy Dept. of Water Resources, State of California.

FIGURE 11. Salt buildup in soil results in extensive damage in this flax field as shown by the bare areas. Imperial County, California. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

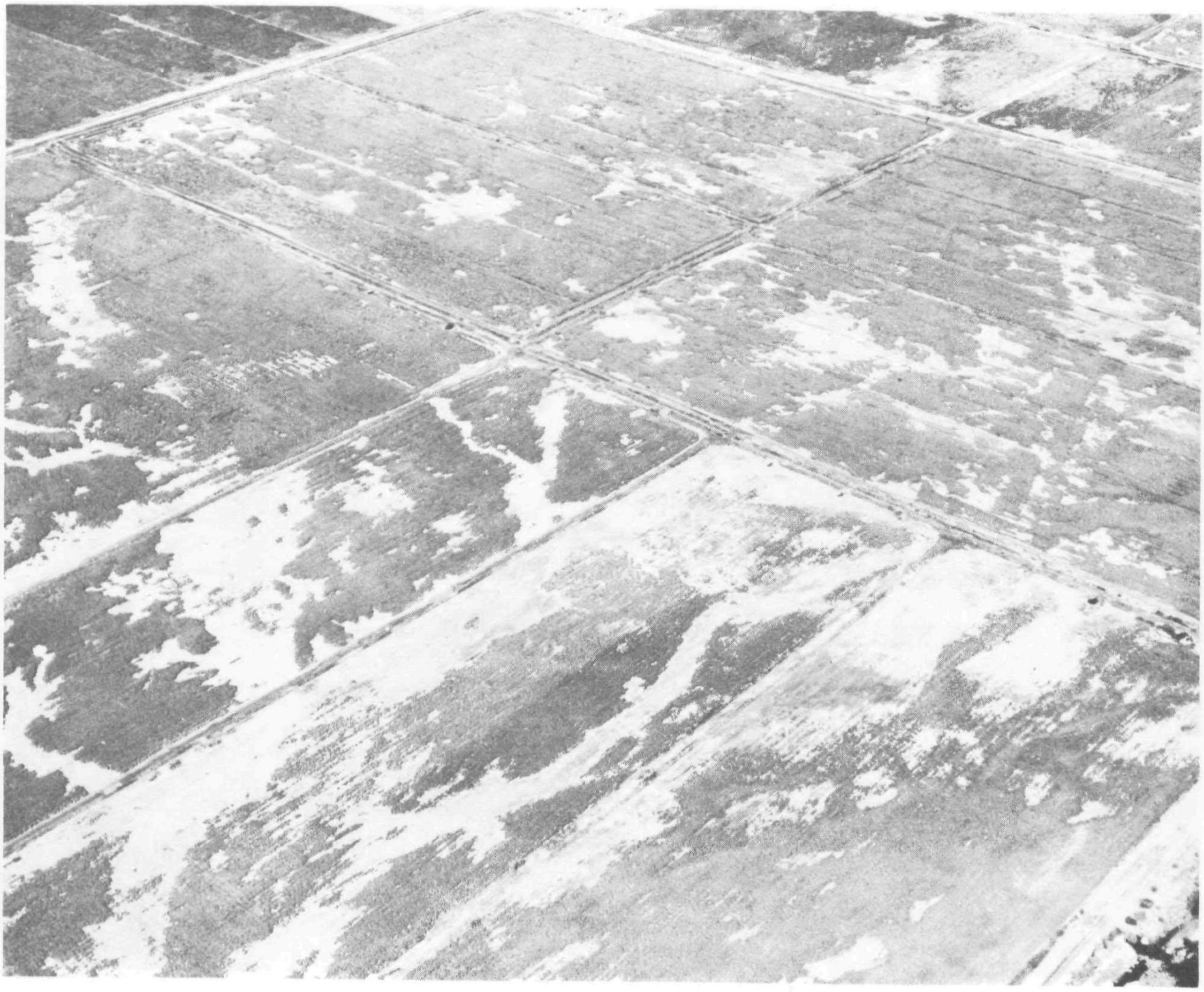

FIGURE 12. Aerial view of irrigated farmland southwest of Roll, Arizona. Standing salty water and saline soils resulted in a loss of approximately 1000 acres of crops. Photo courtesy Bureau of Reclamation, U.S. Dept. of the Interior.

soils have a high exchangeable sodium ion content whereas saline soils may contain excessive concentrations of soluble salts other than, or in addition to, exchangeable sodium. Both soil types require special management practices, particularly when irrigated and subject to leaching, inasmuch as the high concentrations of mineral constituents impair their productivity (10). Leachates from these soils may contribute significantly to return flow salinity. It is estimated that salt-affected soils comprise about 28 percent of all irrigated acreage in the Western states.

Excess water applied to the land to control root zone salt must be removed or the land may become waterlogged as the water table rises. Measures to control the elevation of the ground water table require drainage systems which in turn requires high capital investments on the part of the irrigator. An example is the region in southern California served by the Imperial Irrigation District and covering 553,000 acres (223,800 hectares). Facilities to drain saline irrigation return flows in the Imperial Valley have required the construction of approximately 1375 miles (2210 kilometers) of open drainage ditches and nearly 18,000 miles (28,960 kilometers) of subsurface drainage tile in an effort to maintain a favorable salinity balance in the soil (11). Current capital costs to install subsurface tile average $2450 per mile. The elaborate drainage system, designed to maintain a favorable salt balance in the root zone, is needed because of a predominance of clay and heavy loam soils which impede downward percolation of water and encourage salt buildup in the shallow zone. Estimated capital costs of pipe or tile drainage systems ranges from $150 to more than $400 per acre, depending on the depth and spacing of the pipe (12). Avoidance of soil salinity buildup and potential reduction of crop yields obviously requires large capital outlays by the irrigator.

Philosophically, detriments associated with water degradation are fundamentally economic. Any increase in salinity results in an economic penalty inasmuch as additional water is required for equivalent benefit (13).

If water is degraded, the user must either apply more water to the field to maintain crop yield or use the same amount of water and risk a decrease in yield. If more water is required for leaching or to maintain salt balance, the cost of water rises, installation of artificial drains may be necessary, soluble fertilizer requirements may be increased, labor costs may rise, and the danger of soil damage resulting from sodium hazard may increase. If additional water is not available, the irrigator may have to turn to more salt-tolerant crops. In any event, the loss is an economic one.

Direct adverse effects to the plant from increased salinity are; reduction in osmotic action, decreasing water uptake capability, and possible adverse metabolic reaction with resultant toxicity. Indirect adverse effects may include impairment of surrounding soil structure. This in turn may reduce permeability, porosity, and water infiltration capability.

LOCATION OF MAJOR PROBLEM AREAS

Water quality problems of some type and magnitude exist in every irrigated area of the nation. These vary both in intensity and kind of pollutant involved. The most severe return flow problems are found in the conterminous Western States (See Plate I). Soils in these arid and semi-arid regions are ordinarily high in residual mineral salts inasmuch as they have not been subjected to extensive leaching by rainfall or snowmelt as have those in the more humid parts of the nation. The soil profile developed in sub-humid and humid regions is thick and relatively free of readily-soluble minerals.

There are several areas in the United States categorized by agricultural, soil, irrigation and ecological authorities as those in which water quality problems associated with irrigation return flows are serious.

The Colorado River Basin probably contains more major salinity problem areas than any other in the nation. It is closely followed by the Imperial and Coachella Valley of Southern California, the Rio Grande Basin of New Mexico, Texas and Mexico, and the great Central Valley of California which contains the agriculturally important San Joaquin and

SIGNIFICANT IRRIGATION AREAS IN THE SEVENTEEN WESTERN CONTERMINOUS STATES

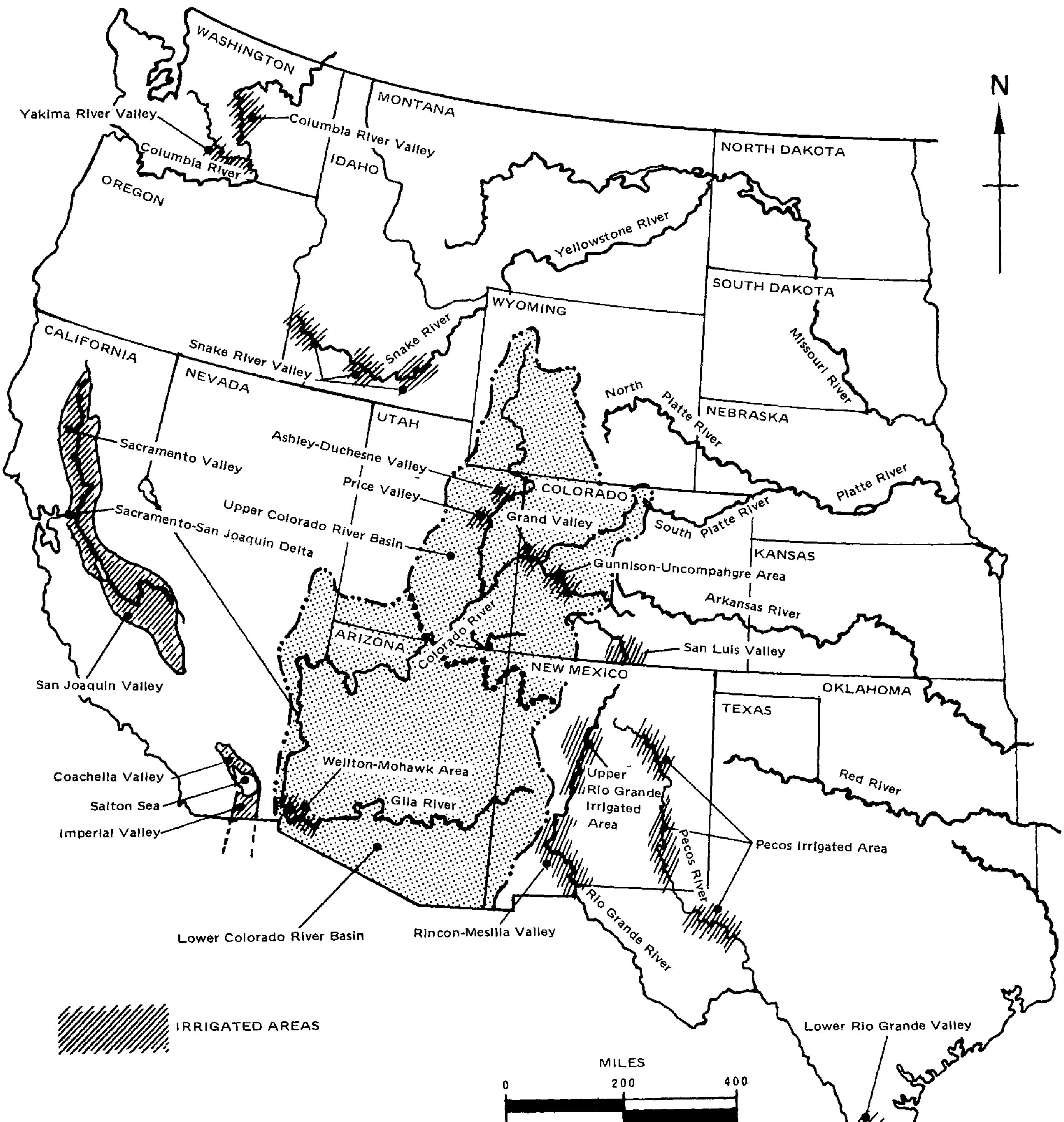

PLATE I

Sacramento Valleys. These , together with several additional, but less serious, areas are reviewed.

Colorado River Basin

The Colorado River heads on the east slope of Mt. Richthofen in the northwest part of the Rocky Mountain National Park, about 70 miles(113 kilometers) northwest of Denver. The river then flows west by south into the Gulf of California 1450 miles (2330 kilometers) distant. The Colorado and its tributaries drain an area of approximately 255,000 square miles (582,750 square kilometers) or about one-twelfth of the area of the conterminous United States. It is unique among the great waterways of the world in that its flow is completely "captured" by a series of large reservoirs. Among these are Lake Havasu, Mohave, Mead, Powell, Flaming Gorge, Fontenelle, Navajo, Morrow Point and Blue Mesa (14). The most acute problem facing future development of water resources in the Colorado River Basin is salinity.

The basin is divided into an Upper and Lower Region by the Colorado River Compact of 1922. The Upper Region contains 113,496 square miles (293,955 square kilometers) located upstream from Lee Ferry, Arizona. Irrigated agriculture, a major industry, utilized 1,621,500 acres

(656,220 hectares) of farmland in 1965 of which 99 percent were irrigated entirely from surface sources - the balance being supplied by ground water (15).

The total annual dissolved solids load (salinity) reaching Lee Ferry, Arizona, during the period 1941-1966 is placed at 8,155,000 tons (7,398,000 metric tons). Of this amount, the estimated loads contributed by irrigated agriculture ranged from 1,995,000 to 3,320,000 tons (1,809,800 to 3,011,800 metric tons). This range, representing a variance of 24 to 41 percent of the total salt load points out a need to develop more accurate prediction of salinity caused by irrigation return flows (16). It is further estimated that nearly 90 percent of the total relative salt load from irrigated agriculture in the entire Basin originates in the Upper Region.

The balance of the salinity in the River at Lee Ferry is attributed to natural sources. These are both non-point or diffuse, and point. The diffuse sources in both the Upper and Lower Basin are the most significant.

The Lower Colorado River Basin Region lies downstream from the Lee Ferry division point and contains 141,137 square miles (365,545 square kilometers). Approximately 1,200,000 acres (485,640 hectares) of Lower Basin farmland were irrigated in 1965 under both organized irrigation systems and privately-owned wells pumping from river aquifers. Of the total, approximately 895,000 acres (362,210 hectares) were located in the important Gila River Subregion (17).

It is estimated that only 12 percent of the total relative salt load from irrigated agriculture in the entire Colorado River Basin originates in the lower portion.

Upper Colorado River Basin Region

The Grand Valley irrigated agriculture area located in the valley of the Colorado River both upstream and downstream from its confluence with the Gunnison River in western Colorado is the most serious salinity problem area in the Upper Basin. Deep percolation from excessive amounts of applied water, plus leakage from old canal and ditch distribution systems in the Valley reaches the underlying saline aquifer developed over the highly mineralized Mancos Shale of Cretaceous Age. The excess water has elevated the ground water table to the point where a substantial amount of base flow is introduced into the Colorado River Channel. This has added significantly to the salt load of the river. The excessive amount of salt represents that dissolved from the highly saline shale beds. It is estimated that 88,000 irrigated acres (35,315 hectares) in the Grand Valley contribute about 8 tons of salt per acre per year or a total of 704,000 tons (638,655 metric tons) annually to the Upper Basin. This is an estimated 18 percent of the total irrigated agriculture salt load of the entire Colorado River Basin! (13).

Deterioration of water quality in the Grand Valley increased to the point where it became the target of several special investigations funded, in part, by the Environmental Protection Agency. Recent valley-wide land-use studies indicated that almost 30 percent of the available agricultural acreage in the valley has become unproductive due to high water table and attendant salinity problems (18, 19, 20,21).

Another major area of salinity created by irrigation return flows is the Gunnison River - Uncompahgre River Valley System in western Colorado south of Grand Valley. The Uncompahgre Valley contains 6,000 acres (2430 hectares) of irrigable land from which the salt yield is placed at an estimated 4.5 tons per acre per year or a total contribution of 27,000 tons (24,495 metric tons) annually. The valley of the Gunnison River and its tributaries contain 167,000 acres (67,585 hectares) of irrigated land, most of which is underlain by the highly mineralized (gypsiferous) Mancos shale and yields and average of 6.7 tons of salt per acre per year, or an annual total of 1,118,900 tons (1,015,045 metric tons). The significance of applying irrigation water to soils derived from highly mineralized bedrock becomes readily apparent. The Gunnison-Uncompahgre complex accounts for an estimated 29 percent of the total irrigation-associated salt load of the entire Colorado River Basin. The salt load of the combined irrigated area of the Grand Valley and Gunnison-Uncompahgre Basins totals 47 percent or almost one-half of the salt load from irrigated areas in the entire Colorado River Basin. Their combined yearly salt contribution to the Colorado River is about 1,850,000 tons (1,678,000 metric tons).

Additional return flow problem areas in the Upper Basin are located in the Green River Subbasin. Relative salt loads from irrigated agriculture in the Subbasin contribute an estimated 32 percent of the total salt load of the entire Colorado River Basin. The Green River is the largest tributary of the Colorado and drains parts of Wyoming, Colorado and Utah. The river and its tributaries contain numerous irrigated valleys, several of which have significant salinity problems associated with irrigated agriculture. Among the more important areas having return flow problems are the Big Sandy Creek Basin in southwestern Wyoming together with Ashley Valley and Duchesne Valley, both in eastern Utah.

The Big Sandy Creek Basin contains an irrigated area of approximately 13,000 acres (5260 hectares) underlain by highly gypsiferous, relatively soluble, sedimentary rocks which, upon weathering, form the soils that support agriculture in the basin. Irrigation return flows contribute an estimated 5.6 tons (5.08 metric tons) of salt per acre per year or a total of 73,000 tons (66,225 metric tons) per year to the Green River System.

Ashley Valley, located in northeastern Utah, also referred to as the Vernal Unit Area, has long been identified with water quality deterioration imparted by irrigation return flow salinity. The approximate 20,000 acres (8,094 hectares) of irrigated land in the Valley contributed an annual salt load of 4.2 tons (3.8 metric tons) per acre during the period of June 1965 to May 1966 or a total of 84,000 tons (76,205 metric tons) to the Green River. The predominant ion is sulfate leached from gypsiferous soils. The Ashley Valley-Vernal locale, while relatively small in areal extent, is intensely saline and has been the subject of recent studies funded by the Environmental Protection Agency and the Bureau of Reclamation (22,23).

The Duchesne area of northeastern Utah contains 166,000 acres (67,180 hectares) of irrigated land, mostly concentrated in the valleys of the Uinta and Duchesne River and their tributaries. Return flows contribute an estimated three tons of salt per acre per year or about 498,000 tons (451,775 metric tons) annually to the Green River System.

Irrigation in the Price River Valley of northeastern Utah, located about 60 miles (97 kilometers) southeast of Provo, is developed in soils derived from the Mancos shale. Approximately 20,000 acres (8100 hectares) are under irrigation and the total salt load attributed to return flow could be as great as 8.5 tons (7.7 metric tons) per acre per year or 170,000 tons (154,220 metric tons) annually. Difficulty has been experienced in attempting to establish the total quantity of salt assignable to return flows in the Valley. The contribution of naturally-occurring salinity in the area of ground water is known to be sizeable. Both irrigation returns and ground water in the Valley owe their excessive salt pickup to leaching of soils developed upon the Mancos shale. The Mancos is an excellent example of an off-repeated condition in arid lands in which a rock formation, usually shale, is a valley-builder capable of yielding gentle topgraphy well-suited to irrigated agriculture but is at the same time capable of severely degrading the quality of water applied to its weathered mantle (soil).

Lower Colorado River Basin Region

Significant increases in salinity in the Lower Colorado River mainstem occur in its reaches upstream from Imperial Dam. This dam represents the southernmost point of diversion of Colorado River water for irrigation in the United States. Principal increases in salinity involving return flows originate in the Parker Valley, nearly all of which lies within the Colorado River Indian Reservation. The valley contains about 110,000 acres (44,517 hectares) of river flood plain of which 31,700 acres (12,830 hectares) were irrigated in 1962. The Reservation has unused water rights sufficient to irrigate an additional 67,500 acres (27,320 hectares) which, if developed, will create a further increase in the total amount of dissolved solids in the downstream reaches of the river. The projected increase will be the result of salt concentration by stream depletion (17).

The Palo Verde Irrigation District located in the Palo Verde Valley immediately downstream from the Colorado River Indian Reservation contains approximately 85,000 acres (34,400 hectares) under irrigation. The district contributes a salt load of about two tons per acre per year to the mainstem. Much of this is groundwater salinity currently being withdrawn through deepened existing drains.

The Colorado River emerges from mountainous terrain fourteen miles upstream from Yuma, Arizona and is joined by the Gila River. The floodplain immediately below the junction is an important irrigated area. It widens downstream from Yuma and merges with the Colorado River delta system, a vast arable plain, which extends westward to the Salton Sea Basin and south to the Gulf of California (8). Agriculture, the mainstay of the area's economy is made possible by irrigation with Colorado River water diverted at the Imperial Dam located 26 miles (42 kilometers) upstream from the Northern International Boundary with Mexico. This great diversion point supplies the Yuma, Gila and Wellton-Mohawk irrigated areas in Arizona and the Imperial and Coachella Valleys in California through two major conveyances -- the Gila Gravity Main Canal into Arizona and the All-American Canal into California. The total annual diversion of water from the Imperial Dam into the canals is approximately 6,000,000 acre-feet (7,400,940,000 cubic meters). Water is also released at Imperial Dam for delivery to Mexico under provisions of the 1944 Treaty with that country. Summarizing, most of the Colorado River water used in the United States is diverted at the Imperial Dam.

The major irrigation return flow salinity problem in the Lower Colorado region is that created by ground water pumped to control water levels beneath the Wellton-Mohawk Irrigation District in the Gila River Valley. The pumped water was originally discharged into the Colorado River downstream from Imperial Dam. Past irrigation during the early part of the century used ground water pumped from an aquifer underlying Wellton-Mohawk and eventually increased the salinity of the water to the point where it was no longer usable. The increase in salinity is a classic example of the combined effect of continued evapotranspiration of the applied water plus deep percolation of the remainder (irrigation returns) to the aquifer from which it was withdrawn. The irrigation water was, in essence, continuously recycled. Inauguration of the Gila Project revived irrigation in the Gila Valley. Subsequent application of Colorado River water diverted at Imperial Dam elevated the water table and the Wellton-Mohawk area became waterlogged. Land reclamation required much larger quantities of water than were originally anticipated. High capacity withdrawal wells were drilled, beginning in 1955, to control ground water levels. The quality of the effluent discharged into the Gila River underwent severe deterioration during the summer of 1961. During that year returns from more than 60 wells in the Wellton-Mohawk Valley were discharged into a wastewater conveyance channel (the Wellton-Mohawk Main Outlet Drain) which emptied into the Gila River. The problem was aggravated by greatly increased pumping rates and the development of additional wells. The result was an alarming elevation of salinity in the Colorado River immediately north of the international boundary. The salinity trend has since reversed and the quality of Wellton-Mohawk drainage has shown steady improvement. It reached a maximum of 6,000 parts per million total dissolved solids in 1961, then decreased to an average of 4,620 ppm during the water year 1966 and to 4,100 ppm in 1969 (9,12).

The control of salinity of Colorado River water reaching Mexico has been the subject of international discussion and negotiation. Initial control measures designed to reduce the salinity included the release of additional water at Imperial Dam to provide dilution; the elimination of several highly saline drainage wells in the Wellton-Mohawk Project; and the construction of a concrete-lined conveyance channel to divert undesirable saline drainage to the Colorado River immediately downstream from Mexico's Morelos Dam. Morelos dam is the point of diversion of water for irrigation in Mexico's Mexicali Valley, a southward extension of the Imperial Valley. The concrete-lined conveyance channel was constructed in fulfillment of a formal international agreement with Mexico and was placed in service on November 16,1965. While the primary function of the channel is to divert saline returns downstream of the Morelos Dam, provision is made for directing the flow into the Colorado River either upstream from or downstream from the dam if requested by Mexico.

The Imperial Valley

The Imperial Valley of California, located south of the Salton Sea is a broad, flat plain flanked by low, barren mountain ranges and is a part of an elongated desert valley extending northward from the Gulf of California. Physiographically, it is a segment of the Colorado River delta fan tributary to the Salton Sea Basin (24). The valley is a closed depression and represents the southern part of the bed of ancient Lake Cahuilla. Most of its area is below sea level.

The Imperial Valley is one of the most intensively irrigated areas in the world. Agricultural production depends entirely on water supplied from the Colorado River through the All-American Canal. The average annual rainfall in the region is about 3 inches (7.6 centimeters). Approximately 475,000 acres (192,250 hectares) were irrigated in 1971, yielding a gross value of agricultural products in excess of $300,000,000.

The control of salt buildup in Imperial Valley soils caused by consumptive use of irrigation water requires continual leaching and carefully controlled irrigation management practices, particularly with respect to amount, frequency and methods of water application. The physical and chemical properties of the soils require additonal management practices to prevent salt accumulation in the plant root zone. The salts in the soil lend themselves readily to leaching, and are composed principally of the chlorides and sulfates of sodium, calcium and magnesium.

About 50 years ago it became apparent that drainage of the valley soils was grossly inadequate. A rapidly rising water table along with an alarming increase in ground water salinity combined to seriously affect crop productivity. Figure 13 illustrates land and crop damage associated with high water tables in the Valley. The Imperial Irrigation District initiated the installation of a series of open drainage ditches to depress the water table and conduct returns to the Salton Sea. Construction of a tile drainage system to augment the surface drainage network and further remove accumulated saline ground waters that threatened to waterlog the valley began as early as 1929. Today there are 17,834 miles (28,695 kilometers) of tile drains serving more than 377,000 irrigated acres (152,570 hectares) in the valley. The type of tile drain used in the valley and the

FIGURE 13. Here high water table prevents removal of surface water after irrigation, resulting in ponding of water and drowning of crop. Imperial Valley, California. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

method of discharge of collected irrigation return flows into conveyance ditches are shown in Figures 14 and 15.

It is necessary to earmark about 20 percent of the total irrigation water diverted to the Imperial Valley for root zone leaching in order to achieve a condition wherein the total annual quantity of salts removed is somewhat greater than the total annual quantity introduced. Also, as the salinty of the source water, diverted from the Colorado River increases, the leaching requirement will have to be increased (27). Salt balance in Valley soils was initially achieved in 1946 and has been maintained continuously.

Furrow irrigation is the water-application technique used almost entirely in the Imperial Valley because of the low infiltration rates and elevated soil salinities. The more versatile and efficient sprinkler methods are seldom used due to the relatively high concentration of salt in the applied water coupled with the very high summer temperatures. Rapid drying of saline water on the leaf surface leaves a toxic concentration of salt and often results in the death of the foliage (27).

Irrigation return flows from the Imperial Valley amount to approximately 900,000 acre-feet (1,110,140,000 cubic meters)per year, all of which is discharged into the Salton

FIGURE 14. Tile, gravel and sights placed ahead of construction on an irrigated farm in the Imperial Valley, California. The tiling operation is engineered and constructed by the Imperial Irrigation District Engineering Department. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

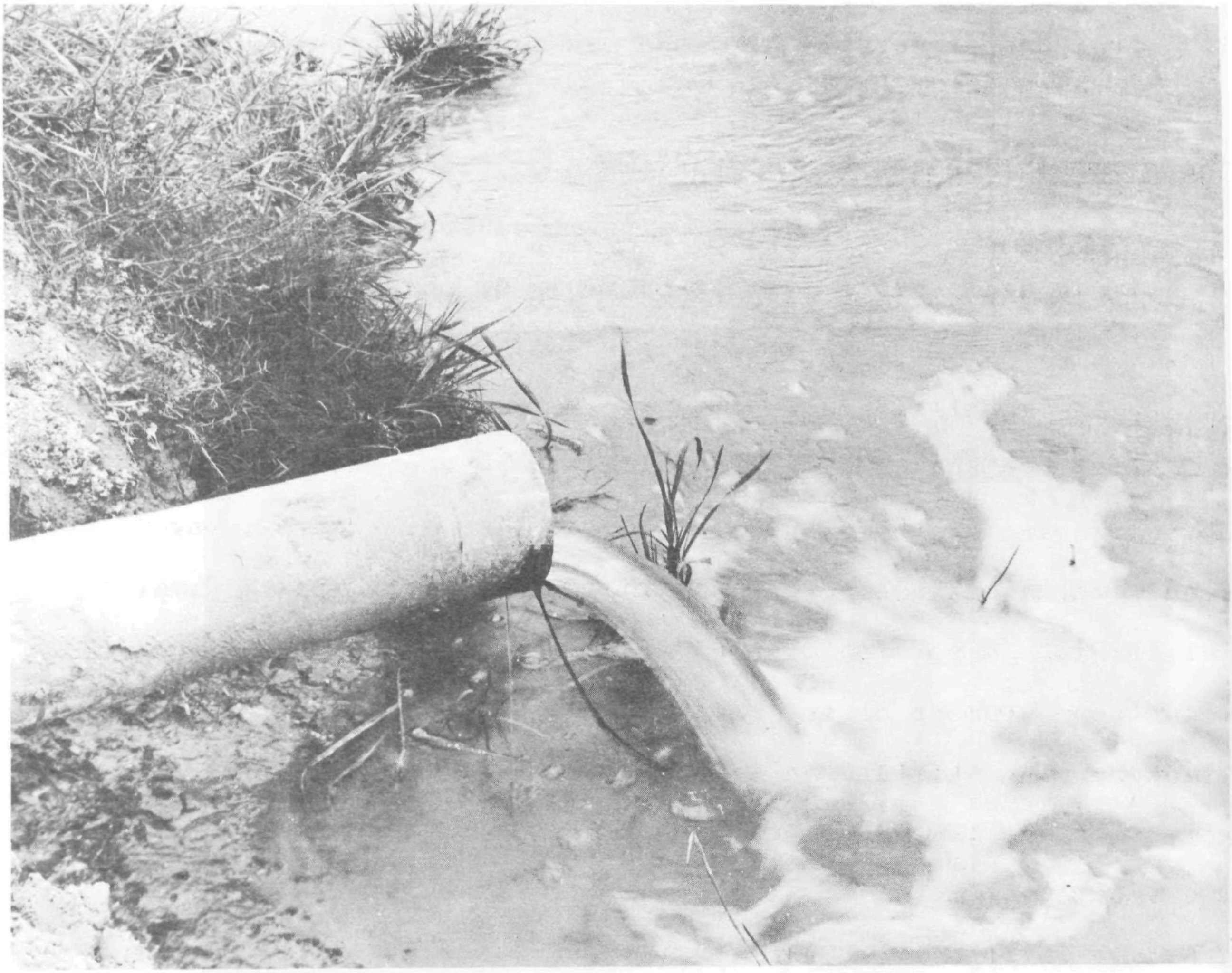

FIGURE 15. Typical discharge of tile drain designed to lower the water table beneath irrigated land. Tile drainage commonly discharges into open collection ditches for ultimate disposal -- in this instance into the Salton Sea. Imperial Valley, California. Photo courtesy Soil Conservation Service U.S. Dept. of Agriculture.

Sea and represents 90 percent of the total annual inflow into that body.

The Coachella Valley

Irrigation return flow problems in the Coachella Valley are similar to those in the Imperial Valley. The Coachella Valley is an intermontane, linear depression located immediately north of the Salton Sea and represents the northern part of the elongate alluvial limb of the Colorado Desert which extends northwestward from the Gulf of California. A portion of the Valley is located within the downstream segment of the Whitewater River Basin and is flanked by the Little San Bernardino Mountains on the northeast and the Santa Rosa Mountains on the southwest. The southern part of the Valley is the bed of ancient Lake Cahuilla which now contains the recently-formed Salton Sea*.

*The present Salton Sea was formed during 1905-1907 when more than 16,000,000 acre-feet (19,735,840,000 cubic meters) of Colorado River water poured through several breaches in the river levee system and flowed westward into the Salton Trough.

Coachella Valley is one of the few areas in the United States where select date palms can be successfully grown. An experimental station was established by the government in 1904 to study and develop date palm culture in this country. Choice date palm varieties were imported from Egypt and Algeria and irrigated groves established (24). The production of dates now represents an important aspect of the economy of the Valley. (Figure 16).

Ground water resources were developed early in the agricultural history of the Coachella Valley. As water levels declined, Colorado River water was imported into the area, beginning in 1948, through the Coachella Branch of the All-American Canal. The availability of ample water, accompanied by expanded irrigation activity, resulted in the development of a shallow, perched ground water body. The installation of tile drainage designed to combat the high water table began in 1950 and continues. More than half of the 60,000 irrigated acres (24,280 hectares) in the valley which overlie areas of restricted ground water movement have been tiled. Salt balance studies indicate that the annual tonnage of salt in the return flows exceeds that applied during irrigation (28). The leaching fraction of the Coachella Valley is approximately 30 percent. Continued high water requirements for leaching will have to be

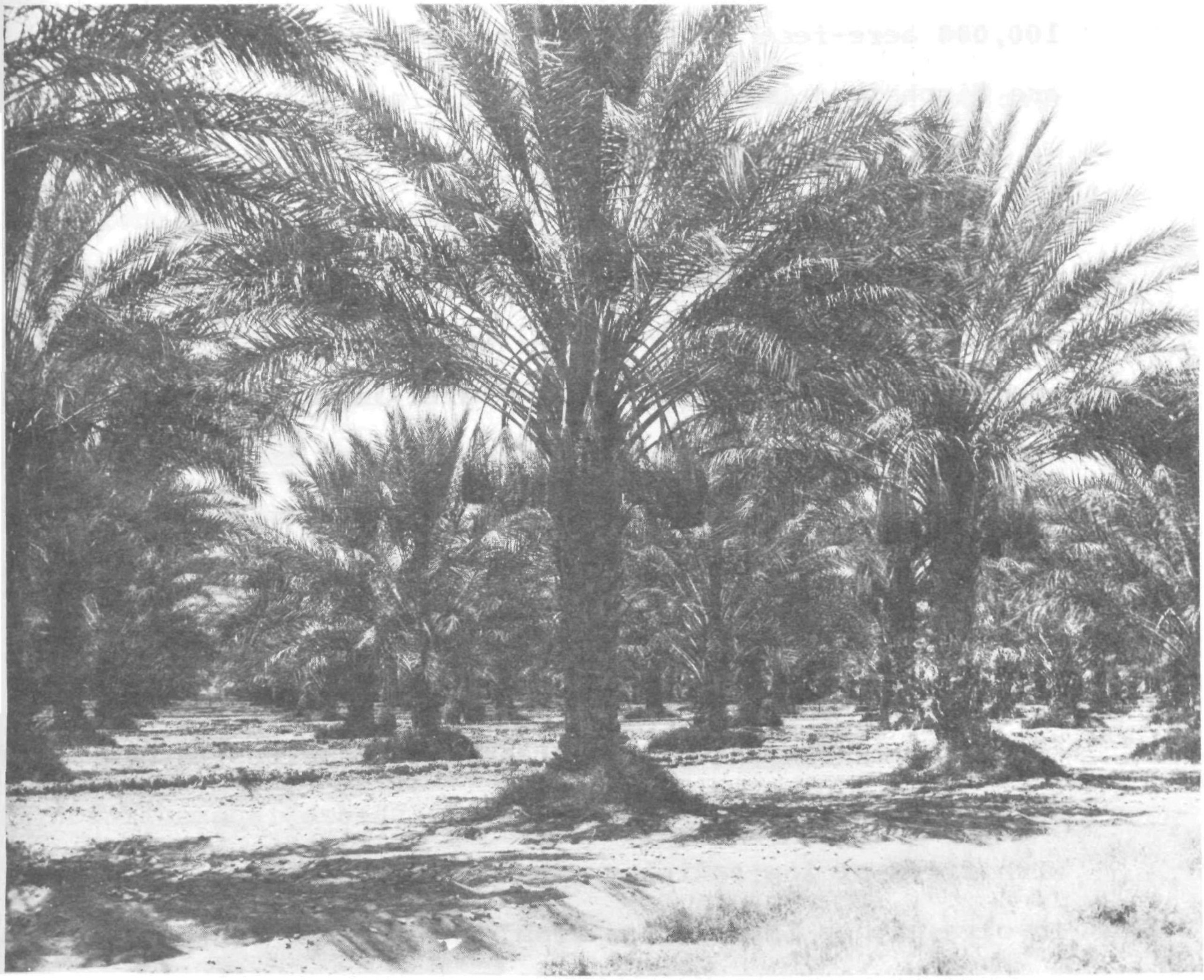

FIGURE 16. Grove of heavy-laden date palms near Indio, California in the Coachella Valley. The Valley is one of the few areas in the United States where the date palm thrives. Photo courtesy Bureau of Reclamation, U.S. Dept. of the Interior.

maintained. Return flows from the Valley amount to about 100,000 acre-feet (123,349,000 cubic meters) annually and are discharged into the Salton Sea.

Irrigation return flows from the combined Coachella and Imperial Valleys literally control the quantity, quality, and related problems of the Salton Sea inasmuch as the total annual inflow into this body of water is composed almost entirely of irrigation returns. Saltwater sport fish were introduced into the Salton Sea when its salinity reached approximately 35,000 ppm or that of the oceans. Its salinity is currently about 37,000 ppm and rising, which means that sport fishing and associated recreation may soon terminate if the salinity increase is not arrested. Reduction of salinity can be accomplished by augmentation with fresh or low-salinity water. This, in turn would involve either importation from out-of-basin sources, desalination of all or part of the return flows or other costly approaches (29). Costs involved in desalting a portion of the Coachella drainage waters were studied recently by the Office of Saline Water and the Bureau of Reclamation (30). Cost estimates, based upon 2870 ppm feedwater and 400 ppm product water, ranged from $220 to $297 per acre foot, using electrodialysis and multistage flash distillation respectively.

The Rio Grande Basin

The Rio Grande Basin is divided into four geographical segments for purposes of water-use discussions. These are the Upper Basin, Middle Basin, Lower Basin and the Pecos River Subbasin. The Rio Grande River begins in southwestern Colorado on the east flank of the San Juan Mountain range and flows approximately 1,900 miles (3,057 kilometers) south and east into the Gulf of Mexico at Brownsville, Texas.

Upper Rio Grande Basin

The Upper Basin, located between the headwaters of the river and Ft. Quitman, Texas, drains an area of about 32,000 square miles (82,880 square kilometers). Important irrigated segments begin with San Luis Valley, located adjacent to the headwaters of the river in south-central Colorado. The valley is a down-faulted, relatively flat, high-altitude depression bounded by the Sangre de Cristo Mountains on the east and by the San Juan Mountains on the west. Its northern part is a closed depression into which surface drainage converges. The valley contains very large amounts of surface and subsurface water. Estimated ground water storage in the aquifer system underlying the valley is placed at more than two billion acre-feet (2,466,980,000,000 cubic meters). This water is contained in several porous formations comprised primarily of extrusive rocks represented by volcanic flows, tuffs, breccias and debris. The thickness of this multiple aquifer may be as great as 30,000 feet (9,145 meters). The uppermost aquifer is unconfined, extensive and contains water at depths normally less than twelve feet. Recharge is chiefly from percolation of applied irrigation water, leakage from canals and ditches, and precipitation. Principal recharge to the deep aquifer system is through infiltration from mountain streams flowing across alluvial fans edging the valley.

Irrigation, dating to 1880, is vital to agriculture in the San Luis Valley inasmuch as the average annual rainfall is only eight inches. During the period 1880 to 1950 the principal source of irrigation water was surface supplies (31). Excessive irrigation returns waterlogged a part of the valley in the early part of this century and a drainage network was constructed between 1911 and 1921 in an attempt to dewater the land but the problem created by the excessively high water table remains, at least in part, to this day.

Subirrigation is practiced in the San Luis Valley and tends to aggravate the waterlogged condition. This method of applying water is common is some areas of the United States and can be highly efficient if water levels are carefully regulated. Subirrigation requires a high water table, water in continuous supply, and controlled drainage.

The quality of the shallow ground water has deteriorated as a result of mineral concentration caused by comsumptive use and valley soils have been adversely affected by significant alkali buildup.

Irrigation is also practiced downstream from San Luis Valley in the middle section of the Upper Rio Grande Basin between the Colorado state line and San Marcial at the head of Elephant Butte Reservoir. Historically, irrigation was practiced in this reach of the river during the Pueblo I and Pueblo II eras, (700 to 1050 A. D.) and it is estimated that at the time of the arrival of the Spanish in the 16th Century, 25,000 acres (10,120 hectares) were being irrigated. The first Spanish irrigation ditch was built in 1598 about 30 miles north of Santa Fe, New Mexico (32). A recent study of water usage on the Upper Rio Grande (33) placed the total irrigated land in the middle section at approximately 150,000 acres (60,705 hectares). Consumptive ground water losses in the section are particularly high as a result of phreatophyte usage.

This reach of the river is served by several conservancy and irrigation districts, some organized as early as 1915, and numerous community ditch systems. Agricultural production is confined chiefly to small subsistence-type farms. The main products are fruits, garden vegetables, hay, forage crops and cotton. Irrigation return flow problems are beginning to receive attention in this area and several significant investigations are in the planning stage.

Middle Rio Grande Basin

The Rincon and Mesilla Valleys lie along a 108 mile reach of the Rio Grande River in the Middle Basin between the Caballo Dam in New Mexico, and El Paso, Texas. The Rincon Valley contains about 15,000 irrigated acres (6070 hectares) and the Mesilla Valley about 70,000 irrigated acres (28,330 hectares). Salinity studies conducted over a period of 20 years by Wilcox (34), indicated an increase of 272 ppm, due almost entirely to the effect of salt loading resulting from irrigation return flows in the Rio Grande River between the Caballo Dam and El Paso. Water quality deterioration in the Rincon and Mesilla Valleys has been accelerated by the increased consumptive use of ground water for irrigation brought about by the drought of 1951 to 1957 when a critical surface water shortage existed. More than 1700 water-supply wells were completed in the alluvial aquifer during this period. Today approximately 42 percent of the water used in the Rincon and Mesilla valleys is supplied by wells. The average salinity of water taken from a representative group of these wells indicates that the ground water is considerably more saline than that in the river (35). There is little doubt that the salinity of both ground water and the river will continue to increase as a result of use and reuse together with attendant concentration through evapotranspiration. The effects of the deterioration of water quality will be increasingly reflected in damage to valley soils.

The overall efficiency of irrigation in the Rincon-Mesilla Valley ranges between 40 and 50 percent. Re-stated, this means that as much as one-half the applied water is lost by deep percolation. The quality of the percolating water is seriously degraded as it passes downward to the water table. Experimental research is currently underway to reduce the amount of return flows through more efficient application of water to the land. The effects of trickle or drip irrigation on water use efficiency in the area are also under investigation (35).

The quality of water in the Rio Grande River, aggravated by irrigation returns, is of particular importance to the cities of El Paso and Juarez. Both are growing rapidly and long-term projections indicate that their municipal and industrial water needs may eventually require the entire river flow. Pumpage for municipal purposes accounted for about 56 percent of the water used in 1960 and the ground water source which receives its recharge from the river will continue to be relied upon to produce the major part of future requirements.

Lower Rio Grande Basin

The Lower Rio Grande Basin includes the downstream drainage area between Ft. Quitman, Texas and the Gulf of Mexico. The river marks the International Boundary between the United States and Mexico throughout this reach and is joined by several important tributaries originating in both countries. Among these are the Pecos and Devils Rivers in the United States and the Rio Conchas, Rio Salado and the Rio San Juan in Mexico.

The principal irrigated area in the United States lies in Hidalgo, Willacy, and Cameron counties in the Lower Rio Grande Valley. The gross value of Valley agricultural products is about $100,000,000 per year.

The fertile lands of the Lower Rio Grande Valley are dependent upon water from the river for irrigation. However, this source is supplemented during drought periods from about 1500 irrigation wells capable of providing an additional 2,200 acre-feet (2,713,680 cubic meters) daily. Poor quality of the return flow limits the use of drainage-canal water but this source is also used as a supplemental supply during periods of serious drought. Drainage water from the Texas side of the Rio Grande is not returned to the river but is diverted to the Gulf of Mexico through the Laguna Madre.

The irrigated area is essentially deltaic, relatively flat, low-lying, and slopes gently to the northeast from the Rio Grande River toward the Gulf of Mexico. There are few natural channels for the removal of surface waters. The surface drainage problem is so severe that much of the surface runoff from Hidalgo County must flow overland through Willacy County to reach the Laguna Madre.

Numerous underground drains have been installed but are inadequate and have failed to keep pace with drainage needs. The subsurface drainage problem is aggravated by over-irrigation, excessive seepage from unlined irrigation canals, undersized outlets, or even complete lack of outlets, plus excessive water contributed by high intensity storms and hurricanes (36). Periodic hurricane-associated floods may inundate the land for days or even weeks.

This impairment of subsurface drainage is reflected in surface drainage deficiencies. Surface drainage ditches lack depths sufficient to adequately lower the ground water table. Additionally, they are overloaded, suffer from improper maintenance, structural deterioration, and lack adequate outlets. Numerous surface obstructions such as roads, railroads, highways, canals, and drainways restrict runoff and further aggravate the problem. Frequent waterlogging of a significant portion of the valley creates serious problems involving ground water salinity and salt-laden soils.

The Comprehensive Study and Plan of Development, Lower Rio Grande Basin, Texas (36) states that the valley contains 690,000 acres (279,245 hectares) of irrigable land having a high water-table problem and, of this amount, 655,000 acres (265,080 hectares) have attendant salinity problems. It is estimated that crop yields are currently being reduced at the rate of 10 to 15 percent by excessive salinity and in some areas croplands may have to be removed from production - a condition that will progressively worsen with time if remedial steps are not taken. The drain waters frequently contain domestic sewage, untreated cannery and other food processing wastes, phosphates, pesticides, organic residues, bacteria and silt. At periods of low flow the chemical and bacteriological quality of the irrigation returns is very poor.

Pecos River Basin

The Pecos River is the principal tributary of the Rio Grande River in the United States. Approximately 200,000 acres (80,940 hectares) of agricultural lands are being irrigated in the Pecos River Basin in New Mexico. Of this amount, about 40,000 acres (16,190 hectares) are being irrigated using surface water; 125,000 acres (50,590 hectares) using ground water and 35,000 acres (14,165 hectares) using combined sources. Principal crops in the Basin are cotton and alfalfa. Secondary crops are grain sorghum, barley and wheat. The average yearly consumptive irrigation usage ranges from 0.85 to 1.8 acre-feet per acre (2625 to 5550 cubic meters per hectare).

It has been stated that "For its size, the Basin of the Pecos River probably presents a greater aggregation of problems associated with land and water use than any other irrigated basin in the United States...."(37). Salinity problems are particularly acute and irrigation return flows add significantly to the dissolved solids content of the river, principally in the Middle and Lower sub-basins in New Mexico and Texas. Very heavy growths of phreatophytes and other vegetation plus saline loads from salt springs and oil field brines combine tc further deteriorate water quality. Studies to date regarding Pecos Valley return flow problems are rather generalized and sparsely documented. However, programs looking toward solutions to the problem of water quality deterioration in the Pecos Valley are in the planning stage.

Central Valley Basin, California

The Central Valley Basin of California constitutes the largest irrigated area in the United States and is not without its share of water quality problems resulting from irrigation return flows. The valley is in the form of a northwest trending, elongate bowl, bordered by mountains. The lone outlet is a gap on the west in the San Francisco Bay area through which the Sacramento and San Joaquin Rivers discharge to the Pacific Ocean. The Basin is roughly 500 miles (805 kilometers) long and 120 miles (195 kilometers) wide and constitutes more than one-third of the entire area of the state. It contains about 10,000,000 acres (4,047,000 hectares) of cropland of which approximately 6,000,000 acres (2,428,200 hectares) are presently under irrigation. The Central Valley is roughly divided into three segments termed the North or Sacramento Valley, the Middle or Delta area, and the South or San Joaquin Valley.

Sacramento Valley

The Sacramento Valley contains approximately 1,000,000 irrigated acres (404,700 hectares). Among important crops produced is rice. This cereal grain represents a major commodity and its cultivation is carried out using modern methods. Aerial techniques are used to seed presprouted rice and to apply pesticides and fertilizers. (Figures 17 and 18). The quality of the applied water is very good. Deterioration is largely caused by excessive nutrients (nitrates and phosphates) and pesticides, with only nominal problems associated with salinity. During the early period of development of irrigated agriculture in the Valley, water was obtained from wells but in recent years surface supplies have been rapidly replacing subsurface sources. Development of additional water resources has brought about increased irrigation and attendant drainage problems associated with high water tables created principally by excessive water application. It is estimated that approximately 50,000 acres (20,235 hectares) are affected in this manner in the Sacramento Valley (27).

Sacramento-San Joaquin Delta

The Delta area, also known as the Delta Lowlands, contains 738,000 acres, (298,670 hectares) of which more

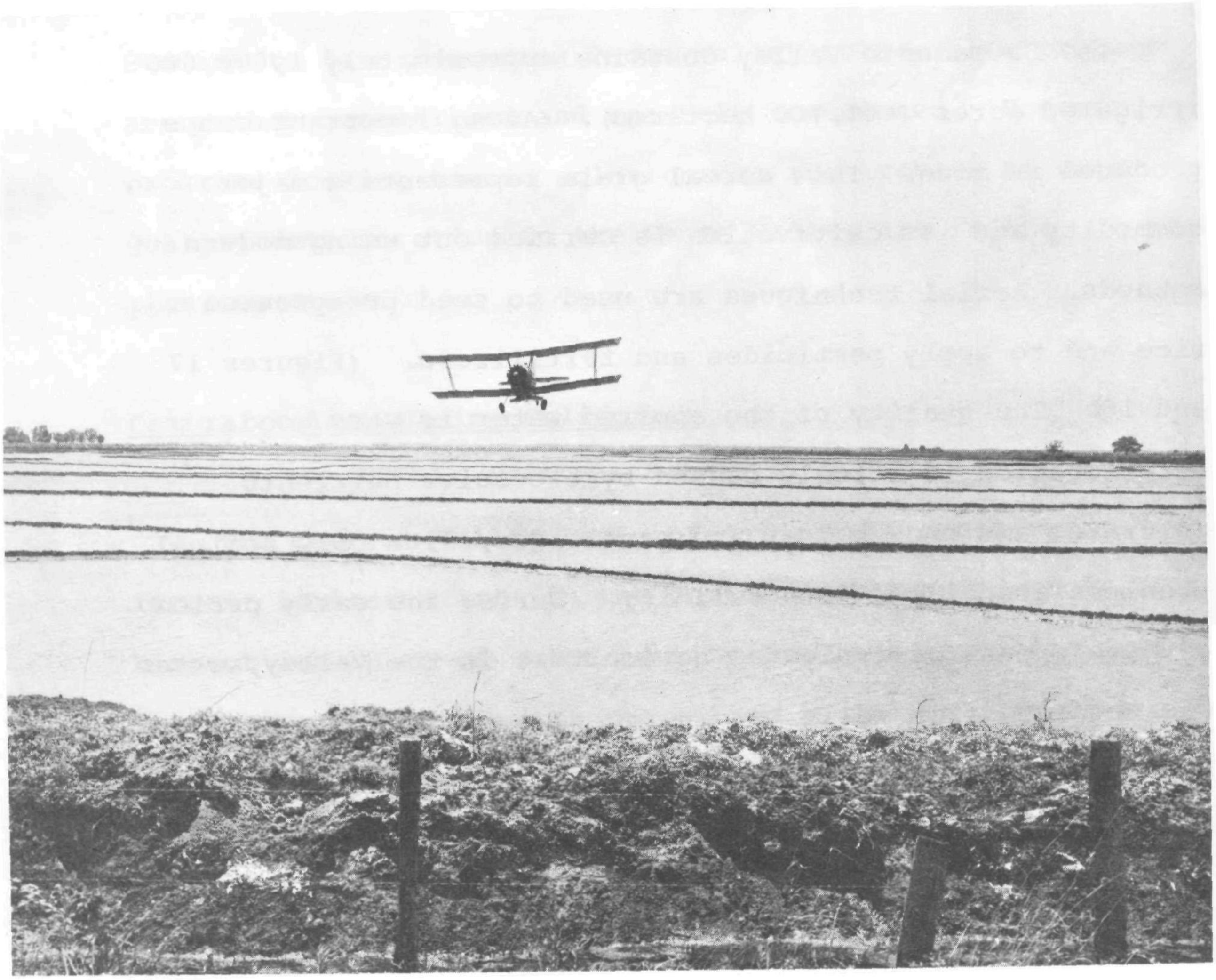

FIGURE 17. Seeding of presprouted rice using aircraft. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 18. Application of pesticide by aerial crop spraying. Photo courtesy Bureau of Reclamation, U.S. Department of the Interior.

than 500,000 acres (202,350 hectares) are in irrigated agriculture. The Delta is located at the confluence of the Sacramento and San Joaquin Rivers and is one of the most productive in California.

The Delta is unique inasmuch as a significant amount of its cultivated acreage lies below the level of the Delta channels and the water must be siphoned over the channel levees into deep drainage ditches where irrigation is accomplished by capillary movement upward from the water table into the plant root zone. Salts accumulate in the root zone and must either be removed or reduced to non-toxic levels. This is accomplished by periodic leaching, usually during the winter months, and the saline return flows discharged to the channel system.

San Joaquin Valley

The San Joaquin Valley contains over 7,000,000 acres (2,832,900 hectares) of irrigable land of which slightly less than 4,000,000 (1,618,800 hectares) are currently developed. Of this amount, 2,700,000 acres (1,092,690 hectares) are located in the Tulare Lake Basin at the southern end of the valley. The importance of the San Joaquin Valley as an agricultural province is readily apparent when it is realized that the valley contains about

40 percent of the irrigable land of California. Rapid expansion of irrigation in the San Joaquin segment of the Central Valley was stimulated by construction of the California State Water Project, the Federal Delta - Mendota Canal, and the San Luis Project.

Salinity of irrigation returns is significant in the valley. Additionally, and of great importance, is the high nitrate content, the source of which is inherent in the soil. The total solids content of irrigation water supplied from the Sacramento River system ranges from 500 to 700 parts per million. Severe degradation of quality resulting from concentration through consumptive use and leaching of natural salts, including nitrates and boron compounds from the soils by deep percolation, has occurred and is progressively worsening. The salinity of some returns has reached 20,000 ppm (27). Deterioration of water quality is often accompanied by high water tables in areas where subsoil permeability is restricted and irrigation is intensive. Extensive damage to crops and soil has occurred as a result of these factors. Tile drains have been emplaced beneath 34,000 acres (13,760 hectares) in an attempt to alleviate the problem. It is estimated that the amount of acreage actually benefited is much greater inasmuch as the drainage network intercepts subsurface water from adjacent and upslope areas (38). Plans call for construction of a massive complex of tile drains beneath an additional 300,000 acres (121,410 hectares) of valley land.

The effluent from the drainage system is either returned to the San Joaquin River or recycled into the canal delivery system. The discharge of the returns into the river poses a serious threat to the ecology of the San Francisco Bay system. The most troublesome pollutant is nitrate. Construction of the San Joaquin Master Drain, a joint U.S. Bureau of Reclamation and California Department of Water Resources project designed to collect, transport and discharge the highly saline and nitrate-charged agricultural waters from the valley to the Sacramento-San Joaquin Delta will aggravate the ecological problem. Evaluation of the effect of the discharge on the quality of Delta and Bay waters has been undertaken by the Central Pacific Basins Comprehensive Water Pollution Control Project of the Federal Water Pollution Control Administration, predecessor of the Environmental Protection Agency (39). An additional study has been made by the California Regional Water Quality Control Board (40). Proposed methods of denitrification of Master Drain waters include both bacterial, and algal production and harvesting (algae stripping). The study also considered desalination of the wastewater to remove salts, including boron compounds.

Summarizing, the vast San Joaquin Valley agricultural province is beset by a complex set of return flow problems including high concentrations of natural salts, toxic boron compounds, excessive native (plus applied) nitrates, high water tables and poor drainage conditions.

Yakima River Basin, Washington

The Yakima River Basin, located in south-central Washington, contains about one-half million irrigated acres and is one of the most intensively farmed in the United States. Five government-owned irrigation facilities plus several privately-owned systems and districts serve the Basin's water needs.

Ample supplies of water in the Yakima Valley during the early days of irrigation resulted in the application of large quantities to the land. Following a long history of excessive irrigation, waterlogging of the soils occurred as the ground water table rose and finally reached a point where surface water accumulated in areas of inadequate drainage. Evaporation of the ponded water left a toxic concentration of salts both on the surface and in the shallow root zone and large amounts of land were severely damaged.

Concentration of mineral salts in irrigation water returning to the Yakima River system, particularly after multiple diversions is caused principally by consumptive use, leaching, and ion exchange. Return flow quality is also affected to a significant degree in the basin by nutrient application, erosion, and crop removal. A detailed study of the return flow problem by the University of Washington pointed to the excessive application of water as the major source of deterioration of irrigation returns in the Basin (41). It is estimated that 6.6 acre-feet per acre (20,350 cubic meters per hectare) are diverted to the surface and, of this amount, about 4.25 acre-feet per acre (13,100 cubic meters per hectare) are actually applied to the land. The balance is lost in conveyance channels by seepage, wastage of various forms, and evapotranspiration. The study concluded, in part, that irrigation return flows, both surface and subsurface, were the responsible factor in influencing the overall water quality of the Yakima River. It further concluded that excessive application of water was instrumental in elevating the ground water table and degrading ground water quality; that quality was lessened by the addition of minerals and soluble nutrients to a degree where the dissolved solids content increased approximately five times that of the adjacent surface water; and, that leaching and ion exchange were the mechanisms largely responsible for the change in water composition.

Crops irrigated with water affected by irrigation returns in the valley were also heavily infested with parasitic nematodes. Unusally high sediment loads, together with attendant adsorbed fertilizers and pesticides are common in Basin return flows and are often of greater importance than the effects of salinity on water quality deterioration. Excessive water application is responsible for the high sediment loads. A study of the effects of sedimentation in the Basin's Roza Irrigation District has recently been undertaken (42). Investigators found that sediment concentrations in return flows, even under the best current irrigation system management, failed to meet the water quality standards established by the Washington State Department of Ecology, the standards-setting agency. Returns often contained turbidity values in excess of 400 JTU (Jackson Turbidity Units). State standards require that turbidity, even in Class "C" waters not exceed 10 JTU over natural conditions.

Snake River Basin, Idaho

Approximately 4,225,000 acres (1,722,000 hectares) are being irrigated in the Snake River Basin of southern Idaho. The Bureau of Reclamation estimates that an additional 6,000,000 acres (2,428,200 hectares) are potentially irrigable. Both surface and ground water in Idaho are of high quality and suitable for irrigation purposes. Ample supplies are available and water allotments in the Snake River Valley are particularly high. They range from about 6.5 acre-feet per acre (20,500 cubic meters per hectare) to nearly 13 acre-feet per acre (40,100 cubic meters per hectare) in areas where a range of between 2 and 3.5 acre feet per acre (6,175 and 10,800 cubic meters per hectare) would probably satisfy most requirements. Surface erosion and deep percolation are problems created by these excessive applications and, while not serious at this time, will no doubt become so when the Basin's irrigable lands are fully developed (27).

An evaluation of the effects of irrigation on water quality in the Pacific Northwest has recently been completed and provides a valuable insight into the problems of the Snake and Yakima River basins (43).

Other Major Problem Areas

The Missouri River Basin and the Arkansas-White-Red River Basin are in need of detailed study. The upper segment of the Missouri River Basin has several areas where irrigation return flow problems exist but where significant salinity increases in the stream system are not obvious because of the diluting effect of ample water supplies.

A study of diffuse or non-point irrigation returns discharging into the North Platte River in Nebraska immediately downstream from the Nebraska-Wyoming state line indicated a 27 percent increase in the salinity of the river during a period of low flow in 1964 (44). The actual range in total solids varied from 509 ppm at the state line to 647 ppm at Bridgeport, Nebraska, a distance of 60 river miles (97 kilometers). Even though the increase was nominal, responsible authorities are concerned. Water taken from the North Platte River is used for irrigating many thousands of acres in Nebraska and its deterioration could impose serious detrimental effects on the economy of the state.

Skogerboe and Law (27) recount examples of serious irrigation return flow quality problems existing in several states. Among these are high sodium concentrations in soils near Riverton, Wyoming where the problem is so severe that reclamation of once-irrigated lands is currently uneconomic in many areas. Problems are also beginning to develop in both North and South Dakota in lands underlain by highly saline formations of very low permeability.

The areas cited are those for which there is documented evidence regarding salinity imparted to water by irrigation return flows. There are additional areas where water quality deterioration caused by irrigation practices are important. The problems involved are similar to those cited and include increases in salinity of the receiving water; elevation of the ground water table to critical levels; damage to the soil, surface and root zone; excessive erosion and sedimentation; transfer of fertilizers and pesticides, plus other water-degrading factors associated with irrigated agriculture.

REMEDIAL AND CONTROL MEASURES

The control of salinity and other pollution caused by irrigation return flow cannot be easily achieved. Control methods include the application of current technology and the development of new technology. Current technology includes known methods of increasing the efficiency of the water development system, on-the-farm water management, and elimination of surface discharges of irrigation waters. These, combined with the application of irrigation scheduling and increased water-use efficiency will minimize pollution caused by irrigation returns. These methods and procedures must be coordinated with a careful reevaluation of the institutional measures affecting irrigation.

Farm Water Delivery System

The water delivery system consists of conveyance channels, beginning with major irrigation canals conveying water from diversion points to the irrigation district or farm system and terminating in the lateral distribution network. Estimates of seepage losses from canal systems vary from 13 percent in the Uncompahgre, Colorado area, to 48 percent in the Carlsbad, New Mexico Project. If 20 percent of all water diverted for irrigation in the United States were lost by seepage (a conservative estimate), the total would amount to 24,000,000 acre-feet (29,603,760,000 cubic meters) per year based on current usage (27). This amount of water could irrigate an additional 8,000,000 acres (3,237,600 hectares) or could be available as a diluent to improve the quality of existing water supplies. Not only do channel losses by seepage represent a potential waste of a valuable resource but percolating waters may leach additional minerals from the soil and further deteriorate the quality of the return flows. The problem can be alleviated or even eliminated by lining the canals and ditches. A study of the effect of lining irrigation conveyance channels on the reduction of ground water and stream salinity was undertaken as part of the Grand Valley Salinity Control Demonstration Project (45). Conclusions drawn as a result of the study clearly indicated that conveyance lining is a feasible salinity control measure.

Conveyance channel lining is incorporated into all new projects initiated by governmental agencies and is a proven, effective deterrent to return flow water quality deterioration. Lining materials may be compacted earth, hard-surface, or membrane. The hard-surface linings include portland cement, concrete, mortar, asphalt cement, and soil-cement. Such lining materials are used where structural stability such as the prevention of canal bank failure or velocity erosion in high-capacity delivery systems is necessary. The use of concrete head ditches results in considerable saving of water, eliminates annual cleaning or remaking earthen ditches and enables more efficient control of water flow and distribution. Figures 19 and 20 illustrate the use of concrete in two methods of ditch lining whereas the use of plastic lining in conveyance channel construction is shown in Figure 21. An operational concrete-lined ditch is shown in Figure 22.

A problem inherent to the open ditch is one of evaporation losses from the free water surface. Substitution of closed conveyances such as steel, concrete or plastic mainline or conduit is the logical alternative. Pipelines, in addition to eliminating seepage and evaporation losses ordinarily occupy less space and usually provide better control over flow regulation. Steel irrigation pipe mainline is shown in Figure 23. The early stage of construction of a 30-inch steel pipe flume designed to convey snow-melt runoff directly to a major irrigation diversion is shown in Figure 24.

Large earthen irrigation storage reservoirs are often constructed to provide water for multiple users such as

FIGURE 19. Earthen water conveyance ditch being lined by spraying or "shooting" with concrete. No reinforcement is used in this method. Pinal County, Arizona. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture

FIGURE 20. Pouring concrete ditch with size 12 wire mesh being placed in the concrete. This ditch is 34 inches deep with 1 to 1 side slopes. Pueblo County, Colorado. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 21. The Delta B Canal, a large conveyance channel near Delta, Utah being lined with plastic. Two 32 foot plastic strips are being used to line the canal. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 22. A modern concrete-lined irrigation canal. Note control gates which can be closed in order to regulate the flow of water into the desired channel. The crop is alfalfa. Installation near Red Bluff, California. Photo Courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

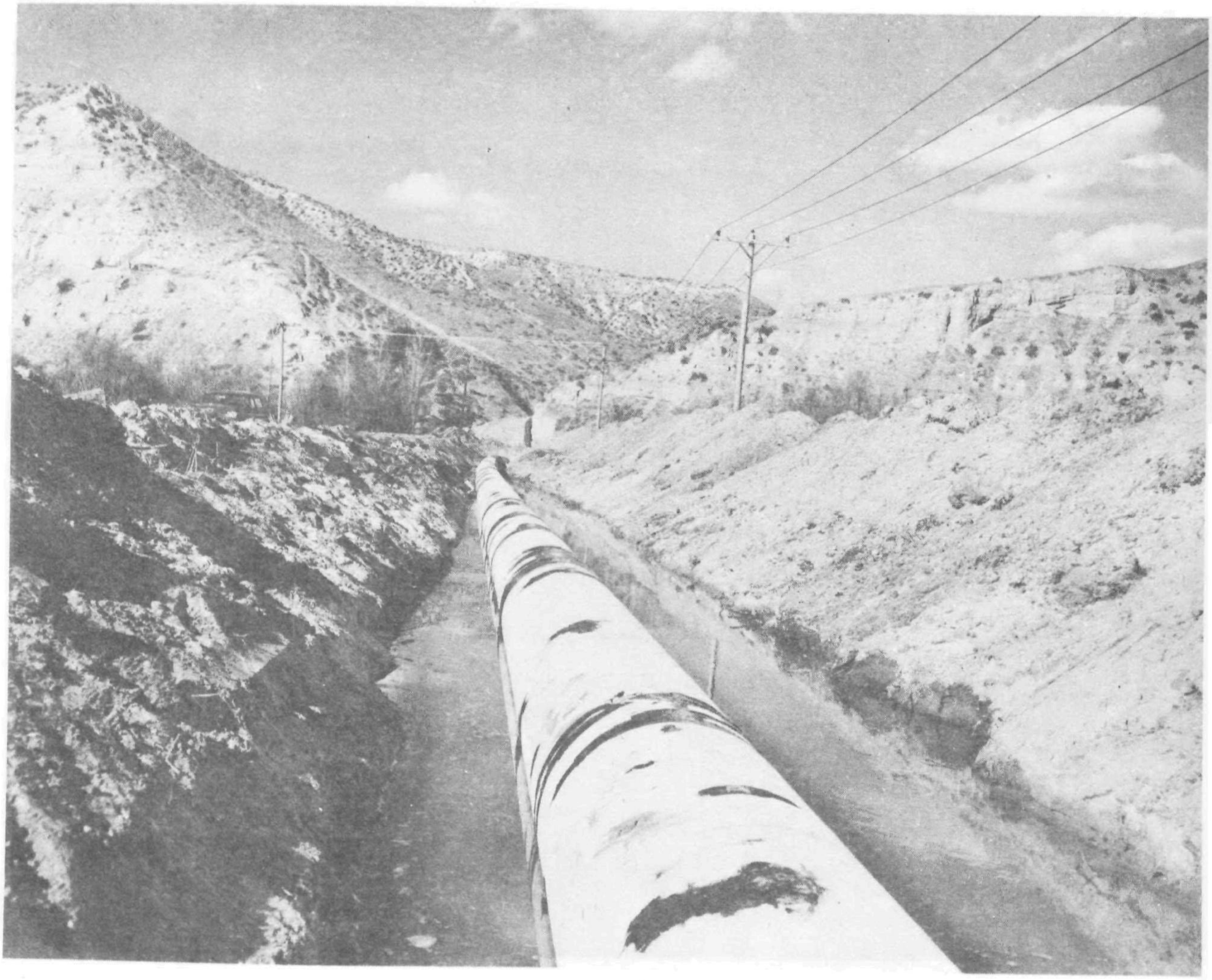

FIGURE 23. Steel mainline (42 inch penstock) capable of delivering 50 cubic feet per second of irrigation water to 3000 acres of cropland. Near Payette, Idaho. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 24. Irrigation pipe being delivered by helicopter to site in mountainous terrain. This 30 inch flume will deliver snow-melt runoff water directly to an open diversion ditch. Near Gypsum, Colorado. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

irrigation or conservation districts. Storage reservoirs are also useful in areas where the sources of water are limited. For example, a low-productivity well or wells can supply water continuously to the reservoir while the latter is used intermittently to irrigate. These structures may be a source of seepage and subsequent impairment of ground water quality if improperly constructed. Leakage can be eliminated by sealing the reservoir walls and floor with impervious materials. Figure 25 illustrates the application of "gunnite" (grout) to excavation walls. Figure 26 illustrates the placement of polyethylene lining in an irrigation reservoir. Excellent treatments of the subject of ditch lining and reservoir sealing have been issued by the U.S. Department of Agriculture and the U.S. Bureau of Reclamation (46, 47, 48).

Many delivery systems in use today contain no provision to meter or otherwise regulate the amount of water provided to the irrigator. Correct measurement not only increases water application efficiency, but is a sound water management practice. A higher degree of water-use efficiency can be attained when the amount of water passing principal points in a delivery system is known.

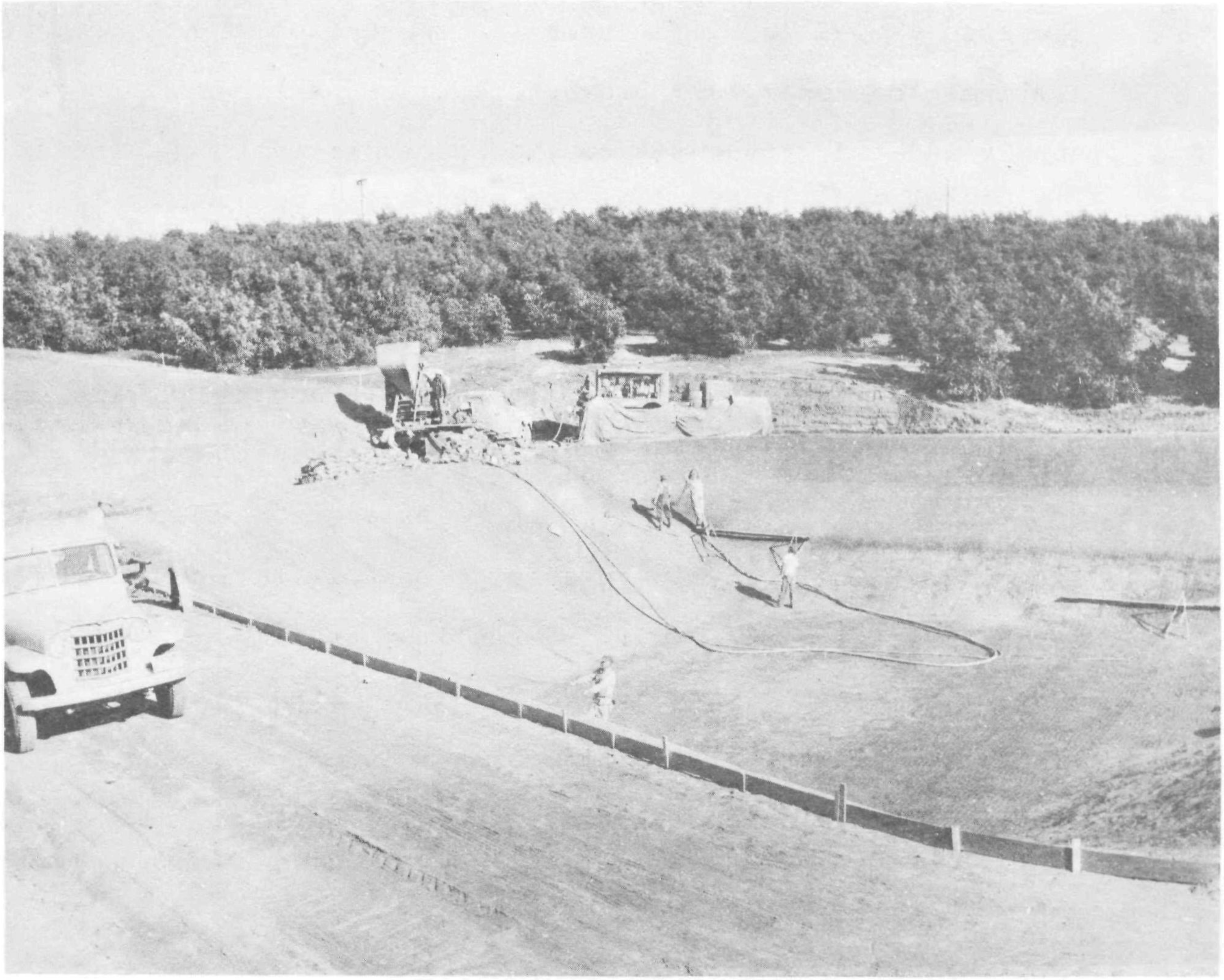

FIGURE 25. Earthen irrigation storage reservoir being lined with grout or "gunnite reinforced with wire mesh. Sealing the walls and floor of the structure virtually eliminates seepage. San Diego County, California. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

FIGURE 26. Polyethylene lining being placed in large irrigation reservoir to render the water-holding facility impervious to leakage. Riverside County , California. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

Farm Water Management System

The judicious management of water applied to irrigated crops on the farm represents the most practicable method of controlling water pollution imparted by irrigation return flows.

Controlled application such as irrigation scheduling will reduce excessive seepage losses and eliminate surface runoff while maintaining correct available moisture capacity in the plant root zone.

Irrigation scheduling is defined as the process of applying an optimum amount of water to any particular crop when it is needed. In many irrigated areas the farm operator is inclined to irrigate when his field is dry rather than attempt to maintain an optimum moisture level in the soil. Over-application of water on a discontinuous basis frequently occurs and may result in possible damage to the crop, unnecessary runoff, and excessive deep percolation. Optimum irrigation scheduling is currently being practiced in a number of areas in the western states and may ultimately be adopted as the accepted method of irrigation on a nation-wide scale. Demonstration projects using scheduling techniques are becoming more numerous and computerized programs involving water application to irrigated farms are being developed.

The Bureau of Reclamation is conducting a pilot irrigation-management study in southern Idaho to develop a useful computerized-management program that can be employed by both irrigation districts and individual irrigators (49, 50). The program's goal is the development of a system which will schedule both the application of irrigation water to the farm and delivery of water through the system. The program was the outgrowth of a study which indicated that regional farmers were obtaining less than 45 percent effective use of applied water. The low efficiency resulted from excessive application and inexact timing. The soil moisture reservoir was not being fully utilized. Experts estimated that proper scheduling of irrigation, plus improved on-the-farm water management, could increase efficiency to 55 or 60 percent. The program was implemented in 1969 with eight farmers initially participating on a non-assessment basis and has since expanded to 76 users, irrigating approximately 14,000 acres (5,665 hectares) of the 76,000 irrigable acres (30,755 hectares) in the project area. Scheduling techniques involving the field-computer approach have also been developed by the Salt River Project's Agriculture section, Arizona (51, 52). Project personnel work closely with the individual irrigator in an effort to achieve optimum use of water for a particular crop growing in a typed soil. Field services rendered include fertilizer application recommendations along with the evaluation of current in-use irrigation system efficiencies. The concept of scientifically-determined irrigation scheduling is rapidily expanding and several commercial irrigation management services capable of providing the irrigator with computerized analyses and trained agriculturists are available to the prospective client.

On-the-farm water management practices, less sophisticated than computerized scheduling, can be applied by the irrigator to effect substantial decreases in return flow volumes. These include the prevention of overflow in head ditches and laterals; improved distribution of water over the field, elimination of "lows" or depressions in the graded field to prevent ponding of water; contoured terraces constructed to prevent runoff; and prudent choice of irrigation method. These factors, along with others somewhat less important, constitute good conservation-irrigation practices.

Modern equipment and methods to accurately control distribution of water applied to the land are available to the present-day irrigator. Substantial reductions in the amount of applied water can be achieved after leveling or releveling the land and maintaining the improved configuration. Reductions as great as 40 to 50 percent in water use may occur following leveling and the installation of simple (Parshall flume) water measuring devices. Over-irrigation results in excessive water losses due to abnormally high seepage and evaporation, causes soil waterlogging in low spots, and creates potential drainage problems. Planned water use reduces labor costs. The well-managed system also requires less attention. Farm ditches kept clean and free of weeds, grasses and debris will prevent clogging, overflowing, and attendant water wastage and erosion.

Water Application Methods

There are three basic methods of applying water to an irrigated tract. These are surface, sprinkler, and subsurface. Choice of method is principally a function of land slope, soil type, water quality, plant acceptance and soil erodability.

Surface Methods

In the surface method, water is applied directly to the ground at ground level and flows by gravity over the surface of the field. The amount of land slope is important in the surface irrigation system inasmuch as the distribution of water over the field is totally dependent upon natural flow. The surface must be relatively flat and any slope present must be very gentle. Irrigation of close-growing crops is accomplished by flooding the entire field, which is surrounded by a dike, levee, or border to confine the water. In the irrigation of row crops, the water is directed down the furrows between the rows through siphon tubes from an adjacent water supply ditch. Surface application by the level border or furrow method is adapted to soils that have relatively low infiltration rates. Care must be taken to avoid too rapid application which could result in abnormal waste, excessive leaching, waterlogging, erosion, and accumulation of tailwater. Absolute control over these factors probably cannot be achieved. Control of tailwater, however, can be accomplished by recirculating or reusing the excess water applied on the farm. The reuse system also allows the irrigator a reasonable degree of application latitude and enables the use of minimum allowable stream flows in each furrow. Minimal furrow stream flow in turn, normally results in decreased furrow erosion, higher irrigation efficiencies and larger crop yields.

Trickle and Drip Methods

A variation of the surface method is the relatively new trickle or drip irrigation system. In the trickle method, water is applied very slowly to the soil surface adjacent to the base of the plant through a series of tiny holes or valves in irrigation pipe laterals. Water from these point sources moves through the soil by the action of gravity and capillarity. Evaporation losses are greatly reduced and water released is confined to a relatively small segment of soil adjacent to the plant root zone. This method offers considerable promise in future control of return flows and is capable of achieving very high irrigation efficiencies under many conditions (53, 54).

Drip irrigation is versatile and can be applied to field crops, orchards, vineyards, or pasture. A problem inherent to the method is the accumulation of salts at the periphery of the wetted portion of the moisture profile, where evaporation leaves a deposit of solids. Periodic leaching may be required to carry these salts below the root zone. Other problems are mechanical and involve a lack of uniform water application caused by manufacturing imperfections in water emitters, emitter clogging, and emission rate fluctuations resulting from friction-induced pressure drops in the conveyance lines. These have been the object of recent investigations (55). Problems and potentials of both trickle and drip systems have recently been summarized (56).

Sprinkler Methods

Sprinkler irrigation imitates rainfall -- nature's ordinary method of applying moisture to the land. Sprinkler methods can be applied to soils having high intake rates, on steep and irregular slopes, and on soils that are rough or too thin to level because of danger of exposure of subsoil. Irrigation of sloping, irregular land must be almost entirely limited to sprinkler methods inasmuch as homogeneous distribution of water can only be accomplished by sprinkling -- provided water is applied slowly enough to prevent erosion. Automatic controls are adaptable to sprinkler methods so that systems can be designed with a high degree of operational flexibility. Fertilizers, including liquid animal wastes, cannery waste lagoon effluents, and pesticides can be readily applied through sprinkler systems. Drawbacks to the use of sprinkler methods exist. If the crop grown is subject to fungi development or other diseases aggravated by high-moisture conditions, the method may have severe limitations. Also, highly saline water may leave toxic, and often lethal, deposits on the foliage if applied during periods of high ambient temperatures. High winds may distort spray patterns and reduce the efficiency of sprinkler application. Excessive amounts of silt, along with sand and trash in the water supply may cause nozzle plugging and excessive erosion of moving parts. This foreign material must be removed from the water prior to its introduction into the system.

Subsurface Methods

Subsurface irrigation or subirrigation, as originally defined, required that the ground water table be close to the plant root zone or that an impervious layer of rock or soil be present to confine the applied water to a position immediately below the root zone. In the subsurface method, water is supplied to the ground water mass through canals and laterals or by a system of subsurface pipelines in quantities which carefully regulate the height of the water table below the root zone. Capillarity then conveys the water to the roots of the plant. The system possesses a dual capability and is, in reality, a combination irrigation and drainage network capable of both supplying water and disposing of excess water if well-managed and properly monitored.

An interesting adaptation of water table management in subirrigation is cited in recent investigations of the use of subsurface drains to maintain the water table at proper depth to supply the needs of growing crops (57).

A new concept in subsurface irrigation, and one that shows exceptional promise in the field of return flow quality control, does not require the presence of a shallow ground water table. Water is applied underground to the root zone through tiny holes or valves in small diameter pipes buried in the row at the level of the root zone. Application rates can be carefully regulated to irrigate at frequent intervals with small amounts of water. Evaporation is reduced and salinity concentrations minimized. The application of water directly to the root of the plant has reportedly resulted in comparable crop yields using one half, or less, of that needed in "conventional" irrigation methods. This method then, may literally double the potential acreage that can be irrigated by a given quantity of water in those areas where its use is feasible. The method needs further testing over several agricultural cycles before its range of application can be established. A significant drawback is the system's capital cost which ranges from $345 to $850 per acre ($850 to $2100 per hectare), depending on pipe spacing. The principal application of subsurface irrigation techniques of this type will be in the cultivation of high-value crops in areas where water is expensive (56).

Minimum Tillage

Suppression of evaporation and transpiration of moisture from the soil reduces irrigation water demand and subsequently lessens the likelihood of excessive return flows. A cultural practice, known to agronomists for many years but not widely applied in irrigated agriculture is the no-tillage or minimum-tillage technique. The system requires that mulch left by a prior planting be retained on the soil surface. Significant reductions in runoff, soil erosion and nutrient loss, caused by destructive action of rainfall, can be achieved by preserving this protective ground cover. Rises in crop yields are the result of increased water infiltration and decreased evaporation.

Minimum tillage techniques do have disadvantages. Weeds must be controlled by application of herbicides prior to planting. Plantings in areas infested by bermudagrass or johnsongrass are ineffective inasmuch as herbicides fail to control these grasses. Pests such as cutworms, armyworms, wireworms and slugs tend to be protected by the mulch. It may be difficult to control volunteer crop plants and, unless reasonable use of herbicides can effect control, reversion to tillage or cultivation will be necessary. The possible application of the technique to irrigated farming was discussed during a recent no-tillage symposium (58).

Farm Water Removal System

The removal of applied water is an important aspect of the irrigation water management system. Both surface and subsurface returns must be considered.

Cultural practices designed to conserve water applied to the field and thereby reduce surface returns are well known and basically simple. Surface runoff is likely to occur if application of water to the land is unavoidably excessive as it might be in areas having very tight soils. Such soils have very low intake rates and require large amount of water for leaching.

Runoff can be minimized by deep-plowing. This creates a rough surface and facilitates soil moisture uptake and retention. Infiltration into deep-plowed soils may be increased by a factor of eight-to-fifteen times that of lightly-plowed soils. Contour planting and contour tilling can reduce soil loss caused by runoff, particularly on slopes of low-to-moderate grade, by as much as 50 percent. Contour strip cropping, a method of alternating strips of grass, which is close-growing, with strips of grain or other row crops can likewise be very effective in suppressing field erosion in addition to reducing runoff. The grass strip acts as a partial barrier to runoff, decreases its velocity, and acts as a filter, trapping a significant quantity of sediment while allowing the water to pass. Formed structures such as terraces and berms are commonly used to reduce concentrated runoff or intercept moderate-to-high velocity flows.

Surface runoff control lessens the degree of sediment transport and decreases the likelihood of important losses of nutrients and pesticides adsorbed on sediment particles. Filtration of water through a few feet of soil ordinarily eliminates nearly all adsorbable pesticides and nutrients but may have little effect on soluble minerals or highly soluble nutrients. The irrigator should remain continuously aware of the fact that a significant increase in water retention will tend to increase the subsurface component of irrigation return flow and increase the risk of stream and ground water pollution.

Excess water applied to the field can be collected in a reuse reservoir or tail ditch and recycled through the irrigation distribution system. In this manner, nutrients, pesticides, organic debris, dissolved solids, bacteria and plant parasites can be confined to the field. If not reused, tailwater may enter the surface or subsurface drains and provide contaminant loads similar to that of surface runoff, its non-consumptive counterpart. The difference in composition between applied water and irrigation runoff water in small watersheds has been the subject of recent studies by the U.S. Department of Agriculture (59).

Reuse of runoff water is a desirable conservation practice and can significantly reduce the ultimate cost of water, particularly to the irrigator who has found it necessary to develop a water well system at considerable capital expenditure. Reuse systems are not uncommon and need not be complex. The components usally consist of a collection pit, screen, pump, and automated controls (Figure 27). The system, including the possibility for use as an animal waste disposal facility in conjunction with farm livestock programs, has been described by the Nebraska Agricultural Experiment Station in cooperation with the Agricultural Research Service (60). Recycling excess irrigation water offers an excellent method of return flow control.

Subsurface drainage systems are often necessary to prevent waterlogging of the soil and are used to control buildup of salinity at or near the ground surface. Shallow water tables impede achievement of salt balance by increasing leaching requirements. Tile drainage networks

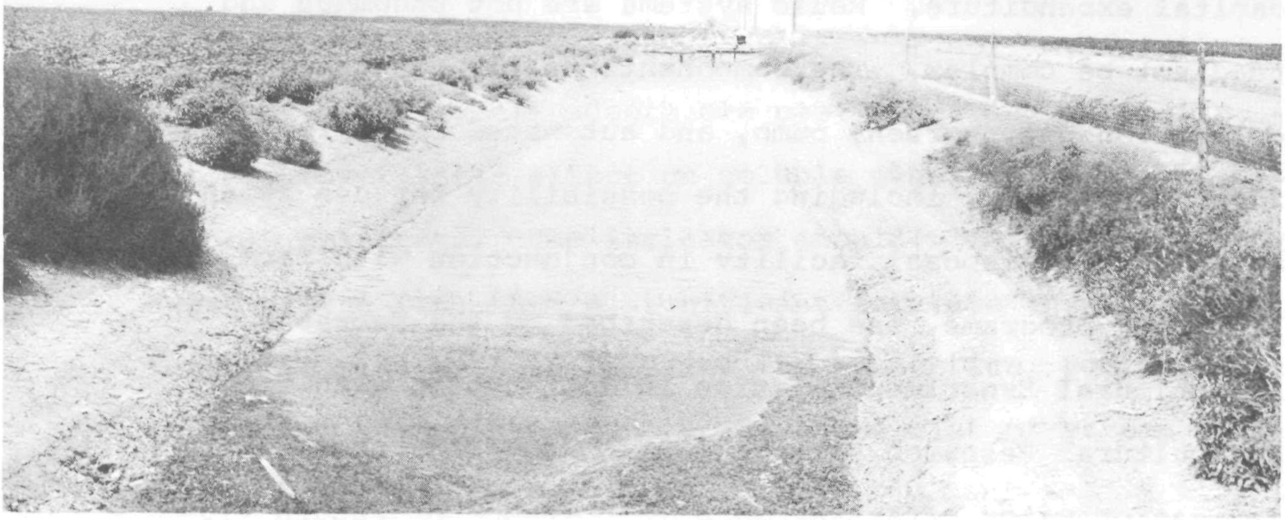

FIGURE 27. On-farm irrigation tailwater return pit. Intercepted water is recycled by pumping through a plastic pipeline to a concrete-lined ditch for reuse. Near Pecos, Texas. Photo courtesy Soil Conservation Service, U.S. Dept. of Agriculture.

are extensively used to convey water from the soil and to depress the ground water table to a point where it will not endanger crops. The tile drain and collection system offers a point source for treatment and control of pollutants. The problem of pollution by water emanating from tile drains has been addressed by the Federal Water Pollution Control Administration and others (39, 61).

Future Methods of Return Flow Control

The methods and procedures cited as pollution controls are those currently available to the irrigator and can be catergorized as state-of-the-art measures. They are technically feasible, practicable, economically viable, socially acceptable, and without adverse legal constraint. Their implementation would require few additional structural facilities or institutional changes on the part of the irrigator.

Feasiblity investigations that may provide additional measures of control of pollution created by irrigation return flow include several important studies now underway. Among these are measures designed to conserve water by minimizing evapotranspiration. The rate and amount of this loss is a function of numerous factors including solar radiation, temperature, relative humidity, wind velocity, available soil moisture, type of crop, stage of crop growth, length of growing season, degree of tillage, and surface mulch conditions. Any practicable method to reduce evapotranspiration is desirable and will increase irrigation efficiency. Reduction of evapotranspiration losses can be accomplished through judicious project planning (62). It has been shown that evapotranspiration can be diminished by using artificial barriers. These inhibit the downward movement of water and thereby curtail losses by deep percolation. Soil water evaporation losses to the atmosphere may also be reduced by these barriers (63, 64, 65). The most successful of these methods employ asphalt emplaced by tractor at depths of approximately two feet. The work is in the experimental and demonstration stage. Implementation costs range from $200 to $250 per acre.

Consumption of water by phreatophytes (those plants that habitually obtain their water supply from the zone of saturation either directly from or through the capillary fringe) is quite large in arid and semiarid regions. The control and partial elimination of these water users would release appreciable volumes of water for beneficial uses. However, the destruction of phreatophytes such as saltcedar, willow, cottonwood and mesquite would have to be undertaken on a limited orderly and carefully planned basis inasmuch as many forms of animal life such as birds, fowl, game animals and useful predators depend on the sanctuary of dense phreatophytic environments for survival.

Of all water uses (and losses) involved in the field of agriculture, the use of water by a growing plant is the most wasteful and involves efficiencies of only one to two percent. It is apparent that if plant efficiency could be increased by only a few percent, millions of acre-feet of water could be conserved. An interesting technology in evapotranspiration control is aimed at reducing the fluid loss from the growing plant per se. The concept is not new and has been used by nurserymen to combat desiccation of damaged trees and shrubs whose preservation was considered essential. A family of non-toxic chemicals designed to accomplish transpiration control more efficiently than at present is currently being developed. These compounds, called antitranspirants, fall into three catergories and include chemical leaf sealants, materials that increase leaf reflectivity and thus reduce plant heat load and, finally, chemicals which tend to reduce the size of the stomata or plant pore.

NEEDED DEMONSTRATIONS AND RESEARCH

Research and demonstration projects needed in the field of irrigated agriculture should emphasize those aspects with the greatest near-term impact upon water quality control. These fall into two major catergories and are, 1) technical, including management of the soil-plant-water system and, 2) institutional-legal, involving possible innovation, revision and reformation of irrigation district structure, reevaluation of Western water law and its conflict with water quality standards, and other institutional constraints. Both recognize that excessive water use is the greatest cause of water quality degradation associated with irrigation.

Technical

A blend of research and demonstration is neeeded to develop methods of increasing efficiency in irrigation practices. This concept involves sound design and subsequent operation of an irrigation project which will maintain crop yields and at the same time reduce water requirements, volume of irrigation returns, and amount of salt transported to surface or subsurface waters. Elements of the project must also be economically feasible.

Increased efficiency can be accomplished in several ways. Included is judicious management of the water-soil-plant system conducted under conditions where climate, water salinity and soil type are the major variables. Such methods use proven irrigation techniques to increase the efficiency of the water delivery system, the on-farm application system and the water removal system.

Methods of water application can greatly influence irrigation efficiency. Significant increases using subirrigation, drip-trickle and bubbler methods can be attained but will create a need for additional research inasmuch as the environment to which the irrigated crop will be exposed is radically changed. Soil-water in drip-trickle methods remains uniformly and continuously high. Organism populations in the surface soil may change and give rise to new and differing plant diseases. The possibility of adverse pathogenic effects also exist. Poor management of the drip-trickle system could be damaging and create hitherto unknown problems. Nutrient utilization will also be affected by a continuously moist environment. Salinity-nutrient interactions under these conditions are known to occur but little is known of the mechanism or its effects on plant response. Plant stress interactions between relative humidity and salinity, and between ozone (polluted air) and salinity are recognized. Adverse effects of air pollution can occasionally be overcome by salt stress and may be useful in maintaining ornamentals in a healthy state by artificial salination of the soil where air pollution is a problem.

Control of water application to establish a uniformly moist environment might be achieved through the use of sensors to monitor soil salinity at given depths. Soil salinity is a function of the amount of transitory drainage water. A salinity sensor grid might represent a major component of future irrigation systems. The foregoing concepts represent only a few of many possibilities designed to increase irrigation efficiency through advanced technology (66). The concept of irrigation return flow water quality improvement through application of more efficient methods is in harmony with the Environmental Protection Agency's position that remedial measures should be applied at the pollution source rather than by treatment of the effluent.

Research within the framework of the National Irrigation Return Flow Research and Development Program prepared for the Office of Research and Monitoring, Environmental Protection Agency contains a summary of worthwhile needs (16). A major thrust of the program is directed toward the development and demonstration of improved crop, plant, nutrient and pesticide management methods, -- all based upon interaction between soil, hydrology, salt and nutrient movement, fate of pesticides, and other factors. The development and demonstration of new and improved water delivery systems, application methods, drainage systems and tailwater reuse systems must necessarily be an integral part of the same program. Additional research needs and potential solutions for controlling quantity and quality of irrigation return flow are summarized in a prior Environmental Protection Agency publication (27).

Institutional-Legal

A demonstration or research program need not necessarily be limited to technologically-oriented projects but can include institutional approaches. These, like the technological approach, employ the concept of improved water management practices. Projects could include the restriction of irrigation development in areas of potentially high salinity; consolidation of irrigation companies and water supply districts into single management units; and encouragement of local acceptance of control measures through educational programs on the local, regional and State levels.

Other projects might include evaluations of the operational and proposed programs of Federal, State and local agencies to determine what future courses of action will be required to achieve reduction in pollution created by irrigation return flows. An important facet of such evaluation would include regulatory powers and authorities needed regarding land and water management and the possibility of integrating these into a return flow control program.

The control of diffuse returns is complicated by the difficulty of quantification, including determination of their measurement of pollutional effects. Additional complications are the basic conflicts between Western water law and water quality standards. The legal rule that water must be used to maintain the continued right to its use aggravates the problem.

Institutional constraints have been responsible for numerous salinity problems in many irrigated areas in the United States. Among these constraints are legal, political, cultural and economic. The legal constraint involves water rights. A water right is the legal right to the use of water and grants the right to divert and excerise physical control over the water. The right determines who can take the water, the amount to be taken, and the time of taking. The right is established as to priority of use and affords legal protection to the user. An irrigator having an adequate water right has little economic incentive to institute efficient water management practices. As a result, excessive irrigation often occurs. Rights cannot be bartered, bought, sold or leased, but must revert to the original grantor if not used. The "property right in water" concept created through the prior appropriation doctrine thus is a major deterrent to the implementation of water management technology. The element of water quality is not considered. The path to the resolution of the water management problem in the West could be cleared to a large degree by changes, or reinterpretation, of the doctrine. Perhaps strict enforcement of the law may, in many instances, be all that is required to implement control. For example, there are direct statutory restrictions to the excerise of a water right as in 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 water 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 (67).

A particularly troublesome institutional deterrent to control of return flow salinity exists in the Lower Rio Grande Valley. Irrigation is controlled and administered by 34 separate irrigation districts and four drainage districts plus water and other metropolitan districts. Each district has its own power and authority over the use, development, protection and administration of water within its jurisdiction. Each district designed and built its distribution and drainage facilities to serve only the area within its boundaries. Little attention was paid to the overall effect on Valley irrigation. These and other factors pertinent to the institutional problem of the Valley are presented in several important studies prepared by Texas A&M University (68, 69, 70). Conflicts created by these numerous and overlapping authorities account for a significant part of the Valley salinity and drainage dilemma. Cultural institutions in the Valley involve the continued use of time-honored concepts, customs and traditions that are no longer applicable in many instances and should be discontinued. These involve water application and use practices, labor use and crop preference.

A recent Environmental Protection Agency in-house study of salinity created by irrigation return flows concluded, in part, that the solution of the problem can only be accomplished through a basin-wide control program. The study also concluded that, "Improved water management practices, particularly the use of water at optimum efficiencies on the farm, is the most feasible approach to controlling excessive salt loads from irrigation return flows to many of our western river systems. Present technology would permit the implementation of several salinity control measures that are not now widely employed ....", and "Legal and institutional means must be found to control water salvaged through improved water management in order to finally achieve a solution to basin-wide salinity problems".

Present levels of government concern and effort can be expected to produce major achievements relating to permanent and definitive solutions to the problem of control of salinity and other pollutants.

GLOSSARY OF TERMS

Bypass water - water diverted for irrigation but returned to the source without having been applied to the land.

Consumptive use - water discharged into the atmosphere as vapor and no longer available for use by the discharging system.

Evapotranspiration - water lost as vapor from the combined process of evaporation from the soil and transpiration from vegetation. Evapotranspiration represents an important consumptive use of water.

Furrow irrigation - the application of water to furrows (narrow trenches dug by farm equipment) to irrigate crops planted in, or between, the furrows.

Leaching requirement - the amount of water that must pass through the root zone to maintain a prescribed salt level. Expressed as a percentage of the total water applied to the land.

Osmotic action - the diffusion of water through a semipermeable membrane (example - soil moisture extracted by plant root hairs).

Perched ground water body - a ground water mass located within the zone of aeration, and seprated from the main underlying ground water body by a zone of unsaturated rock.

Permeability - the capacity of a material (soil) to transmit fluid (air and water).

Porosity - the ratio of the aggregate volume of interstices, voids, pores or other openings of a soil sample to the total (bulk) volume. Usually expressed as a percentage.

Prior appropriation doctrine --a basic doctrine that all waters in a State, whether above or below the ground, are the property of the people. A vested right to the use of the water is acquired by appropriation and the application of the water to beneficial use. The individual first in time is first in right and beneficial use is the basis, the measure, and the limit of the right.

Salt loading - the addition of dissolved solids to water from both natural and man-made sources. Not to be confused with salt concentrating which increases salinity by stream flow depletion and concentration of the salt burden in a lesser volume of water. Salt loads may originate in surface runoff, diffuse ground water discharges, mineral springs, municipal and industrial waste, and irrigation.

Soil amendments - a group of low-nutrient organic materials such as compost, peat, and sewage sludge that may be incorporated into the soil or used as mulches. Amendments have a dual effect of improving the condition of the soil while providing some plant nutrient.

Tailwater - water which is the excess remaining after an irrigation.

Trickle irrigation - water applied very slowly to the surface of the soil through tiny holes or valves in plastic pipe.

Water infiltration - the downward flow of water from the soil surface into the soil. Infiltration implies flow into the soil as contrasted to percolation which denotes flow through the soil.

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