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POLLUTED GROUNDWATER: SOME CAUSES, EFFECTS, CONTROLS, AND MONITORING

UNDERGROUND INJECTION REFERENCES

Volume III

Reference 7

Office of Water Supply
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POLLUTED GROUNDWATER:
SOME CAUSES, EFFECTS, CONTROLS, AND MONITORING

By

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Task 4

Program Element No. 1H1325

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FOREWORD: WHAT IS "WATER QUALITY"?

The term "pollution" is defined by Section 502(19) of Public Law 92-500, the Federal Water Pollution Control Act Amendments of 1972, as "the man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water." But what is meant by "water quality"?

Perhaps the best discussion of the elusive definition of water quality is one provided by P. H. McGauhey (1968):

> "The idea that 'quality' is a dimension of water that requires measurement in precise numbers is of quite recent origin. Ancient British common law . . . was content to state that the user of water was not entitled to diminish it in quality. But the question of what constituted quality was neither posed nor answered. . . . A precise definition of water quality lay a long way in the future.
>
> "More than half a century ago a Mississippi jurist said, 'It is not necessary to weigh with care the testimony of experts — any common mortal knows when water is fit to drink.' Today we find it necessary to enquire of both common mortal and water expert just how it is that we <u>know</u> when water is fit for drinking. Moreover, in the intervening years, interest in the 'fitness' of water has gone beyond the health factor and we are forced to decide upon its suitability for a whole spectrum of beneficial use involving psychological and social, as well as physiological goals.
>
> "Looking back on the history of water resource development, one is impressed that under pioneer conditions it was usually sufficient to define water quality in qualitative terms, generally as gross absolutes. In such a climate, terms such as swampwater, bilgewater, stumpwater, blackwater, sweetwater, etc., produced by a free combination of words in the English language, all conveyed meaning to the citizen going about his daily life. 'Fresh' as contrasted with 'salt' water was a common differentiation arising from both ignorance and a limited

need to dispel it. If a ground or surface water was fresh, as measured by the human senses rather than the analytical techniques of chemists and biologists, it little occurred to the user that it was any different than rainfall in producing crops. The Lord has the sun at his disposal whereas the farmer has to rely upon ingenuity and hard labor to deliver the water; but delivery rather than content of the delivered product occupied attention. Thus the pioneer in search of water for his agricultural needs was content with a crude definition of its quality.

"As the author has noted elsewhere (McGauhey, 1961; 1965)

"A need to quantitate, or give numerical values to, the dimension of water known as 'quality' derives from almost every aspect of modern industrialized society. For the sake of man's health we require by law that his water supply be 'pure, wholesome, and potable.' The productivity and variety of modern scientific agriculture require that the sensitivity of hundreds of plants to dissolved minerals in water be known and either water quality or nature of crop controlled accordingly. The quantity of irrigation water to be supplied to a soil varies with its dissolved solids content, as does the usefulness of irrigation drainage waters. Textiles, paper, brewing, and dozens of other industries using water each have their own peculiar water quality needs. Aquatic life and human recreation have limits of acceptable quality. In many instances water is one of the raw materials the quality of which must be precisely known and controlled.

"With these myriad activities ... going on simultaneously and intensively, each drawing upon a common water resource and returning its waste waters to the common pool, it is evident to even the most casual observer that water quality must be identifiable and capable of alteration in quantitative terms if the word is to have any meaning or be of any practical use.

"Thus it is that those unwilling to go along with the Mississippi jurist must express quality in numerical terms.

"The identification of quality is not in itself an easy task, even in the area of public health where efforts have been most persistent. For example, the great waterborne plagues that swept London in the middle of the nineteenth century pointed up water quality as the culprit; yet it was another quarter of a century before the germ theory of disease was verified, and more than half a century before the water quality requirements to meet it were expressed in numbers. Even in 1904, when our Mississippi jurist spoke, children still died of 'summer sickness' (typhoid) often ascribed to such things as eating cherries and drinking milk at the same meal; and scarcely a family escaped the loss of one of its members by typhoid fever. Yet when it came to defining the water quality needed to avoid this, the best we could do was to place on some of the 'fellow travelers' of the typhoid organism numerical limits below which the probability of contracting the disease was acceptably small. Nor has this dilemma been overcome. In 1965, an outbreak of intestinal disease at Riverside, California, which afflicted more than 20,000 people and caused several deaths, was traced to a newcomer (Salmonella typhimurium) in a water known to be safe by 'experts' watching the coliform index. So once again the search begins for a suitable description of quality.

"A second dilemma which survived the struggles that codified and institutionalized our concepts of water quantity lies in the definition of the word 'quality.' While the dictionary may suggest that quality implies some sort of positive attribute or virtue in water, the fact remains that one water's virtue is another's vice. For example, a water too rich in nutrients for discharge to a lake may be highly welcome in irrigation; and pure distilled water would be a pollutant to the aquatic life of a saline estuary. Thus, after all the impurities in water have been cataloged and quantified by the analyst, their significance can be interpreted in reference to quality only relative to the needs or tolerances of each beneficial area to which the water is to be put.

"Shakespeare has said, 'The quality of mercy is not strained....' And indeed it is not as long as mercy is defined in qualitative terms. One can but imagine the problems which might arise if it were required that justice be tempered with 1.16 quanta of mercy in one case and 100 quanta in another. Yet this is precisely what confronts us in establishing measures of the dimension of quality of water."

References

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SCOPE

Public Law 92-500

Section 304(e) of Public Law 92-500, the Federal Water Pollution Control Act Amendments of 1972, provides that

> "The Administrator [of EPA] ... shall issue ... within one year after the effective date of this subsection (and from time to time thereafter) information including (1) guidelines for identifying and evaluating the nature and extent of non-point sources of pollutants, and (2) processes, procedures, and methods to control pollution resulting from —
>
> "(A) agricultural and silvicultural activities, including run-off from fields and crop and forest lands;
>
> "(B) mining activities, including runoff and siltation from new, currently operating, and abandoned surface and underground mines;
>
> "(C) all construction activity, including runoff from the facilities resulting from such construction;
>
> "(D) the disposal of pollutants in wells or in subsurface excavations;
>
> "(E) salt water intrusion resulting from reductions of fresh water flow from any cause, including extraction of ground-water, irrigation, obstruction, and diversion; and
>
> "(F) changes in the movement, flow, or circulation of any navigable waters or groundwaters, including changes caused by the construction of dams, levees, channels, causeways, or flow diversion facilities..."

Contractual Requirement

Task 4 was added to TEMPO's EPA contract on January 18, 1973. Under Task 4, TEMPO is required to provide information for developing EPA guidelines/reports in compliance with groundwater aspects of Section 304(e)(2)D, E, and F of the Federal Water Pollution Control Act Amendments of 1972, excluding surface-water aspects. This report is submitted in satisfaction of the requirements of the following sub-tasks:

"4A. Identify sources and evaluate the relative importance of point and nonpoint sources of groundwater pollution applicable to Section 304(e)(2)D, E, and F.

"4B. Identify and evaluate available processes, procedures, and methods for control of groundwater pollution from the sources identified under Task 4A ...

"4C. Conclusions and recommendations, including discussion of technological reasons and, to a lesser extent, related legal, economic, and institutional factors."

An informal smooth-draft report setting forth the results of work accomplished under Tasks 4A, 4B, and 4C was submitted on May 25, 1973.*

As indicated above, the sources and causes of pollution covered in this report are limited to those included under parts D, E, and F of Section 304(e)(2). Guidelines, Section 304(e)(1), are not included; surface-water aspects are not addressed; only the groundwater-pollution aspects of parts D, E, and F are considered.

METRIC UNITS

Both metric and British units of measurement are used in this report, without conversion. Conversion of British units to the metric system would have been preferable but was felt to be infeasible, because of the numerous illustrations and other information taken from references employing British units. To redraw illustrations (eg, contour maps) to convert them to metric units would have been time-consuming and expensive. Conversion of tabulated information would involve the dilemma of either implying more precision in the independent variable than the author intended, through use of too many significant figures, or of

*Meyer, Charles F. (Editor), Groundwater Pollution Control: An Interim Report, General Electric—TEMPO Report GE73TMP-19; prepared for Office of Research and Development, US Environmental Protection Agency, Washington, D.C. under EPA Contract 68-01-0759; Santa Barbara, California, May 25, 1973.

risking the introduction of errors in the dependent quantities if the metric units were rounded.

APPROACH

A broad interpretation of parts D, E, and F was adopted, in accordance with EPA guidance, in listing and defining the specific topics to be covered.

To supplement TEMPO's staff, a group of eminent consultants was assembled. The resulting TEMPO team is listed in the Acknowledgements. It includes both the depth and the breadth to prepare authoritative material covering each topic. Team members not only authored material in their own fields of expertise but also reviewed and contributed to the material written by other team members.

Several drafts were prepared; successive drafts were submitted to EPA for review and comment, discussed in numerous meetings with EPA personnel and among the TEMPO team members, and modified accordingly. The material was then edited to achieve as much uniformity of style as possible in the final report. In view of the blending of many inputs, and because of the editorial license that has been exercised, the authors are not specifically identified here with their subsections.

The treatment of each topic is not intended to be exhaustive, since this would take many volumes. Rather, the intent is to be as concise as possible, addressing those aspects felt to be most important, with liberal use of selected references to more detailed explanations. The material may be expanded or otherwise revised from time to time, as provided by Section 304(e) of PL 92-500.

Sections II and III of this report cover part D of Section 304(e)(2) of P. L. 92-500; Section IV covers part E; and Section V covers part F. Some overlap exists, because each section and subsection is as self-contained and independent as possible. References are included with each subsection.

The remainder of Section I is a general discussion of groundwater quality and pollution followed by a discussion of institutional and legal aspects of groundwater pollution control.

GROUNDWATER QUALITY AND POLLUTION

The quality of groundwater refers to its chemical, physical, and biological characteristics. All groundwaters contain dissolved solids, all possess physical characteristics such as temperature, taste, and odor, and some contain biological organisms such as bacteria. The natural quality of groundwater depends upon its environment, movement, and source. In general, groundwater quality tends to be relatively uniform within a given aquifer or basin, both with respect to location and time. But in different localities major contrasts in natural quality can be noted. Thus, groundwater temperatures may range from a few degrees above freezing in cold climates to the boiling point in thermal springs, while salinities may range from near zero in newly infiltrated precipitation to several hundred thousand milligrams per liter in underground brines.

For the purposes of this report, groundwater pollution is defined as the man-induced degradation of the natural quality of groundwater. The particular use to which a groundwater can be placed depends, of course, upon its quality. However, the various criteria defining the suitability of a groundwater for municipal, industrial or agricultural use are not considered in describing pollution. Instead, the measure of pollution is a detrimental change in the given natural quality of groundwater. This may take the form, for example, of an increase in chloride content, of a rise in temperature, or of the addition of E. coli bacteria.

Programs to control groundwater pollution are based upon the growing realization that both groundwater and the underground space in which it is stored are valuable natural resources to be conserved by preventing, reducing, and eliminating pollution.

Occurrence of Groundwater

Groundwater forms a part of the hydrologic cycle. It originates as precipitation or surface water before penetrating below the ground surface. Groundwater moves underground toward a natural discharge point such as a stream, a spring, a lake, or the sea, or toward an artificial outlet constructed by man such as a well or a drain.

Aquifers are permeable geologic formations capable of storing and transmitting significant quantities of groundwater. The most common aquifers are those consisting of unconsolidated alluvial materials such as gravel and sand. Other important aquifers occur in limestones, sandstones, and basalts.

A water table defines the level at which the groundwater is at atmospheric pressure; below the water table the permeable soil or rock is completely saturated with water. An unconfined aquifer is one bounded by a water table, whereas a confined aquifer is under a pressure greater than atmospheric due to overlying relatively impermeable rock strata.

Groundwater typically flows at rates of from 2 meters per year to 2 meters per day. Above the water table the flow direction is generally downward, but below the water table in the main groundwater body, the movement is nearly horizontal and governed by the local hydraulic gradient. Once a pollutant is introduced into an aquifer it tends to move in the same direction as the surrounding groundwater and at a velocity equal to or less than that of the groundwater. With time and distance traveled, pollutants decrease in concentration, resulting from dilution, adsorption, decay (eg, radioactive isotopes), and death (eg, bacteria). From a point source of pollution, a plume is often detected extending downstream within the aquifer and gradually dissipating with distance.

<u>Control by Elimination of Pollution Sources</u>

For any source or cause of pollution, an obvious control method would be to eliminate entirely the source or the cause itself. This method, however, is not possible in many situations and then becomes a trivial solution. To illustrate the point, one method for controlling pollution from septic tanks would be simply to eliminate all septic tanks. To completely eliminate the millions of septic tanks in the United States would require alternatives that are not realistic or feasible. Thus, the control methods that are described for septic tanks include not only the possibility of requiring sewers but also deal with regulating their construction, their location as regards subsurface conditions and topography, their density, their operation, and their maintenance. The latter measures, while not eliminating groundwater pollution, will reduce it and can prevent it from exceeding prescribed levels.

The suggestion that the source or cause of pollution be eliminated is not repeated for each of the sources and causes that are discussed. In general, the control methods that are suggested and discussed are those believed to be realistic and feasible. Clearly, the applicability of the suggested methods will depend upon local situations.

Control by Desalination of Pollution Sources

The most extensive type of pollution affecting groundwater is increased salinity (ie, mineralization). Many different pollution sources produce much the same result. For example, industrial wastes, oilfield brines, domestic and municipal sewage wastes, agricultural wastes, and irrigation return flows all contribute to increased mineralization of groundwater.

One method to control the impact of these and other sources on groundwater quality would be to desalt the wastes before permitting them to enter the ground. Although all of the salt from the pollutants need not be removed, salinities would have to be reduced to a level equal to or preferably less than that of the native groundwater before recharging the treated water. But environmental, technical, and economic considerations, at least in the near term future, may preclude application of this procedure in most instances. For example, producing the energy required for desalting, and disposing of the concentrated residual brine, may cause a severe environmental impact.

Urbanization and Pollution

The intensification effect of urban areas on groundwater pollution is an important factor in considering the consequences of various sources of pollution. Because man is responsible for actions leading to groundwater pollution, it follows that a large proportion of the sources and causes of underground pollution are found in and near population centers. This correlation between urbanization and pollution follows from the fact that groundwater may be regarded as relatively stationary in contrast to surface water flowing in streams. Furthermore, because the diversity of man's activities that produce pollution are so concentrated in an urban environment, the sheer density of these pollution opportunities becomes an important aspect of our modern pattern of living.

One section of this report specifically addresses pollution from urban areas. It describes those macroscopic facets of urban environments which produce changes in surface and groundwater flows and, thereby, changes in groundwater quality.

Hydrogeological Investigations

A fundamental concept applicable to almost all groundwater pollution control situations is the need for comprehensive hydrogeological investigations before initiating control procedures. The geologic and hydrologic environment of each groundwater resource system is unique and far more complex and slower reacting than surface water systems. The geologic structure governs the occurrence, the distribution, and the amount of groundwater in storage; the direction and rate of groundwater flow; the sources and locations of natural recharge; and the locations of natural discharge. The local hydrology largely determines the possible amounts of natural recharge. And most importantly, the local geological characteristics determine the movement, the dilution, and the adsorption of pollutants underground.

Groundwater resource systems are dynamic in nature. They respond both in quantity and quality, albeit slowly, to natural phenomena such as droughts. In relation to pollution control, man's activities such as changes in land use, stream channel lining, and artificial recharge produce significant influences. Quality changes result from a variety of causes of which waste discharge is only one. Developed groundwater systems are subject to both seasonal changes and long term trends. A hydrogeological investigation is, therefore, essential to the formulation of a comprehensive pollution control program for a groundwater resource system. The areal extent and detail of the investigation will depend upon the dimensions of the groundwater basin; the present and prospective uses of the groundwater resources; the nature, locations, and characteristics of the sources or causes of pollution; and the control measures required. An investigation in considerable detail may be required solely to identify and evaluate the sources and causes of pollution. Some control methods, such as sea water intrusion barriers, require detailed studies of the geologic formations and the hydraulic characteristics of aquifers.

A comprehensive hydrogeologic investigation should be designed to yield requisite information on:

- The geologic structure of the groundwater basin or aquifer and its boundaries
- The nature and hydraulic characteristics of the subsurface formations
- Groundwater levels, and directions and rates of groundwater flow

- Groundwater in storage and usable storage capacity
- Groundwater quality
- Sources, locations, amounts, and quality of natural recharge and discharge
- Locations, amounts, and quality of artificial recharge
- Land use
- Locations and amounts of extractions
- Quantity and quality of exports and imports
- Characteristics of known sources and causes of pollution.

This information is derived from a variety of investigative techniques such as:

- Geologic reconnaissance
- Geophysical surveys
- Examination of well logs
- Test holes
- Pumping tests of wells
- Measurement of groundwater levels
- Analyses of groundwater, surface water, and wastewater samples
- Analyses of precipitation and runoff records.

Because of the dynamic nature of groundwater resource systems, the historic behavior of the systems involved must be studied as well as future responses to anticipated changes in man's influences. The longer the period and the more extensive the available records, the better will be the evaluation of the system. For stressed systems, continuing data collection and periodic reevaluations are essential for the eventual elimination of pollution.

Time Frame of Pollution

An important aspect of groundwater is that once it is polluted, the effect may remain for years, decades, or centuries. The average residence time of a pollutant in groundwater is 200 years. The comparable residence time of a pollutant in a stream or river is 10 days. To remove existing groundwater pollution is much more difficult than to remove surface water pollution; groundwater pollution control is best achieved by regulating the pollution source.

In many instances reduction or elimination of groundwater pollution requires a two-pronged attack. One involves control of the pollution source or cause. The other concerns measures to physically entrap and, when feasible, to remove the polluted water from underground so that the pollution will not spread and persist.

Reference Materials

Throughout this report references to readily available technical literature have been included. These references amplify the information presented and describe specific examples of the application of particular control measures. However, local groundwater pollution situations vary widely, even for the same type of pollution sources; consequently, published material tends to describe individual case histories rather than encompassing a broader viewpoint. In many cases a useful comprehensive single reference does not yet exist. This limitation should be borne in mind in consulting any of the listed references.

INSTITUTIONAL AND LEGAL ASPECTS

Public Law 92-500 recognizes, as a policy of the Congress, the primary responsibility of the States to prevent, reduce, and eliminate groundwater pollution. The Administrator of the EPA is directed to develop comprehensive programs for groundwater pollution control in cooperation with State and local agencies and with other Federal agencies. Thus, the laws and institutions relating to groundwater, and their adequacy, are of basic importance. In most States, the functions of administration of water rights and of water pollution control are the responsibility of different State agencies (Heath, 1972). In California, both of these are the responsibility of the State Water Resources Control Board, as provided in the California Water Code (Divisions 2 and 7).

Institutional and legal aspects of the control of groundwater pollution resulting from the activities listed in Section 304(e) (2) D, E, and F of Public Law 92-500 are discussed here under three categories:

- Disposal of pollutants
- Other activities, many of which involve water rights, which may adversely affect ground water quality
- Groundwater management.

Disposal of Pollutants

The laws of the several states vary widely in their effectiveness for controlling the disposal of pollutants to both surface and groundwaters; the effectiveness of the state agencies administering those laws varies even more widely (Hines, 1972). Under the Porter-Cologne Water Quality Control Act in California (Division 7, Water Code), the State Water Resources Control Board and the nine Regional Water Quality Control Boards have adequate powers, including investigative and planning authority, and do effectively control waste discharges which affect groundwaters.

In Texas, control over groundwater pollution is divided between two state agencies with differing objectives and policies and with a third agency involved. The Water Quality Board has broad authority to control pollution of groundwater (Chapter 21, Water Code), except as regards the disposal of oil and gas waste which is the responsibility of the Railroad Commission (Sec. 21.261, Water Code). The Texas Water Development Board is responsible for investigating the quality of groundwaters (Sec. 21.258, Water Code). Such fragmentation of authority and responsibility is common.

At the present time, with few exceptions, the laws and institutions of the states appear to be inadequate to control properly the disposal of pollutants to groundwaters. The National Water Commission (1972) recommended that regulation of groundwater quality by the states be undertaken by the same agencies that regulate surface water quality. The Commission further recommended that Federal legislation on control of surface water pollution be extended to include groundwater pollution.

Water Rights

Any attempt to control an activity involving the diversion and use of surface or groundwaters, in order to prevent groundwater pollution, will involve vested water rights and usually will be in conflict with these water rights. For many streams, groundwater basins, and aquifers throughout the United States, rights to the full yield have long since vested, either through actual diversion and use, or because of the riparian status of lands or ownership of overlying lands, even though no use of water is being or has been made.

There is little question that the Federal Government has the constitutional power to control the use of most of the surface waters of the United States (Banks, 1967). Under the reservation doctrine, confirmed by the United States Supreme Court in Arizona vs California, 373 US 546 (1963), the Federal Government can control and use the waters originating on or flowing across reserved or withdrawn public lands. A large proportion of the natural runoff of the western states originates on such lands, under the jurisdiction of the US Forest Service, the National Park Service, and other federal agencies. The federal power to control navigable waters has long been established and confirmed by a series of US Supreme Court decisions (Banks, 1967). The Court definitions of what constitutes navigable waters are broad enough to encompass nearly all surface streams of any significant magnitude and their tributaries (United States vs Grand River Dam Authority, 363 US 229, 1960).

The Federal Government has never elected to assert these constitutional powers over surface waters in a general manner except with respect to control of pollution resulting from the disposal of wastes. Rather, the Congress has repeatedly stated that the states shall control the use of intrastate waters. Section 8 of the Reclamation Act of 1902 (32 Stat. 388, 1902) explicitly provides that the Secretary of the Interior shall obtain water rights for reclamation projects in accordance with state water laws. The same provision or one expressing the same intent has been included in acts amendatory of and supplementary to the original Reclamation Act, and in numerous other enactments concerning water resources, including the Flood Control Act of 1944 (58 Stat. 887, 1944).

In further support of this apparently consistent Congressional intent, it is significant that there are no federal statutes governing the allocation of water resources, surface or ground, or the administration of water rights. Although periodically bills are introduced in Congress for those purposes, these have never passed beyond the committee stage. Up to 1973, therefore, responsibility for the allocation of water resources and the granting and administration of rights to intrastate waters has been left to the states. Interstate compacts have been executed for many of the more significant interstate streams systems. Some of these (the

Delaware River Basin Company, for example) encompass the associated interstate aquifers.

To date, federal power over groundwater resources has been asserted only in specific instances involving water supplies for federal installations (State of Nevada vs United States, 165 F. Supp. 600, 1958).

Indian water rights, now almost entirely unquantified, and apparently definable only by individual actions brought before the US Supreme Court, are becoming highly controversial and becloud the entire water rights situation over much of the United States (Trelease, 1971, p 160).

For surface waters, the riparian doctrine of water rights is followed in several of the eastern, southern, and midwestern states; only Florida, Indiana, Iowa, Minnesota, Mississippi, New Jersey, and Wisconsin have strong statutes governing the diversion and use of such waters (Davis, 1971). In other States, the appropriation doctrine is followed, and the right to divert and use surface water must be acquired in accordance with state law (Meyers, 1971). Most of these State laws are based on the objective of maximizing the economic beneficial uses for municipal and industrial water supply, irrigation, power production, and the like. With but few exceptions (eg, California) State water rights laws do not provide adequately for water quality control and in-stream uses such as for fish and wildlife resources. Generally, the hydrologic and hydraulic interrelationships of surface waters and groundwaters are not recognized in State water laws (Corker, 1971; National Water Commission, 1973).

Some States, namely, Colorado, Florida, Indiana, Iowa, Minnesota, Nevada, New Jersey, New Mexico, and Utah, have statutes governing the extraction and use of groundwater. The State Water Resources Control Board of California has only the power to initiate an adjudicatory action in the courts; imposition of a physical solution depends upon a finding that such action is necessary to prevent destruction of or irreparable damage to the quality of groundwaters (Sec. 2100 et seq, Water Code). Most groundwater laws have been laid down by the courts and vary widely from State to State. In California, for example, the courts follow the correlative doctrine, whereas in Texas, the courts have consistently followed the doctrine of absolute ownership or the rule of capture (City of Corpus Christi vs City of Pleasanton, et al, 154 Tex. 289, 276 S.W. 2^d 798, 1955). Under the latter doctrine, it is impossible to control the extraction and use of groundwater in any significant way, although certain limited powers to control well spacing, thus affecting extraction rates, are granted to underground water conservation districts formed in a few areas of the State (Chap. 52, Texas Water Code).

Present state statutes and case law concerning the rights to the use of water are completely inadequate to control the pollution of groundwaters that might result from the diversion and use of either surface or groundwater. State laws need to be revised and broadened, as has been recommended by the National Water Commission (1973).

Groundwater Management

Groundwater management is not explicitly mentioned in Public Law 92-500, but is essential if the maximum overall benefit is to be derived from development and use of the underground resources, while at the same time protecting and maintaining groundwater quality. The many interrelated sources and causes of groundwater pollution and the inherent complexity of groundwater resource systems make it mandatory that the problem of pollution control be approached on a "systems" basis through management, if control is to be effective (Amer. Soc. of Civil Engineers, 1972).

Groundwater management may be defined as the development and utilization of the underground resources (water, storage capacity and

and transmission capacity), frequently in conjunction with surface resources, in a rational and, hopefully, optimal manner to achieve defined and accepted water resource development objectives. Quality as well as quantity must be considered. The surface water resources involved may include imported and reclaimed water as well as tributary streams (Amer. Soc. of Civil Engineers, 1972; Corker, 1971; Mack, 1971; Orlob and Dendy, 1973; Santa Ana Watershed Planning Agency, 1973).

Generally, management can be most effectively accomplished at the local or regional governmental level, operating within a framework of powers and duties established by state statutes. A few such local management agencies with adequate powers have been formed and are operating; an example is the Orange County Water District, California (Orange County Water District Act, as amended).

Except for California, there are few, if any, State statutes under which effective management agencies can be established and operated. Current statutes and case law concerning water rights impede, and in some cases block, effective management. Principal weaknesses in the present legal and institutional posture at the State level with regard to control of groundwater pollution from sources and causes other than waste disposal stem from these basic points:

- In most States, private ownership of groundwater attaches through ownership of the land surface, and the States have not enunciated or implemented jurisdiction in terms of allocation or administration of the resource.

- State law and court decisions have generally dealt with surface and groundwater as separable resources.

- Most State statutes and court decisions do not recognize that pollution of both ground and surface water may result from the effects of activities not necessarily involving waste generation and disposal; pollution has been narrowly defined.

When these three weaknesses are considered in their total ramifications, it is evident that groundwater pollution control is possible only within the context of a comprehensive management program for optimal allocation, conservation, protection, and use of the water together with related land resources available within a region.

The legal and institutional factors that must be considered in a groundwater pollution control program are, as a consequence, largely dictated by the requirements of a management structure. Effective management of ground and surface waters as interrelated and interdependent resources is undertaken as a means of achieving regional, social, environmental, and economic goals. Implementation of such management requires that those goals be articulated; that management tools required to allocate the total water resource equitably among purposes, to abate and prevent pollution, and to equitably allocate the cost involved, be identified; and that government actions required for management be initiated and carried forward.

The objectives sought by managing ground and surface water resources on a conjunctive "systems" basis are not the same from area to area. Objectives that might be important in one area, such as extending the life of the groundwater aquifer, protecting spring flows, or controlling subsidence, might have little relevance elsewhere. Many alternative institutional structures could be considered for the management vehicle. But the extremely diverse hydrologic, geologic, economic, legal, political, and social conditions affecting the occurrence, protection, and use of ground and surface waters in the United States suggest that no single structure would be universally applicable nor politically acceptable.

While management entities might not have the same organizational structure everywhere, certain geographic characteristics, fundamental resource information, and certain basic management powers and duties are commonly required. Delineation of the geographic area to be encompassed by a workable management entity must include consideration of areas having definable hydrologic boundaries. Furthermore, to the extent possible, the area should have social and economic identity or common interests and be generally contiguous with existing political subdivisions.

Data and analysis are needed regarding a range of hydrologic, geologic, physical, environmental, social, and economic factors that will largely determine the processes through which management objectives are attained. Through development of new analytical techniques by which the performance of a groundwater basin under various conditions can be simulated or modelled mathematically, computerized management tools have become available. Depending upon their intended use, these models require adequate data (in appropriate formats and on a timely basis) such as the following:

- Streamflow—normal and flood; water quality; waste discharges—quantity and quality; silt loads; precipitation; evaporation; storm and drought frequency, duration, and intensity; water supply facilities and costs; waste treatment processes and costs.

- Water uses; water rights; projected uses; return flow— quantity and quality; projected economic, demographic, and social trends; relationship between the factors affecting water quality such as source of pollutants, water development, water quality criteria and objectives.

- Available energy sources, facilities, and costs; wildlife and fishery resources; recreational facilities and uses; historic, esthetic, and scenic areas; unique aquatic, zoologic, or biologic habitats.

- Areas, sources, rate and quality of groundwater recharge; surface and groundwater inflow-outflow relationships; volume of aquifer storage capacity; aquifer transmissibility, specific capacity, and boundaries; volume of surface water storage; seasonal relationships of water demand and water in storage; relationships of surface and groundwater use and quantity and quality of return flows.
- Social problems and goals.

Assuming that adequate programs are conducted to gather and make information available to a viable management entity, that entity must be vested with powers and authority to fully exercise a complex management function. Among these powers and duties must be the following as recommended by the National Water Commission

> "State laws should recognize and take account of the substantial interrelation of surface water and groundwaters. Rights in both sources of supply should be integrated, and uses should be administered and managed conjunctively. There should not be separate codifications of surface water law and groundwater law; the law of waters should be a single, integrated body of jurisprudence.
>
> "Where surface and groundwater supplies are interrelated and where it is hydrologically indicated, maximum use of the combined resource should be accomplished by laws and regulations authorizing or requiring users to substitute one source of supply for the other.
>
> "The Commission recommends that states in which groundwater is an important source of supply commence conjunctive management of surface water (including imported water) and groundwater through public management agencies.
>
> "The states should adopt legislation authorizing the establishment of water management agencies with powers to manage

surface water and groundwater supplies conjunctively; to issue revenue bonds and collect pump taxes and diversion charges; to buy and sell water and water rights and real property necessary for recharge programs; to store water in aquifers, create saltwater barriers and reclaim or treat water; to extract water; to sue in its own name and as representative of its members for the protection of the aquifer from damage, and to be sued for damages caused by the operations, such as surface subsidence.

"The states should adopt laws and regulations to protect groundwater aquifers from injury and should authorize enforcement both by individual property owners who are damaged and by public officials and management districts charged with responsibility of managing aquifers."

Implementation of the National Water Commission's recommendations would go far toward equipping a management entity to control groundwater pollution. There are many other questions, however, largely unanswered in present statutes and court decisions, that will require very careful analysis. Among these are the following:

- Where groundwater pumpage results in quality deterioration (intrusion either horizontally or vertically of poorer quality waters in response to altered pressure equilibrium), will the power to levy pump taxes and diversion charges be an adequate assurance of an equitable system of cost sharing where users must forego a free choice between water sources? Would this loss of a free choice constitute a "taking" of property without due compensation? Would condemnation be required?

- Where groundwater quality has deteriorated due to sources and causes other than waste disposal, who should have cause of legal action— the surface owner after validation by the state pollution control agency? by EPA? by the management entity? Who must identify the source and evaluate the effects?

- Local zoning

  Can zoning authority now vested in local entities be superimposed on or made compatible with a state or federally administered surface disposal permit system where the proposed disposal is on or tributary to a groundwater basin recharge area? How can the effects of diffuse urban and agricultural runoff on recharge quantity and quality be controlled at the local level within the framework of state or federal waste discharge permits?

- Land use (related to "Local zoning")

  For operations such as feed lots, and the use of agricultural pesticides and herbicides, there may be a need for land use codes administered at the state level that could be integrated with enforcement power for pollution control vested in a local or regional entity. What effect would this have on regional economies? on local or county tax bases?

- Interstate aquifers

  How can common standards and enforcement incentives as between states be assured?

  Where an aquifer is wholly intra-state but is recharged in part by an interstate stream, how do the states interact?

  What is the federal interest in either case, that of primary enforcer, concurrence in state programs (as in interstate compact arrangements) or only in event of non-action by affected states? If the latter, how is the action initiated?

- Artificial recharge

  Must state water rights statutes be expanded (where now silent) to include artificial recharge as a beneficial use?

Does the management entity have the right to store water underground beneath private property and later recapture the water? Or must the right be purchased or condemned?

These are difficult questions, which need to be resolved on a nationwide basis. For purposes of this discussion, it is assumed that the present relationship between state and federal jurisdiction in water matters will continue. Even so, the Congress and state legislatures will need to clarify a number of areas.

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SECTION II

DIRECT DISPOSAL OF POLLUTANTS

The first eight parts of this section consider wells for injection of wastewaters into saline water aquifers. The references for these eight parts are combined (pp 2-41 – 2-45). Primary emphasis is placed upon disposal of industrial wastewaters; wells for this purpose are a relatively recent development, and currently are receiving increasing attention in view of their attractiveness as a possible disposal mechanism in selected locations and under certain operating conditions. The discussion of industrial wells is, therefore, relatively extensive and detailed. Wells for disposal of other types of wastes, such as oil field and geothermal brines, sewage, and radioactive wastes, are treated more briefly.

Disposal of pollutants into freshwater aquifers through wells, lagoons, basins, pits, septic systems, spraying, stream beds, and landfills is discussed beginning on page 2-46.

INDUSTRIAL INJECTION WELLS

The potential of wells for subsurface disposal of industrial wastes was first recognized and implemented by at least one industrial company as early as the 1930's. However, the extent of such use was small until the 1960's when increasing emphasis on water pollution control caused industrial companies to seek new alternatives for wastewater disposal, including subsurface injection.

As of mid-1972, at least 246 such wells had been constructed in the United States (Warner, 1972). Although this is a relatively small number, considerable concern has been expressed about the use of injection wells. Among the technical reasons for this concern are the following:

- Some of the wastewaters that are being injected contain chemicals that are relatively toxic and will persist indefinitely in the subsurface environment
- Monitoring of the subsurface environment is quite difficult in comparison with monitoring of the surface
- If contamination of usable groundwater or other resources should occur, decontamination may be difficult or impossible to effect.

Why should such wells be used at all in view of these and other possible objections? The alternatives available for ultimate disposition of wastewaters containing dissolved inorganic chemicals, relatively non-degradable dissolved organic chemicals, or combinations of these, are limited to disposal to the ocean, disposal to the land surface, disposal to fresh waters, storage, incineration, recovery of the chemicals for reuse, or subsurface injection. Of these alternatives, subsurface injection may be the most satisfactory in some cases. The need for continuous reevaluation of the problem of ultimate disposition of such wastewaters may become even more pressing as a result of the goals stated in PL 92-500, the Federal Water Pollution Control Act Amendments of 1972.

The following subsections discuss trends in usage of industrial wastewater injection wells in the United States, the environmental impacts of such wells, and methods for control of groundwater pollution from such wells.

Current Situation

An inventory of industrial wastewater injection wells in the United States by Donaldson (1964) listed only 30 wells. Subsequent inventories by Warner (1967), the Interstate Oil Compact Commission in 1968 (Ives and Eddy, 1968) and Warner (1972) listed 110, 118, and 246 wells, respectively. The 1972 data show that only 22 wells had been constructed before 1960, and that about twice that number existed in 1964. Between 1964 and 1972 about 25 wells per year were constructed, on the average.

Table 2-1 lists the number of wells that had been constructed in each of the 22 states having such wells as of 1972. Other statistical information concerning the wells inventoried in 1972 is included in Tables 2-2 through 2-8.

These tables are useful in establishing the total range and dominant characteristics of wells that have been constructed. The data also show that patterns existing in 1967 have persisted since then, and might, therefore, be expected to continue. Some significant observations that can be made from the tables are:

- More than 50 percent of existing wells have been constructed by chemical, petrochemical, or pharmaceutical companies, and about 25 percent by refineries and natural gas plants. These data identify the dominant present and probable future industrial users of injection wells.

- About 80 percent of wells that have been constructed are presently operating or will be put into operation. Only 5 percent of wells that have been constructed were initial failures and never operated. Thus, the geologic success ratio of such wells is very high.

- About 75 percent of existing wells are between 2000 and 6000 feet in total depth. Less than 10 percent of the wells are shallower than 1000 feet. This fact tends to provide considerable assurance of protection to usable groundwater resources.

- About 70 percent of present wells inject less than 200 gallons per minute and 86 percent less than 400 gallons per minute. This suggests the capacity that can be expected for most wells and reduces the need to consider wastewater streams that exceed these amounts.

Table 2-1. Distribution of existing industrial wastewater injection wells among the 22 states having such wells in 1972 (Warner, 1972).

Alabama	5	Nevada	1
California	4	New Mexico	1
Colorado	2	New York	4
Florida	5	North Carolina	1
Illinois	5	Ohio	8
Indiana	12	Oklahoma	9
Iowa	1	Pennsylvania	8
Kansas	27	Texas	71
Kentucky	3	Tennessee	4
Louisiana	40	West Virginia	7
Michigan	27	Wyoming	1
			246

Table 2-2. Distribution of injection wells by industry type (Warner, 1972).

Industry Type	Percent of Wells	
	1967	1972
Refineries and natural gas plants	22	26
Chemical, petrochemical & pharmaceutical companies	50	56
Metal product companies	7	7
Other	21	11

Table 2-3. Operational status of industrial injection wells (Warner, 1972).

Initial failure (never operated)	5%
Operation pending	13%
Presently operating	66%
Operation rare or suspended	11%
Abandoned and plugged (after operating)	5%

Table 2-4. Total depth of industrial injection wells (Warner, 1972).

Total Well Depth	Percent of Wells	
	1967	1972
0 - 1,000 Ft.	7	8
1,000 - 2,000	29	16
2,000 - 4,000	22	29
4,000 - 6,000	31	34
6,000 - 12,000	9	12
Over 12,000	2	1

Table 2-5. Rate of injection in industrial wells (Warner, 1972).

Injection Rate	Percent of Wells	
	1967	1972
0 - 50 gpm	27	36
50 - 100	17	13
100 - 200	25	20
200 - 400	26	17
400 - 800	4	7
Over 800	1	7

Table 2-6. Pressure at which waste is injected in industrial wells (Warner, 1972).

Injection Pressure	Percent of Wells	
	1967	1972
Gravity flow	14	27
Gravity - 150 psi	29	22
150 - 300	27	14
300 - 600	9	16
600 - 1,500	20	18
Over 1,500	1	3

Table 2-7. Type of rock used for injection by industrial wells (Warner, 1972).

Rock Type	Percent of Wells	
	1967	1972
Sand	30	36
Sandstone	45	25
Limestone and Dolomite	22	35
Other	3	4

Table 2-8. Geologic age of injection zone of industrial wells (Warner, 1972).

Quaternary		3%
Tertiary		33%
Mesozoic		6%
Permian – Mississippian	15%	
Devonian – Silurian	15%	57%
Ordovician – Cambrian	27%	
Precambrian		1%

- Only about 3 percent of existing wells are injecting at well-head pressures exceeding 1,500 psi. This information, in conjunction with the range of depths of wells previously mentioned, is reassuring; it suggests that presently-operating wells are generally injected at pressures compatible with well depth and that wastewaters are generally being injected into naturally-occurring porosity, rather than into continuously induced fractures.

Tables 2-7 and 2-8 can be interpreted to show the distribution of wells by geologic provinces. The 36 percent of wells injecting into poorly consolidated sands of Quaternary and Tertiary age are principally located in the Gulf Coastal Plain. The 57 percent of wells injecting into consolidated sandstones and limestones of Paleozoic age are located in certain interior geologic provinces. Further examination of other well characteristics shows that there is a good correlation between the geologic provice, depth, construction method, and performance of existing wells, which will permit emphasis on selected locations, aquifers, and construction and operating requirements in a national monitoring program.

Environmental Consequences

Tangible impacts of wastewater injection that can be predicted to occur in every case are:

- Modification of the groundwater system
- Introduction into the subsurface of fluids with a chemical composition different from that of the natural fluids.

Tangible impacts that could occur in individual cases are:

- Degradation of high-quality groundwater
- Contamination of other resources, such as petroleum, coal, or chemical brines
- Stimulation of earthquakes
- Chemical reaction between wastewater and natural water
- Chemical reaction between wastewater and rocks in the injection interval.

The degree to which any of these impacts can be predicted and quantified in advance depends on the individual situation. In the case of existing permitted wells, significant adverse environmental effects are not anticipated to occur, otherwise the regulatory authorities would not have licensed the wells. Where untenable impacts have been anticipated, permits have been denied.

CONTAMINATION OF FRESH GROUNDWATER. The impact of greatest concern to most regulatory agencies is that of contamination of potable groundwater. This could occur where a well injects into a saline-water aquifer by:

- Escape of wastewater through the well bore into a freshwater aquifer because of insufficient casing, by corrosion, or by other failure of the injection well casing.
- Vertical escape of injected wastewater, outside of the well casing, from the injection zone into a freshwater aquifer.
- Vertical escape of injected wastewater from the injection zone through confining beds that are inadequate because of high primary permeability, solution channels, joints, faults, or induced fractures.
- Vertical escape of injected wastewater from the injection zone through other nearby deep wells that are improperly cemented or plugged, or that have insufficient or corroded casing.

Direct contamination of fresh groundwater could also occur by lateral travel of injected wastewater (from a region of saline water) to a region of fresh water in the same aquifer. In most cases, the distances involved and the low rates of travel of wastewater make the probability of direct contamination very small.

Indirect contamination of fresh groundwater can also occur when injected wastewater displaces saline formation water, causing it to flow into a freshwater aquifer. Vertical flow of the saline water can be through paths of natural or induced permeability in confining beds or through other inadequately cased or plugged deep wells. If large volumes of wastewater were injected near a freshwater-saline water interface, such as occurs in many coastal aquifers and also in inland locations, the interface could be displaced with saline water replacing fresh water. Ferris (1972) discussed this response of hydrologic systems to waste injection.

In most presently existing wells, the potential for direct contamination of fresh groundwater is small because of the construction used in these wells and because of the large vertical distance between the injection zones and freshwater aquifers. The belief that the potential for this type of contamination is small is supported by the few instances of direct contamination that have been documented. The vertical or lateral movement of saline water into freshwater aquifers as a result of increased formation pressures can be expected to occur, but will be less dramatic than direct contamination in most cases because the effects will be dispersed and difficult to recognize.

CONTAMINATION OF OTHER SUBSURFACE RESOURCES. No instance of contamination of other subsurface resources by injected industrial wastewater has yet been reported. The fact that little evidence of degradation of potable groundwater and other resources by this type of injected wastewater has been found should not be cause for relaxation of vigilance in regulating and operating such wells. On the contrary, as more wells are constructed each year, regulation and operation must be increasingly more sophisticated to maintain this record.

Chemical reaction between wastewater and formation minerals and water is a possible problem in well operation, but does not present much potential for environmental impact that would be of concern to the public.

EARTHQUAKE STIMULATION. The exact geologic and hydrologic circumstances in which earthquakes can be stimulated by wastewater injection are not yet known. However, the general requirement is the presence of a fault along which movement can be induced in an area where earth strains are present that can be relieved by movement along the fault. It is believed that fluid injection can act as a trigger for release of such strain energy, thus causing an earthquake. Among the presently existing industrial injection wells surveyed by Warner (1972) few are present in such locations, and none other than the Rocky Mountain Arsenal well near Denver has yet been related to earthquake occurrence. *

Control Methods

The following list describes processes, procedures, and methods for control of industrial wastewater injection into saline aquifers. Each item is briefly discussed in subsequent subsections.

- Evaluation of regional hydrogeologic framework and restriction on regionally unsuitable locations and aquifers for wastewater injection.

- Evaluation of local hydrogeologic environment and restriction on locally unsuitable locations and aquifers for wastewater injection.

- Evaluation of fluids for injection and restriction on those disposed of by injection, including estimation of nature and extent of chemical reactions between injected fluids and aquifer fluids and minerals, and of heat generation and its effects in the case of radioactive wastes.

- Requirement of suitable construction features for injection wells.

- Requirement of thorough hydrogeologic evaluation during construction and testing of wells.

- Determination of aquifer characteristics and estimation of aquifer response to injection and direction and rate of movement of injected liquid and aquifer fluids.

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* Earthquakes have also been linked to a water flooding operation in the Rangely oil field in Colorado (Raleigh, 1972).

- Restriction on operating programs for injection wells.
- Surface equipment and programs for emergency procedures in the event of malfunction, including rapid shut-off and standby facilities; programs for long-term decontamination in areas of important but not critical occurrences.
- Abandonment procedures for all wells.
- Monitoring programs for injection wells.
- Monitoring programs for aquifers.

REGIONAL GEOLOGIC CONSIDERATIONS. The suitability of a specific injection-well site must be evaluated by a detailed analysis of local geology, but generalizations based on regional geologic considerations can be made concerning the suitability of certain areas for waste-injection wells.

Synclinal basins (Figure 2-1) and the Atlantic and Gulf Coastal Plains are particularly favorable sites for deep waste-injection wells because they contain relatively thick sequences of saltwater-bearing sedimentary rocks and because commonly the subsurface geology of these basins is relatively well known.

Just as major synclinal basins are geologically favorable sites for deep-well injection, other areas may be generally unfavorable because the sedimentary-rock cover is thin or absent. Extensive areas where relatively impermeable igneous-intrusive and metamorphic rocks are exposed at the surface are shown in Figure 2-1. With the possible exception of small parts, these areas can be eliminated from consideration for waste injection. The exposure of igneous and metamorphic rocks in the Arbuckle Mountains, Wichita Mountains, Llano and Ozark uplifts, the exposures just south of the Canadian Shield, and other such exposures are perhaps not extensive, but they are significant because the sedimentary sequence thins toward them and the salinity of the formation waters decreases toward the outcrops around the exposures.

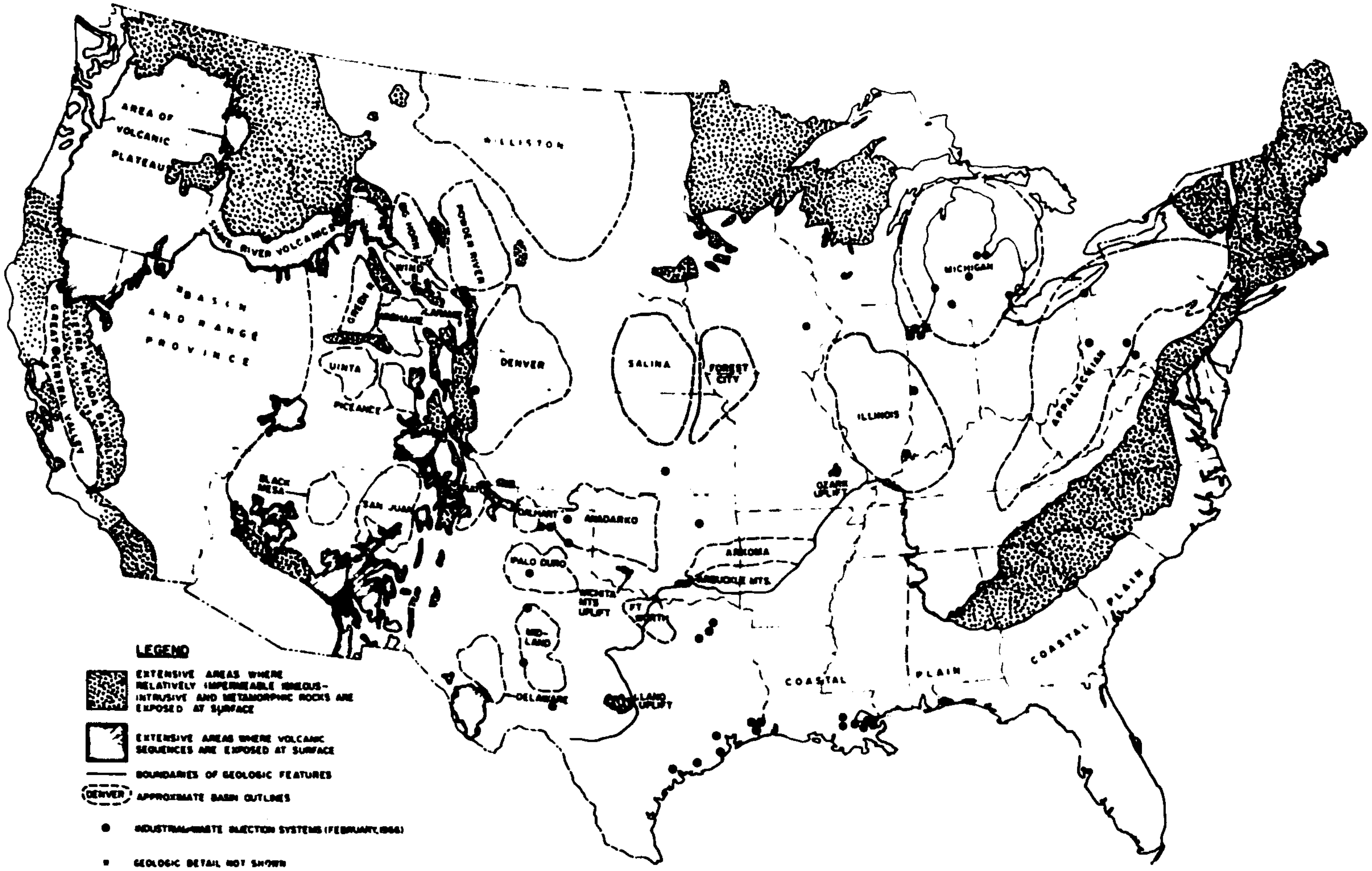

Figure 2-1. Geologic features significant in deep waste-injection well-site evaluation, and locations of industrial-waste injection systems (Warner, 1968).

Regions shown on Figure 2-1 where a thick volcanic sequence lies at the surface generally are not suitable for waste-injection wells. Although volcanic rocks have fissures, fractures, and interbedded gravel that will accept injected fluids, they contain fresh water.

The immense and geologically complex Basin and Range province is a series of narrow basins and intervening, structurally positive ranges. Some of the basins might provide waste-injection sites, but their geology is mostly unknown and the cost of obtaining sufficient information to insure safe construction of injection wells would be very great.

The geology of the West Coast is complex and not well known. Relatively small Tertiary sedimentary basins in southern California yield large quantities of oil and gas, and probably are geologically satisfactory sites for waste-injection wells. There are similar basins along the coast of northern California, Oregon, and Washington, but little is known about their geology.

Areas not underlain by major basins or prominent geologic features may be generally satisfactory for waste injection if they are underlain by a sufficient thickness of sedimentary rocks that contain saline water, and if potential injection zones are sealed from freshwater-bearing strata by impermeable confining beds.

LOCAL SITE EVALUATION. An outline of the factors for consideration in the evaluation of waste injection well sites is given in Table 2-9.

Experience has shown that nearly all types of rocks can, under favorable circumstances, have sufficient porosity and permeability to yield or accept large quantities of fluids. Sedimentary rocks, especially those deposited in a marine environment, are most likely to have the geologic characteristics suitable for waste-injection wells. These characteristics are (1) an injection zone with sufficient permeability, porosity, thickness, and areal extent to act as a liquid-storage reservoir at safe injection

Table 2-9. Factors for consideration in the geologic and hydrologic evaluation of a site for deep-well industrial waste injection.

<u>Regional Geologic and Hydrologic Framework</u>

- Structural geology
- Stratigraphic geology
- Groundwater geology
- Mineral resources
- Seismicity
- Hydrodynamics

<u>Local Geology and Geohydrology</u>

- Structural geology
- Geologic description of sedimentary rock units
  1. Lithology
  2. Detailed description of potential injection horizons and confining beds
     a. Thickness and vertical and lateral distribution
     b. Porosity (type and distribution as well as amount)
     c. Permeability (same as b)
     d. Chemical characteristics of reservoir fluids
  3. Groundwater aquifers at the site and in the vicinity
     a. Thickness
     b. General character
     c. Amount of use and potential for use
  4. Mineral resources and their occurrence at the well site and in the immediate area
     a. Oil and gas (including past, present and possible future development)
     b. Coal (as in a)
     c. Brines (as in a)
     d. Other (as in a)

pressures, and (2) an injection zone that is vertically below the level of freshwater circulation and is confined vertically by rocks that are, for practical purposes, impermeable to waste liquids.

Vertical confinement of injected wastes is important not only for the protection of usable water resources, but also for the protection of developed and undeveloped deposits of hydrocarbons and other minerals. The effect of lateral movement of waste on such natural resources also must be considered.

Sandstone, limestone, and dolomite are commonly porous and permeable enough in the unfractured state to be suitable injection zones. Naturally fractured limestone, dolomite, shale, and other rocks also may be satisfactory. Rocks with solution or fracture porosity may be preferable to rocks with intergranular porosity, because commonly solution and fracture flow channels are relatively large in comparison to intergranular pores and are not, therefore, as likely to be plugged by suspended solids in the injected liquids. Waste injection into limestone and dolomite has proved particularly successful in some places because the permeability of these rocks can be improved greatly with acid treatment.

Unfractured shale, clay, slate, anhydrite, gypsum, marl, and bentonite have been found to provide good seals against the upward flow of fluids. Limestone and dolomite may be satisfactory confining strata; but these rocks commonly contain fractures or solution channels, and their adequacy must be determined carefully in each case.

The minimum depth of burial, the necessary thickness of confining strata, and the minimum salinity of water in the injection zone have not been established quantitatively, and it may be possible to specify these constraints only for individual cases, as has been done in the past.

The minimum depth of burial can be considered to be the depth at which a confined saline-water-bearing zone is present; it may range from a few hundred to several thousand feet.

The minimum salinity of water in the injection zone probably will be specified by regulatory agencies in most states, but will be at least 1,000 mg of dissolved solids per liter of water except under unusual circumstances. Water containing less than 500 mg/ℓ now is considered to be acceptable for potable water used by interstate carriers. Formerly, if such water was not available, water containing 1,000 mg/ℓ of dissolved solids was considered acceptable. The minimum salinity may be set at a level higher than 1,000 mg/ℓ of dissolved solids to provide a margin of safety and because water with several times this dissolved-solids content is used in certain areas for domestic, industrial, or agricultural purposes.

Illinois agencies have determined that groundwater with a dissolved solids content less than 10,000 mg/ℓ should be protected. All groundwaters in New York have been classified, based on quality. According to the New York classification, waste injection is prohibited in aquifers containing water with a dissolved solids content of 2,000 mg/ℓ or less.

It has been found that a confining stratum only 10 to 20 feet thick may provide a good seal to retain oil and gas. Such thin confining beds generally would not be satisfactory for containing injected waste because they would be very susceptible to hydraulic fracturing, and even a small fault could completely offset them vertically. Fortunately, in many places hundreds or thousands of feet of impermeable strata enclose potential injection zones and virtually ensure their segregation.

The thickness and permeability necessary to allow fluid injection at the desired injection rate can be estimated from equations developed by petroleum engineers and groundwater hydrologists. The geometry of the injection zone also determines its suitability for waste-injection. A thick lens of highly permeable sandstone might not be satisfactory for injection if it is small and surrounded by impermeable beds, because pressure buildup in the lens would be rapid in comparison to that in a "blanket" sandstone.

In addition to stratigraphy, structure, and rock properties, which are factors routinely considered in subsurface studies, aquifer hydrodynamics may be significant in the evaluation of waste-injection well sites. The presence of a natural hydrodynamic gradient in the injection zone will cause the injected waste to be distributed asymmetrically about the well bore and transported through the aquifer even after injection has ceased.

Hydrodynamic dispersion—the mixing of displacing and displaced fluids during movement through porous media—may cause much wider distribution of waste in the injection zone than otherwise would be anticipated. Dispersion is known to occur in essentially homogeneous isotropic sandstone, and it could lead to particularly rapid lateral distribution of waste in heterogeneous sandstone and fractured or cavernous strata. Sorption of waste constituents by aquifer minerals retards the spread of waste from the injection site.

Mathematical models now available are satisfactory for accurately predicting the movement of waste in aquifers only under restrictive, simplified physical circumstances. Even if knowledge of the physics of fluid movement in natural aquifers were considerably more advanced, the determination of the physical parameters that characterize an injection zone would still be a problem where few subsurface data are available. These restrictions do not, however, preclude the quantitative estimation of the rate and direction of movement of injected waste.

The maximum pressure at which liquids can be injected without causing hydraulic fracturing may be the factor limiting the intake rate and operating life of an injection well. The injection pressure at which hydraulic fracturing will occur is related directly to the magnitude of regional rock stress and the natural strength of the injection zone (Hubbert and Willis, 1957). In some areas, the pressure at which hydraulic fracturing will occur can be estimated before drilling on the basis of experience in nearby oil fields.

Other considerations in the determination of site suitability are (1) the presence of abnormally high natural fluid pressure and temperature in the potential injection zone that may make injection difficult or uneconomical; (2) the local incidence of earthquakes that can cause movement along faults and damage to the subsurface well facilities; (3) the presence of abandoned, improperly plugged wells that penetrate the injection zone and provide a means for escape of injected waste to groundwater aquifers or to the surface; (4) the mineralogy of the injection zone and chemistry of interstitial waters, which may determine the injectability of a specific waste; and (5) the possibility that in tectonically unstable areas, fluid injection may contribute to the occurrence of earthquakes.

WASTEWATER EVALUATION. A foremost consideration in evaluating the feasibility of wastewater injection is the character of the untreated wastewater. Table 2-10 lists the pertinent factors.

The suitability of waste for subsurface injection depends on its volume and physical and chemical properties of the potential injection zones and their interstitial fluids.

Table 2-10. Factors to be considered in evaluating the suitability of untreated industrial wastes for deep-well disposal.

- Volume
- Physical Characteristics
  1. Specific gravity
  2. Temperature
  3. Suspended solids content
  4. Gas content
- Chemical Characteristics
  1. Chemical constituents
  2. pH
  3. Chemical stability
  4. Reactivity
     a. with system components
     b. with formation waters
     c. with formation minerals
  5. Toxicity
- Biological Characteristics

Waste disposal into subsurface aquifers constitutes the use of limited storage space, and only concentrated, very objectionable, relatively untreatable wastes should be considered for injection. The fluids injected into deep aquifers do not occupy empty pores; each gallon of waste will displace a gallon of the fluid which saturates the storage zone. Optimal use of underground storage space will be realized by use of deep-well injection only where (1) more satisfactory alternative methods of waste treatment and disposal are not available and (2) minimization of injected-waste volumes is achieved through good waste management.

The intake rate of an injection well is limited, and its operating life may depend on the total quantity of fluid injected. The variable limiting the injection rate or well life can be the injection pressure required to dispose of the produced waste. Injection pressure is a limiting factor because excessive pressure causes hydraulic fracturing and possible consequent damage to confining strata, and the pressure capacity of injection-well pumps, tubing, and casing is limited. In most states maximum injection pressures are specified by regulatory agencies and are seldom allowed to exceed about 0.8 psi/ft of well depth. The initial pressure required to inject waste at a specified rate and the rate at which injection pressure increases with time can be calculated if the physical properties of the aquifer and the waste are known. The intake rate of most waste-injection wells now in use has been found to be less than 400 gpm, but intake rates can be higher than this in particularly favorable circumstances.

The operating life of an injection well may be related to the volume of injected waste, because the distance injected waste can be allowed to spread laterally may be restricted by law or by other considerations. The storage volume or effective porosity in the vicinity of an injection well can be computed very simply, but dispersion, adsorption, and chemical reaction complicate the calculation of the distribution of injected waste.

The injectability of a particular waste depends on the physical and chemical characteristics of the waste, the aquifer, and the native aquifer fluids, because physical or chemical interactions between the waste and the aquifer minerals or fluids can cause plugging of the aquifer pores and consequent loss of intake capacity. Plugging can be caused by suspended solids or entrained gas in the injected waste, reactions between injected fluids and aquifer minerals, reactions between injected and interstitial fluids, and autoreactivity of the waste at aquifer temperature and pressure. Plugging at or near the well bore also can be caused by bacteria and mold. Wastes that are not initially injectable commonly can be treated to make them so.

Knowledge of the mineralogy of the aquifer and the chemistry of interstitial fluids and waste should indicate the reactions to be anticipated during injection. Laboratory tests can be performed with rock cores and formation and wastewater samples to confirm anticipated reactions.

Selm and Hulse (1959) listed the reactions between injected and interstitial fluids that can cause the formation of plugging precipitates — (1) precipitation of alkaline earth metals such as calcium, barium, strontium, and magnesium as relatively insoluble carbonates, sulfates, orthophosphates, fluorides, and hydroxides; (2) precipitation of metals such as iron, aluminum, cadmium, zinc, manganese, and chromium as insoluble carbonates, bicarbonates, hydroxides, orthophosphates, and sulfides; and (3) precipitation of oxidation-reduction reaction products.

The plugging effect of such precipitates is not certain, but if plugging is considered to be a possibility the waste can be treated to make it nonreactive. Alternatively, nonreactive water can be injected ahead of the waste to form a buffer between the waste and the aquifer water (Warner, 1966).

Common minerals that react significantly with wastes are the acid-soluble carbonate minerals and the clay minerals. Acidizing of reservoirs containing carbonate minerals is an effective well-stimulation technique, and reaction of acidic wastes with carbonate minerals thus might be expected to be beneficial. An undesirable effect of the reaction of acid waste with carbonate minerals could be evolution of CO_2 that might increase pressure and cause plugging if present in excess of its solubility. Roedder (1959) reported that the reaction of acid aluminum nitrate waste with calcium carbonate results in a gelatinous precipitate that could cause plugging.

Clay minerals are known to reduce the permeability of sandstone to water in comparison to its permeability to air. The permeability of a clay-bearing sandstone to water decreases with decreasing water salinity, decreasing the valence of the cations in solution, and increasing the pH of the water.

Ostroff (1965) and Warner (1965, 1966) gave additional references and discussion concerning waste injectability. Factors that bear on waste injectability, such as aquifer mineralogy, temperature and pressure, and chemical quality of aquifer fluids, are a logical part of feasibility reports because the treatment necessary to make a waste injectable can be an important part of a total waste management program.

WELL CONSTRUCTION AND EVALUATION. The variability of geologic situations and the characteristics of wastes precludes establishment of rigid specifications for injection-well construction. Each injection system requires individual consideration with respect to waste volume and type, and the geologic and hydrologic conditions that exist. Certain general requirements, however, can be outlined.

Construction of well facilities for an injection system includes drilling, logging and testing, and completion activities. A hole must first be drilled, logged, and tested before it can be ascertained that it should be completed as an injection well. The completion phase includes installation and cementing of the casing, installation of injection tubing, and other related procedures such as perforating or slotting the casing and stimulating the injection horizon. Generally, it is necessary to install and cement at least some of the casing during drilling.

Drilling programs should be designed to permit installation of the necessary casing strings with sufficient space around the casing for an adequate amount of cement. Samples of the rock formations penetrated should be obtained during drilling. It may be necessary to have formation cores or water samples at horizons of particular importance to provide necssary geologic and hydrologic data. Complete logging and testing of wells intended for injection should be required, and the data should be filed with the appropriate state agency or agencies.

In Table 2-11 is summarized the information desired in subsurface evaluation of the disposal horizon and the methods for obtaining this information.

Design of a casing program depends primarily on well depth, character of the rock sequence, fluid pressures, type of well completion, and the corrosiveness of the fluids that will contact the casing. Where fresh groundwater supplies are present, a casing string (surface casing) is usually installed to some point below the base of the deepest groundwater aquifer (Figure 2-2). One or more smaller-diameter casing strings are then set, with the bottom of the last string just above or through the injection horizon, depending on whether the hole is to be completed as an open hole or is to be cased and perforated.

The annulus between the rock strata and the casing is filled with a cement grout, to protect the casing from external corrosion, to increase casing strength, to prevent mixing of the waters contained in the aquifers behind the casing, and to forestall travel of the injected waste into aquifers other than the disposal horizon. Neat portland cement (no sand or gravel) is the basic material for cementing. Many additives have been developed

Table 2-11. Summary of information desired in subsurface evaluation of disposal horizon and methods available for evaluation.

Information Desired	Methods Available for Evaluation
Porosity	Cores, electric logs, radioactive logs, sonic logs
Permeability	Cores, pumping or injection tests, electric logs
Fluid pressures in formations	Drill stem tests, water level measurements
Water samples	Cores, drill stem tests
Geologic formations intersected by hole	Drill time logs, drilling samples, cores, electric logs, radioactive logs, caliper logs
Thickness and character of disposal horizon	Same as above
Mineral content of formation	Drilling samples, cores
Temperature of formation	Temperature log
Amount of flow into various horizons	Injectivity profile

to impart some particular quality to the cement. Additives can, for example, be selected to give increased resistance to acid, sulfates, pressure, temperature, shrinkage, and so forth.

Temperature logs, cement logs, and other well-logging techniques can be required as a verification of the adequacy of the cementing. Cement can be pressure-tested if the adequacy of a seal is in question.

Waste should be injected through separate interior tubing rather than being in contact with the well casing. This is particularly important when corrosive wastes are being injected. A packer can be set near the bottom of the tubing to prevent corrosive waste from contacting the casing. Additional corrosion protection can be provided by filling the

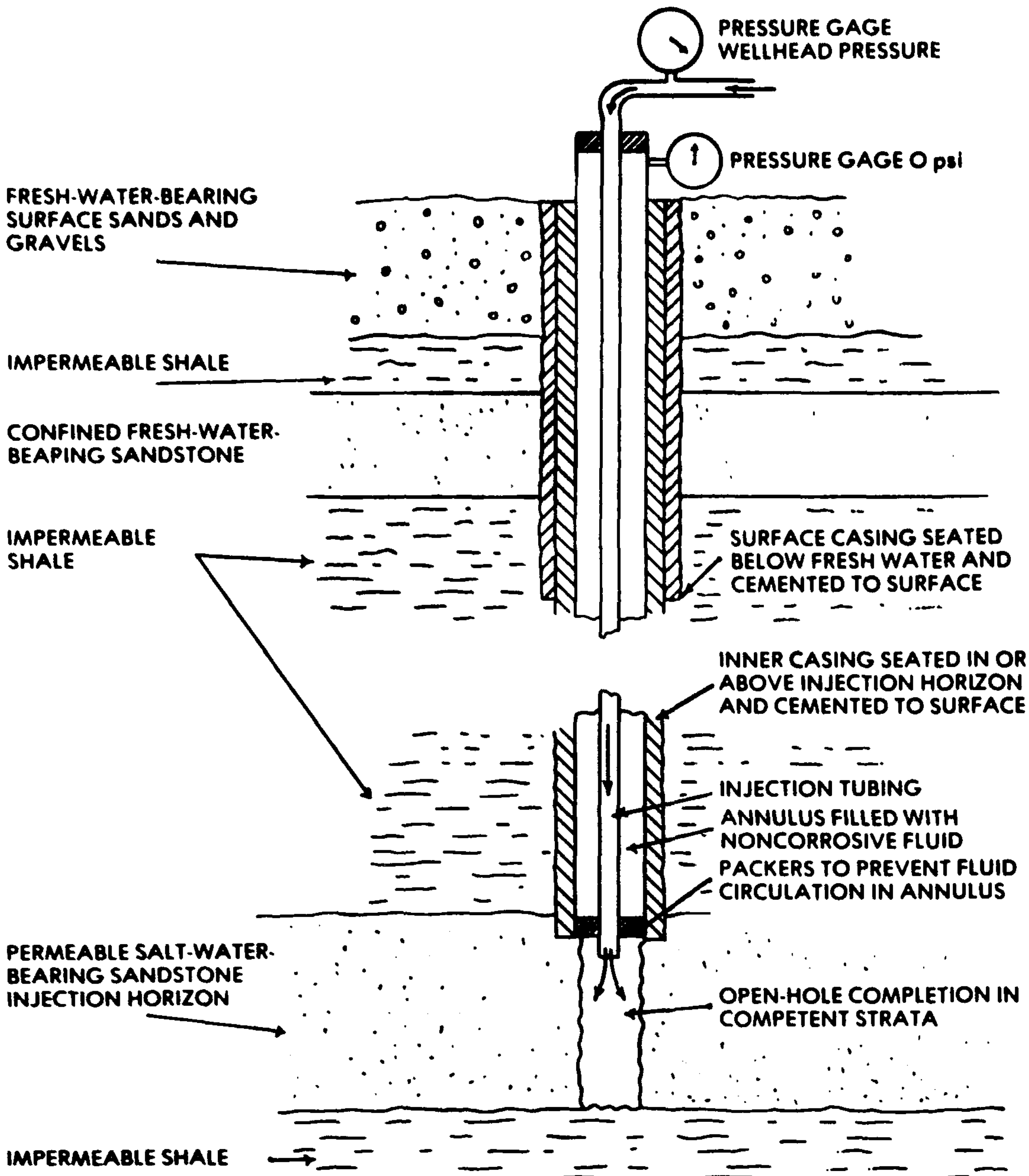

Figure 2-2. Schematic diagram of an industrial waste injection well completed in competent sandstone (modified after Warner, 1965).

annular space between the casing and the tubing with a neutralized fluid.

It is frequently desired to increase the acceptance rate of injection wells by chemical or mechanical treatment of the injection zone. Careful attention should be given to stimulation techniques such as hydraulic fracturing, perforating, and acidizing to insure that only the desired intervals are treated and that no damage to the casing, cement, or confining beds occurs.

AQUIFER RESPONSE AND WASTEWATER MOVEMENT. Estimates of the rate of pressure buildup in the receiving aquifer are important because the maximum pressure at which liquids can be injected may be the factor limiting the intake rate and operating life of an injection well.

From data obtained during construction and testing of an injection well, estimates can be made of the rate of increase of pressure in the receiving aquifer for a projected rate of wastewater injection. Van Everdingen (1968) outlined the methodology for estimating the pressure buildup resulting from injection wells.

Estimates of the lateral extent of wastewater movement are needed so that the location of the underground space occupied by the wastewater can be made a matter of record to be used in regulation and management of the subsurface.

Estimates of the extent and direction of wastewater movement can be made after the geohydrologic characteristics of the receiving aquifer have been determined. This estimate is potentially very complex, since the cylindrical pattern that can be assumed as the most elementary case may be modified by the natural flow system in the aquifer, hydrodynamic dispersion, porosity and permeability variations, and density and viscosity differences between injected and interstitial fluids.

OPERATING PROGRAM. The operating program for an injection system should conform with the geological and engineering properties of the injection horizon and the volume and chemistry of the waste fluids.

Injection rates and pressures must be considered jointly, since the pressure will usually depend on the volume being injected. Pressures are limited to those values that will prevent damage to well facilities or to the confining formations. The maximum bottom-hole injection pressure is commonly specified on the basis of well depth. Regulatory agencies have specified maximum allowable bottom-hole pressure of from about 0.5 to 1.0 psi per foot of well depth, depending on geologic conditions, but operating pressures are seldom allowed to exceed about 0.8 psi per foot of depth.

Experience with injection systems has shown that an operating schedule involving rapid or extreme variations in injection rates, pressures, or waste quality can damage the facilities. Consequently, provisions should be made for shut-off in the event of hazardous flow rates, pressure, or waste quality fluctuations.

SURFACE EQUIPMENT AND EMERGENCY PROCEDURES. Surface equipment includes holding tanks and flow lines, filters, other treatment equipment, pumps, monitoring devices, and standby facilities.

Surface equipment associated with an injection well should be compatible with the waste volume and physical and chemical properties of the waste to insure that the system will operate as efficiently and continuously as possible. Experience with injection systems has revealed the difficulties that may be encountered due to improperly selected filtration equipment and corrosion of injection pumps.

Surface equipment should include well-head pressure and volume monitoring equipment, preferably of the continuous recording type. Where injection tubing is used, it is advantageous to monitor the pressure of both the fluid in the tubing and in the annulus between the tubing and the casing. Pressure monitoring of the annulus is a means of detecting tubing or packer leaks. An automatic alarm system should signal the failure of any important component of the injection system. Filters should be equipped to indicate immediately the production of an effluent with too great an amount of suspended solids and/or chemicals that have been previously determined to be deleterious to the injection program.

Standby facilities are essential in order to cope with malfunction of a well that might occur. In all cases, provision should be made for alternative waste management facilities and procedures in the event of injection system failure. Alternative facilities could be standby wells, holding tanks, or a treatment plant.

In situations where the character of the wastewater being injected, or for other reasons, would dictate the need, additional facilities and procedures could be available for use in the event of engineering failures of the system or detection of contamination of a subsurface resource. For example, handling of a particularly corrosive wastewater would be reason for planning in advance the procedure to be used in the event that tubing failure during operation was detected. Such a procedure might be to begin immediately injection of a non-corrosive liquid into the well until the well bore was completely cleared, then to shut the well in until the reservoir pressure had died away to a level that would allow removal of the damaged tubing without backflow of the corrosive wastewater. Such a procedure would help to prevent damage to the casing, packer, etc. Injection of a radioactive wastewater would require establishment of procedures for use during well workovers or any other handling of equipment that might become contaminated.

Emergency procedures should also include notification of nearby users of groundwater or other resources in the event contamination were detected. A program for aquifer rehabilitation might be held in reserve.

Monitoring Procedures

Monitoring can be performed on the injection system itself, in the injection zone, or in aquifers above or below the injection zone.

Well-head pressure and waste injection rate should be continuously measured. If injection tubing is used, the casing-tubing annulus should be pressure monitored. Other types of monitoring include measurement of the physical, chemical, and biological character of injected fluids on a periodic or continuous basis, and periodic checking of the casing and tubing for corrosion, scaling, or other defects.

The possible purposes in monitoring the injection zone or adjacent aquifers are to determine fluid pressures and the rate and direction of movement of the wastewater and aquifer fluids.

As discussed by Warner (1965), monitoring with wells to determine the rate and extent of movement of wastewater within the injection zone is of limited value because of the difficulty of intercepting the wastewater front and of interpreting information that is obtained. For these reasons, and because of the cost, few such monitor wells have been constructed.

A more feasible approach is to monitor the fluid pressure in the injection zone or adjacent aquifers. A larger number of monitor wells have been constructed for this purpose. Goolsby (1971) discussed an example of an injection system where a monitor well was useful for both detection of waste travel and measurement of reservoir fluid pressure.

The most common type of monitor well used in conjunction with wastewater injection systems is that constructed in the freshwater aquifers near the injection well. If these wells are pumping wells, they provide a means for detecting (eventually) leakage from the injection well or injection horizon; pollutants entering the supply aquifer will tend to move toward a discharging well.

Changes in the quality of water in springs, streams, and lakes may also be monitored to detect effects from waste disposal wells.

State Programs

The status of regulation of disposal wells at the state level is highly variable. Most states that have significant oil production regulate the disposal of oilfield water through an oil and gas agency, but other categories of disposal wells are most frequently regulated through water pollution control, environmental protection, or health agencies.

A few states have developed specific laws, regulations, or policies concerning industrial wastewater injection. A chronological list of these and other significant developments is given below:

1961	Texas – Injection well law adopted
1966	Kansas – Regulations adopted
1967	Ohio – Injection well law adopted
	New York – Groundwater classified
1969	Indiana – "Test Hole" legislation enacted
	Michigan – "Mineral Well Law" enacted
	New York – Injection well policy established
	Texas – 1961 law amended
	West Virginia – Injection well legislation enacted
1970	Illinois – Policy specified
	FWPCA – Policy announced
	Colorado – Rules and regulations for subsurface disposal adopted
1971	Missouri – Disposal wells prohibited
1972	Oklahoma – Regulations adopted
	Council of State Governments – Model State Toxic Waste Disposal Act.
1973	Ohio River Valley Water Sanitation Commission – Resolution with supporting procedures and criteria adopted
	EPA – New policy stated.

Texas was the first state to pass a law specifically concerning industrial wastewater injection wells, in 1961. Since that time, several other states have passed similar laws or amended existing ones to include consideration of underground injection. Formal regulations have been adopted by Colorado and Oklahoma. Formal or informal policy guidelines have been specified by several states. With the exception of the specific cases listed above, most states regulate injection wells under general water pollution control laws, oil and gas laws, or both. There is frequently overlapping jurisdiction among state agencies regarding such wells.

Because regulation of industrial wastewater injection wells is a relatively new responsibility, the laws, regulations, and policies in this area are in the developmental stage. During 1970–1972, an advisory committee to the Ohio River Valley Water Sanitation Commission formulated policies, procedures, and technical criteria for use by the eight member states (Illinois, Indiana, Kentucky, New York, Ohio, Pennsylvania, Virginia, and West Virginia). In January 1973, ORSANCO formally adopted the Committee recommendations as Resolution 1-73, incorporating eight steps:

1. Preliminary assessment by the applicant of the geology and geohydrology at the proposed well site and the suitability of the wastewater for injection. These initial studies should be made in consultation with the appropriate state agencies.
2. Application to the state agency with legal jurisdiction for permission to drill and test a well for subsurface wastewater injection. The application must be supported by a report that documents all details of the proposed injection system, including monitoring and emergency standby facilities. On issuance of a permit, the applicant will be apprised of the geologic and geohydrologic parameters that will be employed by the state in

reaching its final determination on feasibility of wastewater injection into the well, anticipated limitations on injection pressure and injected volumes, the probable monitoring requirements, and probable requirements for alternative wastewater management programs in the event that operational problems occur during the use of the injection well.

3. Drilling and evaluation of the well and submission of samples, logs, test information, and a well-completion report to the state.

4. Request by the applicant for approval to inject wastewater into the well. The request should indicate any changes from the original plan in system construction and operating program.

5. Prompt evaluation by the state of the well and approval, approval-with-modification, or disapproval of the proposed injection system based on the geologic, geohydrologic, and engineering data submitted. On approval, the applicant will be provided with specific instructions and monitoring requirements.

6. Operation of the injection system in accordance with state requirements. The appropriate regulatory agency should be notified immediately if operational problems occur, if remedial work is required, or if significant changes in the wastewater stream are anticipated.

7. Abandonment of the well in accordance with state regulations or other technically acceptable procedures.

8. In addition to the seven steps listed above, where a proposed injection well is to be located within five miles of a state border, the appropriate agencies in the adjacent state should be provided the opportunity to review and comment on the application. Further, these agencies should be advised of any significant problems that occur during the operation of such a well.

These procedures are supplemented by forms, outlines, and technical criteria to be used in implementation. It is anticipated that the individual states will formally or informally adopt the procedures and supplementary material, with such modifications as each may wish to make to meet state organizational and administrative needs. It is intended that the recommendations will be updated and modified as experience shows it to be necessary.

An example of the application of ORSANCO Resolution 1-73 to a particular state was provided by Warner (1972) in a report to the Illinois Institute for Environmental Quality.

OTHER WELLS

In addition to the types of industrial wastewater injection wells discussed above, other classes of deep wells are possible sources of groundwater contamination. Such wells include those used in conjunction with oil exploration and production, solution mining, geothermal energy production, sewage treatment, desalination, radioactive waste disposal, and underground gas storage.

Many of the technical and regulatory aspects that have previously been described apply to these wells just as to industrial wastewater injection wells. The differences that exist will be discussed.

PETROLEUM INDUSTRY WELLS

Deep wells are used by the petroleum industry for exploration, for production of oil and gas, and for injection back into the subsurface of brines brought to the surface during oil production. The purpose of brine injection may be to maintain reservoir pressure, to provide a displacing agent in secondary recovery of oil, or to dispose of the brine.

The total number of petroleum exploration and production wells that have been drilled in the United States since the first oil well was constructed in 1859 is unknown, but they number in the millions. Iglehart (1972) reported, in the American Association of Petroleum Geologists 46th annual report on drilling activity in the United States, that 27,300 wells were drilled in 1971, a year in which drilling activity was at a low level. The number of existing brine injection wells is not documented either, but inquiry among the oil producing states indicated that in 1965 about 20,000 such wells existed in Texas alone (Warner, 1965), with probably an equal number distributed among all other states. Information gathered by the Interstate Oil Compact Commission (1964) shows that about 360 billion gallons of water were produced in 1963 in conjunction with petroleum. At that time, about 72 percent of the produced water was reinjected. The percent being reinjected today is undoubtedly higher, since other means of disposal, such as unlined pits, have since been outlawed in Texas and other states.

Hazard to usable groundwater may result from any deep well, including petroleum production wells, that are inadequately cased, cemented, or plugged. Such wells provide avenues for interaquifer movement of saline groundwater and other fluids. A particular danger to usable groundwater is posed by the hundreds of thousands of oil and gas wells that were drilled in the late 1800's and early 1900's and abandoned with inadequate plugging. Examples of groundwater contamination caused by abandoned, improperly-plugged oil and gas wells could probably be found in most petroleum-producing states. Fryberger (1972), Wilmoth (1971), and Thompson (1972) discussed cases from Arkansas, West Virginia, and Pennsylvania, respectively.

The mechanism of possible groundwater contamination from oilfield brine injection wells is essentially the same as was discussed for other industrial wastewater injection wells. Since oilfield brine is a natural water and does not normally contain chemicals that are extremely toxic in small quantities, it may be of less concern as a pollutant from a public health standpoint than some other industrial wastewaters. However, the very high levels of dissolved solids that are found in many cases, and the volumes involved, present the potential for degradation of very large amounts of usable groundwater if brine reinjection is not properly managed (Ostroff, 1965). It is commonly believed that most brine is returned to the same geologic horizon from which it was removed. The relative amount returned to the same horizon as compared with that injected into other shallower horizons is not known, but substantial amounts are injected into aquifers that have not been depressured by petroleum production. A particular example of this is injection of oilfield brines into the Glorieta Sandstone in the Oklahoma Panhandle and adjacent areas (Irwin and Morton, 1969). The hazard from this practice is from interaquifer flow of brine, or alteration of the position of the freshwater saline-water interface.

The procedures and methods for control and regulation of brine injection are essentially the same as discussed for industrial wastewater injection. Locating and plugging abandoned oil and gas wells is difficult and expensive. Pasini and others (1972) discussed the technology and cost of plugging abandoned wells in the Appalachian area. The cost ranged from $8,600 to $14,000 each for the four wells plugged in that study.

A detailed investigation of the problems presented by one incident of pollution of a freshwater aquifer by an oilfield brine was made by Fryberger (1972). The present extent of the brine pollution is one square mile; however, it will spread to affect 4-1/2 square miles and will remain for over 250 years before being flushed naturally from the aquifer. Several methods for rehabilitating the aquifer were examined; costs ranged from $80,000 to $7,000,000, and no method is economically justified at the present time.

WELLS USED IN SOLUTION MINING

For many years, wells have been used to extract sulfur, salt, and other minerals from the subsurface by injection of water and extraction of the minerals in solution. In many cases, the residual brine from such operations is disposed of through injection wells. A similar type operation, widely practiced in areas where salt deposits exist, is the construction of solution caverns for storage of liquid petroleum gas. In this procedure, water is injected into the salt beds and a cavern developed as the salt is dissolved and the brine pumped out. The extracted brine is then disposed of by injection into a suitable aquifer.

A relatively new but growing practice is the in-situ mining of metals, particularly copper, by injection through wells of acid into an ore body or a tailings pile, then extraction of the solution containing the metal through pumping wells or as seepage. In at least one case, a deep injection well is planned for disposal of the spent acid solution, after the metals have been removed.

The potential problems of groundwater pollution from solution mining of soluble minerals and the techniques for prevention of such pollution are similar to those described previously. Solution mining of metallic minerals presents a different problem, in that the mining will, in most cases, be in geologic strata containing usable water. Therefore, the mining itself may need to be carefully managed to avoid groundwater contamination. Disposal of the spent acid solutions by injection would be similar to other industrial wastewater injection.

McKinney (1973) and Pernichele (1973) discussed current trends in solution mining and mining geohydrology and listed a number of recent references.

GEOTHERMAL ENERGY WELLS

The Geothermal Steam Act of 1970 (Public Law 91-581) provides an important impetus to the further development of geothermal energy sources. In the United States, about 1.8 million acres are designated as known geothermal resource areas and an additional 95.7 million acres have prospective value (US Department of the Interior, 1971). Of the known areas, 90 percent lie in the thirteen western states and Alaska. Geothermal reservoirs may contain either dry steam or hot brines, with the latter predominating. Both condensed steam and cooled brines commonly are reinjected through wells into the geothermal structure (US Department of the Interior, 1971).

At present, the two most significant geothermal areas in the United States are the The Geysers and Imperial Valley, both in California.

A substantial amount of electrical energy already is generated from dry steam produced at The Geysers. A three-fold increase in capacity is planned by 1975. Injection wells are used to return condensate to the reservoir. Because of oxygen content, the condensate is reported to be corrosive, necessitating the use of special materials (Chasteen, 1972).

The United States Bureau of Reclamation and others have proposed major developments of geothermal energy from the hot brine reservoirs underlying the Imperial Valley. The Bureau of Reclamation concept contemplates production of 2.5 million acre-feet of fresh water per year from 3 to 4 million acre-feet of brines. The desalted water would be replaced with water from the Pacific Ocean, the Salton Sea, or other sources; mixed with residual brines, the replacement water would be injected through approximately 100 wells on the periphery of the geothermal field, to maintain reservoir pressures and preclude land subsidence and lowering of the overlying freshwater table (Bureau of Reclamation, 1972). The high pressures and temperatures and the corrosiveness of the injected fluid are a particular problem in such injection wells; plugging a well if subsurface casing damage occurs could be difficult or even impossible.

WELLS FOR INJECTION OF SEWAGE EFFLUENT AND DESALINATION PLANT BRINES

A few wells have been constructed in Florida, Hawaii, Louisiana, and Texas for injection of treated sewage effluent into saline water aquifers. Disposal by injection has also been proposed for brines from advanced waste treatment plants using desalination techniques and from plants constructed to produce usable water by desalination methods (Dow Chemical Company, 1972).

The technology of injecting such waters is similar to that previously discussed. The particular problem with this category of wastewaters is the potentially very large volume that may be produced. In general, disposal of sewage effluent by injection into saline aquifers probably is not desirable for at least two reasons: the effluent is of too high a quality to waste, and the amount that can be safely injected is too small to be significant in solving the overall problem of managing such wastes.

RADIOACTIVE WASTE DISPOSAL WELLS

The possible use of injection wells for disposal of radioactive wastes has been the subject of extensive investigation since the early 1950's. To date, at least three wells have been constructed for injection of liquid radioactive wastewaters into deep aquifers, but the only one that has been operated is located at a uranium mill at Grants, New Mexico (Arlin, 1962). In spite of the limited use of injection wells in the past, they may be the most desirable means of handling some radioactive liquids today and perhaps others in the future (de Laguna, 1968; Belter, 1972).

Particular problems related to injection of liquid radioactive waste are the possible extreme toxicity of the waste and heat generation from radioactive decay in the subsurface.

A second method of radioactive waste disposal through wells is injection of radioactive wastes incorporated in cement slurries into hydraulic fractures induced in thick shale beds. This method of disposal has been used for intermediate level wastes at the Oak Ridge National Laboratory since 1966 and is being tested at the Nuclear Fuel Services Chemical Processing Plant site in West Valley, New York (Belter, 1972). A discussion of the environmental aspects of this disposal method was provided by de Laguna and others (1971).

GAS STORAGE WELLS

Underground gas storage may be defined as storage in rock of synthetic gas or of natural gas not native to the location. Storage can be in depleted oil or gas reservoirs, in groundwater aquifers, in mined caverns, or in dissolved salt caverns. Gas may be stored in gaseous or liquid form.

The largest quantities of gas are stored in the gaseous form in depleted oil or gas reservoirs or in groundwater aquifers. In 1971 there were 333 underground gas storage fields in 26 states. About 60 percent of the storage capacity was located in Illinois, Pennsylvania, Michigan, Ohio, and West Virginia. The number of wells per field ranges from less than 10 to more than 100, depending on the size of the structure in which the gas is being stored (American Gas Association, 1967 and 1971).

Underground gas storage fields present a potential for contamination of usable groundwater by upward leakage of gas through the cap rock, through abandoned improperly plugged wells, or through inadequately constructed gas injection or withdrawal wells. Gas could also escape from an overfilled field and migrate laterally in the storage aquifer, which in some cases contains usable water. A case history of a leaky storage field in Illinois was documented by Hallden (1961). In that instance, it was not possible to conclusively determine whether the leakage was from faulty well cementing, lack of an adequate cap rock, faulting of the cap rock, or unplugged abandoned wells. Some leakage from storage fields is common; but, since the gas is a valuable commodity, operating companies have a strong interest in minimizing such losses. In addition, storage fields are subject to state or federal licensing and regulation, the engineering characteristics of a field must be carefully determined prior to licensing, and the fields must be monitored during operation.

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INJECTION WELLS INTO FRESHWATER AQUIFERS

Scope of the Problem

Although most of the estimated 15 million wells in the United States are used for the production of fresh water, many thousands of wells in various parts of the country have been and are still being used only for disposal of pollutants into freshwater aquifers. This practice has been followed, for example, by the petroleum industry in some areas for getting rid of brines and by other industries for disposing of chemical wastes. Fuhriman and Barton (1971), referring to groundwater pollution in the southwestern United States, stated that "occasionally, industries or others have used shallow injection wells to dispose of liquid wastes," and cited as an example electronic industries that disposed of metal-plating wastes by means of injection wells in Arizona.

In parts of Florida and Ohio, wells tapping limestone aquifers have been used to dispose of domestic sewage from individual homes. Similarly, in Oregon (Sceva, 1968; Oregon State Sanitary Authority, 1967) domestic sewage effluent is discharged from septic tanks into deep rock wells drilled into basalt aquifers (Figure 2-3). For the past several decades, thousands of wells in New York, in California, and in several midwestern states have been used to inject heated water from cooling systems into freshwater aquifers.

In the Snake River Plain of Idaho, wells are widely used to dispose of wastes into the underlying permeable basalt aquifer. A recent inventory in the area indicates that there are approximately 1500 wells for disposal of surface runoff and waste irrigation, perhaps 2000 wells for disposal of sewage, and additional wells for street drainage and industrial use. At the National Reactor Testing Station, low-level aqueous radioactive wastes have been discharged into the same basalt aquifer through a drilled well since 1953 (Jones, 1961).

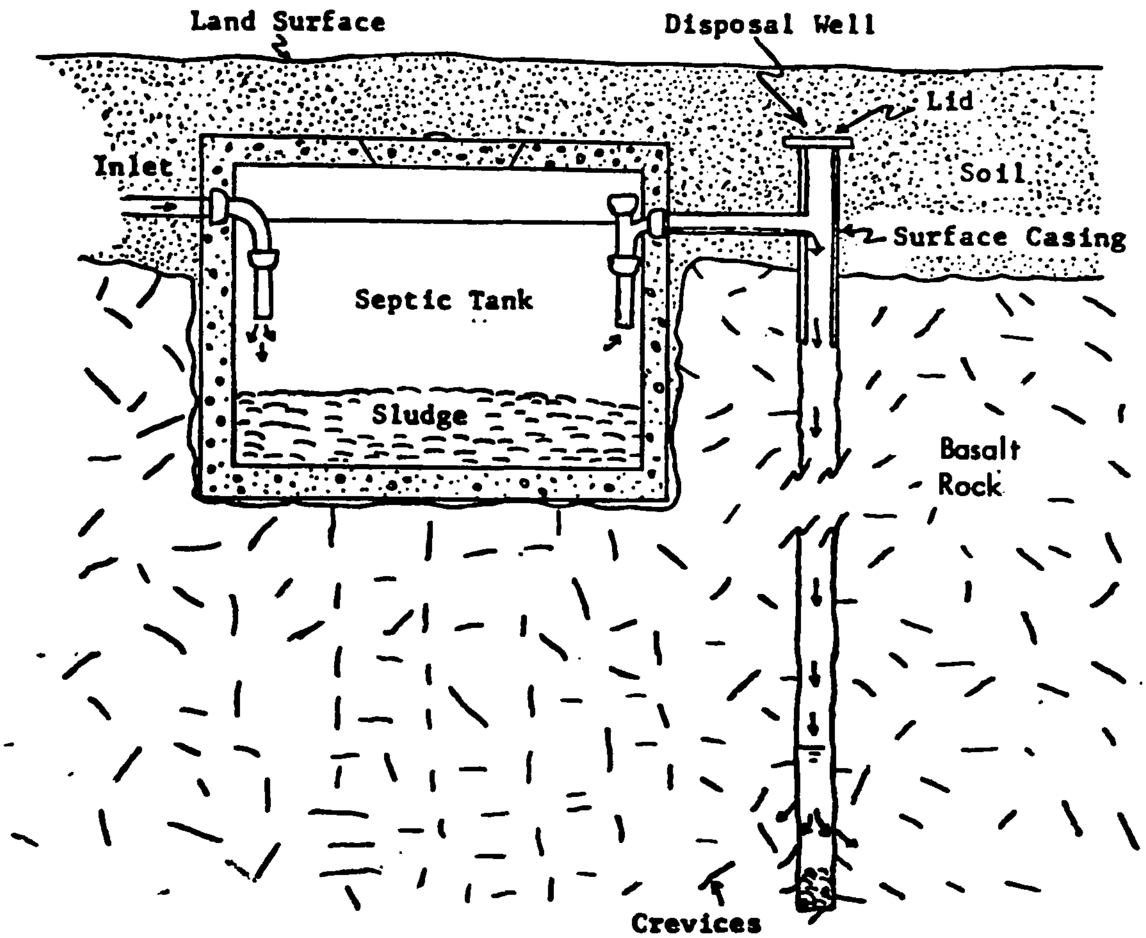

Figure 2-3. Diagram of domestic sewage disposal system employing a disposal well in the middle Deschutes Basin, Oregon (after Sceva, 1968).

In recent years, as pressure on municipalities to abate pollution of surface waters has increased, greater attention has been given to the possibility of injecting treated municipal sewage into wells penetrating freshwater aquifers. Several of the proposed schemes not only would solve a sewage-disposal problem but also would help to recharge freshwater aquifers or to establish hydraulic barriers against saltwater encroachment in freshwater aquifers. Advanced pilot experiments are being conducted along these lines in Long Island (Vecchioli and Ku, 1972) and in California (Baier and Wesner, 1971). The procedure is relatively costly because the sewage must be given at least secondary treatment and preferably tertiary treatment in order to prevent clogging of the injection wells and to reduce or prevent significant chemical and bacteriological contamination of the aquifer.

Modification of the existing quality of the native groundwater caused by subsurface disposal of wastes through a well depends on a variety of factors, including the composition of the native water, the amount and composition of the injected waste fluid, the rate at which the injection takes place, the permeability of the aquifer, the type of construction and life expectancy of the well, and the kinds of biological and chemical degradation that may take place within the well and the aquifer. In general, for economic reasons, wells used for disposal of contaminated liquids in freshwater aquifers tap the shallowest available aquifer. Commonly, this is a water-table aquifer. Some disposal wells, however, are terminated at greater depths in confined freshwater aquifers.

Environmental Consequences

Initially, injection of contaminated liquids through wells into freshwater aquifers causes degradation of the chemical and bacteriological quality of the groundwater in the immediate vicinity of the injection facilities. Eventually, the degradation spreads over a wider region and may ultimately extend into surface waters that are hydraulically connected with the receiving aquifer. If the water-level cones of depression around nearby operating water-supply wells are large enough to include the injection site, or if the wells are down-gradient along natural flow lines from the injection site, contamination of these wells may take place. Another potential effect in some hydrogeologic environments is movement of the contaminated water from the injection zone into overlying or underlying freshwater aquifers.

Nature of Pollutants

The principal kinds of contaminated fluids that are intentionally injected through wells into freshwater aquifers, other than those from agricultural and mining wastes, are cooling water, sewage, stormwater, and industrial wastes.

In the case of cooling water returned to the same aquifer from which it has been pumped, the chemical quality of the water is usually unchanged from that of the native water except for an increase in temperature. Increased solubility of aquifer materials due to a rise in temperature is believed to be insignificant, except perhaps in carbonate aquifers. However, in some instances, sequestering agents such as complex polyphosphate-based chemicals added to the water to inhibit oxidation of iron may become a source of pollution in an aquifer.

Domestic sewage being disposed of into individual household wells is a highly polluted waste with organic and inorganic substances, bacteria, and viruses. It may receive little natural treatment during passage through septic tanks and cesspools except for settling of the solids, some biochemical degradation of the wastes, and filtration of part of the large bacterial population. On the other hand, the quality of the municipal sewage effluent released for disposal into wells depends on the degree of treatment before disposal and the source of the sewage. Municipal sewage generally consists mainly of domestic wastes with a high content of dissolved solids, including nitrogen-cycle constituents, phosphate, sulfate, chloride, and detergents (methylene-blue active substances, or MBAS). In some localities municipal sewage contains substantial amounts of industrial wastes. Different degrees of treatment may remove or reduce the concentrations of certain constituents, but even with the most advanced forms of sewage treatment many dissolved constituents including heavy metals remain in the wastes.

The chemical quality of tertiary treated sewage, native groundwater, and water recovered from observation wells, from an experimental injection study in Long Island, New York, are shown in Table 2-12. The concentrations of ammonia, iron, phosphate, sulfate, and other constituents as well as the dissolved solids content were significantly higher than those of the native groundwater. No analyses of the treated waste were made for heavy metals or other objectionable constituents. The bacterial count in the treated sewage was low due to heavy chlorination before injection.

Stormwater runoff generally has a low dissolved-solids content. However, the initial slug of stormwater may be contaminated with animal excrement, traces of pesticides, fertilizer nitrate from lawns, organics from combustion of petroleum products, rubber from tires, bacteria, viruses, and other miscellaneous contaminants. Where deicing salts are applied to roads in the winter, the chloride content of the stormwater may rise temporarily to several thousand mg/ℓ.

Industrial wastes injected through wells range widely in composition and toxicity, depending on the particular industrial operation and the degree of treatment of the wastes before disposal. Plating wastes, pickling wastes, acids, and other toxic materials are some of the more common fluids disposed of through wells into freshwater aquifers.

Table 2-12. Chemical quality of native water, tertiary treated injection water, and water from observation wells (after Vecchioli and Ku, 1972). (All constituents in milligrams per liter, except pH.)

Constituent	Tertiary Treated Injection Water	Native Groundwater Depth 560 ft.	Contaminated Water Recovered from Observation Wells	
			Depth 480 ft.; Distance 20 ft.	Depth 460 ft.; Distance 100 ft.
Total iron	0.24	0.6	0.91	1.30
Free CO_2	21	-	105	100
Fluoride	.26	.01	.23	<.10
Ammonia nitrogen	25	-	18.5	1.38
Albuminoid nitrogen	.36	-	.24	.04
Nitrite nitrogen	.00	-	<.001	<.001
Nitrate nitrogen	<.05	.00	<.05	<.05
Oxygen consumed	3	-	2	1
Chloride	73	3.7	74	24
Total hardness	72	-	42	34
Total alkalinity	77	-	33	6
pH	7.0	5.6	5.8	5.1
Total solids	357	23	321	123
MBAS	.02	-	<.02	<.02
Calcium hardness	42	-	22	16
Total phosphate	3.6	.01	.60	.02
Orthophosphate	3.1	-	.50	<.01
Sulfate	137	4.1	138	54
Silica	14	7.4	10	8.0
Calcium	18	.34	8.2	7.2
Magnesium	5.2	.17	4.2	3.3
Sodium	69	3.7	67	22
Potassium	11	.60	9	1.6

Pollution Movement

In principle, any well that produces water will also accept water. The rate of acceptance is dependent on the nature of the injected fluid, the hydraulic properties of the aquifer, and other factors. In some wells penetrating very permeable aquifers, water can be introduced under gravity conditions at rates that may be as high as several hundred gallons per minute or more without causing overflows. In contrast, a well penetrating a very poor aquifer may accept only a fraction of a gallon per minute by gravity flow. If pumps are installed so that the fluid is injected under pressure, the rate of injection can be substantially increased.

The rate of injection is governed by the permeability and thickness of the aquifer, the depth to the natural water level in the well, the diameter of the well, the area of openings in the well screen, and the chemical compatability of the injected fluid with the native groundwater. If the fluid being injected contains suspended material or air bubbles, for instance, rapid clogging of the aquifer can occur so that the injection rate falls off sharply. Growth of certain kinds of bacteria and formation of chemical precipitates within the well and the adjacent aquifer also can interfere with injection. In the case of a water-table aquifer, a further limitation on the rate of injection is that the induced rise of the groundwater level may cause breakthrough and overflow at the land surface.

Injection of fluid through a well creates a local groundwater mound in an unconfined aquifer and a pressure mound in a confined aquifer. These mounds are essentially mirror images of the water-level cones of depression that develop around pumping wells tapping the same types of aquifers. The configuration of a particular mound is generally symmetrical, with the maximum rise in water level being observed at the well. Hypothetical shapes of contaminated water bodies in homogeneous unconfined and confined aquifers are shown in Figure 2-4. Departures from these shapes

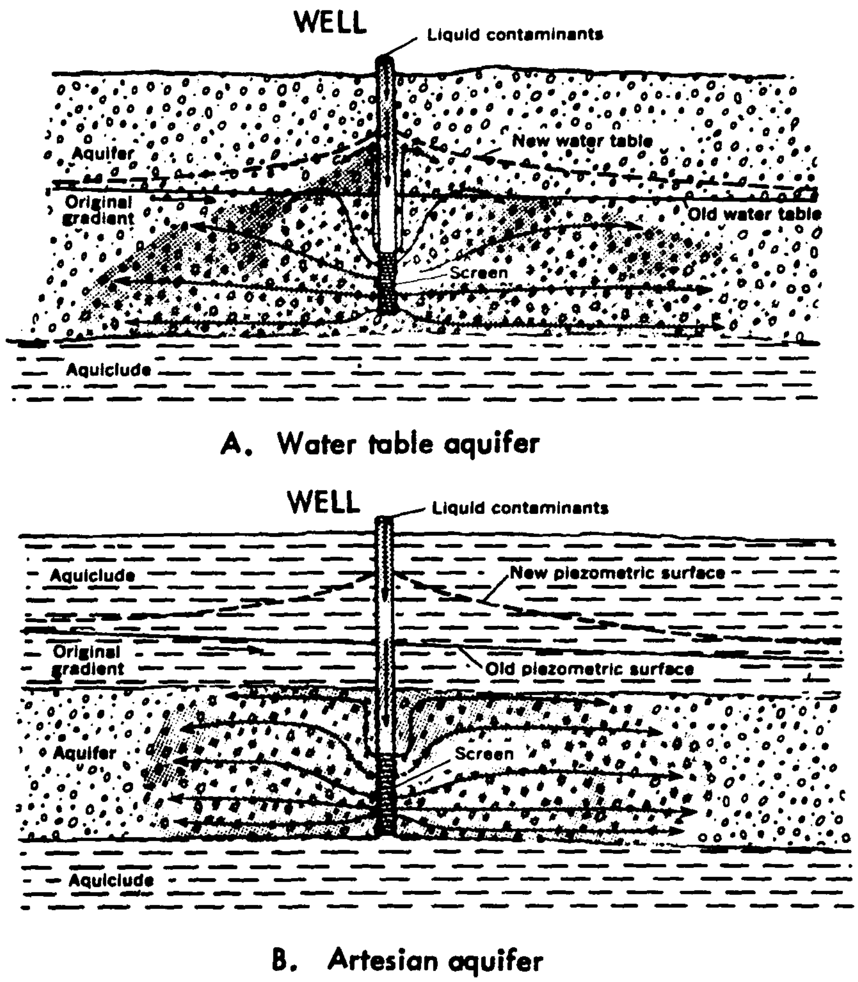

Figure 2-4. Hypothetical pattern of flow of contaminated water (shaded) injected through wells into water table and artesian aquifers (after Deutsch, 1963).

may develop where aquifer lithologies are non-uniform and where the natural groundwater flow is significant.

After it has entered the saturated zone, the injected fluid begins to move radially away from the well, displacing the native groundwater in its path and creating a zone of mixed water along the perimeter of the contaminated body. The polluted water moves slowly in the direction of the hydraulic gradient toward a point of discharge, which may be a well, a spring, or a surface water body. Where injection wells leak due to corrosion, casing breaks, or poor construction, the contaminated water may move into freshwater aquifers above or below the injection zone.

Examples of the Use of Injection Wells

Since 1965, a pilot experiment on recharging tertiary-treated sewage in order to create a hydraulic barrier against saltwater encroachment has been conducted by the U. S. Geological Survey in cooperation with the Nassau County Department of Public Works at Bay Park, Long Island (Vecchioli and Ku, 1972). There, a specially constructed injection well (Cohen and Durfor, 1966), 480 feet deep, with a fiberglass casing, stainless steel screen, and auxiliary monitoring wells at depths ranging from about 100 to 700 feet, were installed to investigate the hydraulic and geochemical problems associated with the injection of treated sewage into a confined aquifer used for public-water supply. The injected water moved radially from the well as a thin body in the injection zone and was detected by monitoring wells as much as 200 feet away. As shown in Table 2-12, significantly higher concentrations of iron, ammonia, sulfate, chloride, sodium, and other dissolved constituents were present in the water after 10 days of injection at distances of 20 feet and 100 feet than in the native groundwater. Bacteria were apparently filtered out after about 20 feet of travel. The experimental results indicated that even low turbidity of the effluent and bacterial growth around the well screen can cause clogging and excessive head buildup in the injection well.

Similar experiments in California on recharging freshwater aquifers with Colorado River water and with reclaimed sewage (McGauhey and Krone, 1954), mainly as a barrier against seawater encroachment, have been successfully conducted. Some barrier systems using highly treated river water are operational. Baier and Wesner (1971) have described experiments by the Orange County Water District in which tertiary-treated effluent from a trickling filter sewage plant was injected into unconsolidated aquifers at depths of about 100 to 350 feet. The experiments indicated that after about 500 feet of travel, the injected water was free of viruses, bacteria, and toxic substances, and the ammonia content was substantially reduced. However, the hardness and alkalinity of the water increased, the water had a musty odor and taste, and the dissolved-solids content exceeded 1,000 mg/ℓ. Additional pretreatment of the reclaimed waste water will improve the quality of the water intended for injection, and the dissolved-solids content will be reduced to drinking water standards by mixing reclaimed waste water with desalted sea water before injection.

Since the early 1930's, the State of New York has required that industrial water pumped from certain wells on Long Island for cooling and air conditioning purposes must be returned, through a closed system of specially constructed recharge wells, into the same aquifer from which the water was pumped. This requirement was imposed because heavy pumping had caused a sharp decline in groundwater levels in western Long Island, with coastal encroachment of sea water. The heated effluent returned to the ground, which may range from 10 to 30°F warmer than the natural groundwater, has increased the local temperature of water in shallow aquifers (Leggette and Brashears, 1938). Warming of the groundwater, although of concern to users of groundwater for cooling, has been regarded as less detrimental than the saltwater encroachment that could result from declining groundwater levels.

In parts of western Long Island, stormwater that collects at street intersections subject to flooding is disposed of into dry wells that act as drains. The wells are lined with large-diameter pre-cast perforated concrete rings. The stormwater moves downward through the wells into a shallow aquifer. Hundreds of dry wells are also used for highway drainage in other parts of the country; notable are those in the Fresno area of California (Gong-Guy, in Schiff, 1963). In a few places, wells also have been drilled within ponds to drain them. Drainage wells commonly provide a short path for potential vertical movement of inorganic and organic contaminants and bacteria into an underlying aquifer.

Control Methods

Where injection of wastes through wells into freshwater aquifers is proposed or is in progress, a hydrogeological investigation should be undertaken as a first measure to control potential groundwater pollution. This should include:

1. Definition of the hydrogeologic environment and the factors affecting the groundwater flow.

2. Existing or planned nearby wells should be located.

3. The directions and rate of movement of the potential contaminated fluid should be ascertained, so that estimates can be made of how much time will elapse before the arrival of the contaminated water at nearby wells.

4. Studies should be undertaken to determine the possibility of inter- and intra-aquifer movement of the injected water.

5. Information should be compiled on the chemical, biological, and physical properties of the waste fluids; the degree of pre-treatment needed; and the compatibility of the treated fluids with the native groundwater.

6. An evaluation should be made of the most suitable locations and spacings of injection wells and of the rate of injection.

7. Consideration should also be given to the future land use of the injection-well sites.

Where the threat from contaminated groundwater is severe, steps may have to be taken to block the underground flow of the waste fluids or to actually remove the fluids by pumping. Blocking of the movement of the contaminant can be accomplished by constructing physical subsurface barriers, although this is not an economically feasible solution in most hydrogeologic environments. Diverting the flow by creating a hydraulic barrier is another approach that may be implemented in many places. This can be accomplished by injecting fresh water through wells installed across the path of flow or by pumping from wells so as to induce the contaminants to flow toward these wells.

Pumping polluted fluids back out of the ground may create a new pollution problem where the wastes are pumped into surface water. However, if facilities can be provided for proper treatment and disposal of the pumped water, pumping from wells can be a practicable solution.

Alternatives to disposing of wastes through injection should, of course, be examined. A careful evaluation of alternatives is required, to avoid adopting an expedient that may prove to have other and perhaps more harmful effects. Sewering, for example, which exports the waste, can have deleterious effects due to loss of recharge and consequent lowering of water levels and possibly saltwater intrusion. In the case of cooling water being returned to the aquifer from which it is drawn, an alternative is to use atmospheric heat exchangers instead of the cooling water. Here, the loss of efficiency of the cooling system must be considered; more electrical energy may be required, with attendant air and thermal pollution problems. The undesirable "heat island" effect noted in large cities may be further increased by widespread use of atmospheric heat exchangers in place of the groundwater for cooling.

Halting the disposal of wastes into wells may be highly desirable, but it should be noted that halting the injection represents only a partial pollution control measure; fluids already injected will continue to pollute the aquifer.

Monitoring Procedures

After a clear understanding has been developed of the hydrogeologic environment and of the mechanisms of contamination, a monitoring system should be designed and implemented to provide continuing surveillance of polluted water and of the efficiency of any control measures that may be instituted. Depending on local conditions, it may be necessary to construct a series of wells at different depths in the polluted aquifer and at scattered nearby locations. Periodic monitoring of these wells for chemical content of the groundwater and changes of groundwater levels can provide valuable data on the behavior of the underground contamination and on the environmental threats to water wells or to other freshwater resources in the vicinity.

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LAGOONS, BASINS, PITS

Use of Lagoons, Basins, and Pits

In general, a lagoon comprises a natural depression in the land or a sector of some bay, estuary, or wetland area diked off from the remainder. No sharp line of definition distinguishes it from a basin, which is most commonly constructed by formal diking or by a combination of excavating and diking. Pits are distinguished by a small ratio of surface area to depth.

Unlike excavations used in septic systems or in landfill operations, lagoons, basins, and pits are usually open to the atmosphere, although pits and small basins may sometimes be placed under roof. Some are intended to discharge liquid to the soil system and hence to the groundwater, others are designed to be watertight. The former are, therefore, unlined structures sited on good infiltrative surfaces; the latter are lined with puddled clay, concrete, asphalt, metal, or plastic sheeting. Thus, both by design and by accident or failure, this type of structure is of concern in the context of groundwater quality.

Lagoons and basins are adapted to a wide spectrum of municipal and industrial uses including storage, processing, or waste treatment on a large scale. For example, the unlined lagoon or basin may serve as a large septic tank for raw sewage, a secondary or tertiary sewage oxidation pond, or as a spreading basin for disposing of effluent from treatment ponds or conventional wastewater treatment plants by groundwater recharge. In industry the unlined system may serve as a cooling pond or to hold hot wastewater until its temperature is suitable for discharge to surface waters, or to store wastewater for later discharge into streams during flood flows or for application to the land during the growing season. Some unlined lagoons are used for a special purpose such as evaporating ponds to concentrate and recover salt from saline water.

Lined basins are used for a number of purposes, including evaporation ponds for concentrating salts or process brines. Recovery of minerals, or more economic disposal of the concentrate, may be the motivating factor. In oil fields, refineries, and chemical processing plants basins are used as holding sumps for brines or wastes as a stage in disposal by deep well injection or other acceptable procedure. In the East Bay area of California, a lined basin has served as a receiving sump for fruit and vegetable cannery wastes to be barged to sea or hauled to land disposal sites.

Unlined pits serve to a limited extent in sewerage; examples include pit privies and cesspools or percolation devices in septic systems. They are also widely used to dispose of storm water from roof drains. In California both pits and basins are used to dispose of storm water which would otherwise collect in highway underpasses and interfere with traffic.

Lined pits have historically been used in industry for processes ranging from tanning of animal hides to metal plating. They are commonly used to house sewage pumps below the ground level. In both industry and municipal sewerage they are used as intake sumps in pumping installations. Although lined pits are commonly concrete or metal structures, leakage — often undetected — of highly concentrated pollutants can have a significant local effect on groundwater.

<u>Scope of Problem</u>

Data by which to evaluate the existing scope of the problem of municipal and industrial waste lagoons and similar open excavations in relation to groundwater quality have not been assembled and analyzed. State health departments and water quality control boards can cite instances in which ponded contaminants have created a local pollution problem. To assess the degree to which the use of lagoons, basins, and pits in fact degrade groundwater quality will require an extensive survey of the literature and of the practice of ponding wastes and process materials. The present outlook is that the need for such an assessment will become increasingly great with time. Two factors support this conclusion:

- As institutionalized in the National Clean Water Act, there is a growing reluctance of regulatory agencies to permit waste discharges to surface waters, thus requiring either land disposal of sewage effluents or the creation of an increasing volume of process brines in achieving an acceptable effluent quality.

- A growing tendency to require industry to process its own wastes prior to discharge to the municipal sewer, thus creating more need to use lagoons and basins either for waste processing or for managing waste processing brines.

Both of these developments suggest a need to control the pathways by which contaminants may move from ponds to groundwater and to monitor the effectiveness of control measures.

<u>Potential Hazard to Groundwater</u>

The potential of sewage lagoons to degrade groundwater quality is essentially the same as that of septic systems. An extensive survey of the literature (McGauhey and Krone, 1967) shows that a continuously inundated soil soon clogs to the extent that the infiltration rate is reduced below the minimum for an acceptable infiltration system. If the groundwater surface is too close to the lagoon bottom, a hanging column of water will be supported by surface tension and the soil will not drain. Clogging will then continue indefinitely even though no new liquid is added to the system. A spreading pond designed to discharge effluent to the groundwater must, therefore, be loaded and rested intermittently to maintain an acceptable recharge rate (California Water Pollution Control Board, 1953; McGauhey and Winneberger, 1964; McGauhey and Krone, 1967). If, however, isolating the contents of the lagoon from the groundwater is the objective of the system, a low infiltration rate may still mean an undesirable quantity of polluted water passing the water-soil interface. The pollutants carried downward with percolating water from a sewage lagoon are those described in the section on septic tanks. Not all of the salts introduced to the groundwater originate in domestic use. In some instances, such as that of Colorado River water delivered to Southern California, the mineral content of the imported water may be higher than that of the local groundwater.

Lagoons and pits used to recharge groundwater with runoff from highways and roofs have little potential to affect groundwater adversely except in highly permeable aquifers. The tendency is to concentrate runoff at low points; however, the effect of this concentration on the groundwater basin is minimal. Oils from the road surface are the principal factor added to rain water in this situation. Lead has been found to be significantly higher on the soils along highways, but its possible movement to groundwater has not been reported.

Liquids percolating from lagoons or basins used by industry have a greater potential to degrade groundwater than does domestic sewage. Chromates, gasoline, phenols, picric acid, and miscellaneous chemicals have been observed to travel long distances with percolating groundwater (Anon., 1947; Davids and Lieber, 1951; Harmon, 1941; Lang, 1932; Lang and Grüns, 1940; McGauhey and Krone, 1967; Muller, 1952; Sayre and Stringfield, 1948). Unlined lagoons, basins, and pits are commonly used by industry for the storage of liquid raw materials and waste effluent. Most of these facilities are simply open excavations or diked depressions in which the liquid is temporarily or permanently stored. Few have been designed with proper consideration to water tightness, so that leakage of potential contaminants into the underlying groundwater reservoir is very common even though the leakage may seldom be known to exist. Liquids stored in industrial lagoons, basins, and pits may contain brines, arsenic compounds, heavy metals, acids, gasoline products, phenols, radioactive substances, and many other miscellaneous chemicals (Anon., 1947; Harmon, 1941; Lang, 1932; Lang and Gruns, 1940; McGauhey and Krone, 1967, Muller, 1952; Perlmutter and Lieber, 1970, Sayre and Stringfield, 1948).

Where these storage areas have been actively used for many years and leakage through the sides and bottom of a particular lagoon or basin has taken place, the quantity of contaminated groundwater can be significant and the plume of polluted liquid may have traveled long distances with the percolating groundwater. In some instances, the first realization that extensive groundwater pollution has occurred may come when the plume reaches a natural discharge area at a stream and contamination of surface waters is noted.

An example of the fate and environmental consequences of a leaky basin containing metal-plating waste effluent from an industrial plant is given in Perlmutter and Lieber (1970). Plating wastes containing cadmium and hexavalent chromium seeped down from disposal basins into the upper glacial aquifer of southeastern Nassau County, New York. The seepage formed a plume of contaminated water over 4,000 feet long, about 1,000 feet wide, and as much as 70 feet thick. Some of the contaminated groundwater is being discharged naturally into a small creek that drains the aquifer. The maximum observed concentration of hexavalent chromium in the groundwater was about 40 mg/l, and concentrations of cadmium have been observed as high as 10 mg/l.

In another case in New Jersey, unlined waste lagoons constructed in sand and gravel beds leaked over 20 million gallons of effluent into the upper 20 feet of aquifer over a period of only a few years. The contaminated groundwater contains high concentrations of phenols, chromium, zinc, and nickel (Geraghty & Miller, Inc., 1972).

Control Methods

In the case of lagoons or basins for deliberate disposal of sewage effluents or surface runoff by groundwater recharge, controls specifically pertinent to groundwater protection are essentially self-generating — the system simply will not work if not properly designed. Existing engineering and hydrogeologic knowledge would prohibit the construction of such systems directly in the groundwater; require adequate distance between the infiltrative surface and the groundwater surface to permit drainage; and prohibit construction in faulted or fractured strata or in unsuitable soils. Therefore, the first control measure in groundwater protection from spreading basins is to apply existing knowledge to their siting and design.

Control of industrial waste discharges to the groundwater is a complex problem. In a state with a highly organized water pollution control agency (eg, California) individual permits are issued on the basis of adequate design and surveillance programs. Because of the variety of industrial wastes and of the varied situations in which they occur, control of groundwater pollution by such wastes depends both upon proper design of new systems and upon discovery and correction of existing systems. Methods for controlling groundwater pollution from industrial lagoons, basins, and pits include:

- Require pretreatment of wastes for removal of at least the toxic chemicals.

- Require lining with impervious barriers of all lagoons, basins, and pits that contain noxious fluids. This is the principal control technique recommended by some agencies, such as the Delaware River Basin Commission.

- Use barrier wells, pumped to intercept plumes of contaminated groundwater from existing industrial basins where leakage has occurred. Such wells have been used successfully, but can be costly to install and operate. The water removed must be treated before redisposal.
- Ban the use of pits. An example is found in Texas, where thousands of brine pits were used by the oil industry. The State found it necessary to ban their use because of the impossibility of inspecting individual installations and enforcing a control program.
- Locate and identify unauthorized pits on industrial sites, on a case-by-case basis, and apply appropriate regulatory action.

Monitoring Procedures

Lagoons, basins, and pits represent multiple point sources of quality factors which may be of significance to groundwater quality. Therefore, a program involving special monitoring wells in the most critical situations is a possible approach.

A program of periodic sampling and evaluation of data from existing wells, selected for their potential to reveal both normal groundwater quality and point contamination, is another monitoring approach. Accompanying this should be a program of monitoring of the control measures themselves to assure, by inspection of sites and of records required of the operator of approved systems, that groundwater protection is indeed being accomplished.

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SEPTIC SYSTEMS

Scope of the Problem

Septic systems are used in every state of the Union, the heaviest concentration being in suburban subdivisions developed following World War II. The predominant type of system is the individual household septic tank. From data available from the Public Health Service and the Federal Housing Administration, it is estimated that 32 million people were served by septic tanks in 1970. In addition to the total subsurface percolation systems associated with these installations, there are an unestimated number of summer cabins, Forest Service campgrounds, and organized group camps which depend upon subsurface disposal of wastewater, primarily during the summer season.

Although the septic tank with an associated subsurface percolation system is the most commonly used type of septic system, raw sewage is still discharged directly from the plumbing system of the house into cesspools dug in the ground. The practice is no longer approved for new installations. Nevertheless, they may be found in the United States wherever soil conditions make the cesspool feasible. In New York state there are probably 100,000 or more such installations. In less populous areas such as New England, the Southwest, and the Northwest, cesspools are known to exist. Several thousand such systems discharging into lava tubes are still in use in Hawaii.

RELATION OF SEPTIC SYSTEMS TO GROUNDWATER. The relationship between a septic system and the quality of nearby groundwater is governed by the design and control of the system.

The septic tank is a water-tight basin intended to separate floating and settleable solids from the liquid fraction of domestic sewage and to discharge this liquid, together with its burden of dissolved and particulate solids, into the biologically active zone of the soil mantle through a subsurface percolation system. The discharge system may be a tile field, a seepage bed, or an earth-covered sand filter. In some instances, as in the vicinity of Sacramento, California, where the soil is sandy and the water table far below the surface, seepage pits are used. These are drilled holes some 30 inches in diameter extending down to a depth of 25 feet or more, and filled with gravel surrounding a wooden center frame.

In the cold Northern and Northeast regions of the United States, tile fields are located below the frost line. This places them below the biologically active zone of the soil. In low lands, notably in the South, a high groundwater table makes it necessary to place the percolation system above the normal ground level. Here a 3-foot deep soil-covered sand bed is used. It discharges back to standing water in the swamps or road drainage ditches if it cannot percolate directly into the groundwater.

In a percolation system located in the biologically active zone, biodegradable organic matter is stabilized by soil bacteria, particulate matter is filtered out, and certain ions (e.g., phosphate) are adsorbed on the soil. Liquid passing through the active soil zone percolates downward until it strikes an impervious stratum or joins the groundwater. In the growing season, a portion, or even all, of the septic tank effluent may be discharged to the atmosphere by evapotranspiration. Salts not incorporated in the plant structure are left in the root zone to be redissolved and carried downward by percolating water at some other season of the year. Thus, the purpose of the percolation system is to dispose of sewage effluents by utilizing the same natural phenomena which lead to the presence of groundwater.

If the percolation system is below the biologically active zone of the soil, filtering and adsorption phenomena predominate. Biodegradation in the system is confined to the partial degradation of organics under anaerobic conditions.

History of Septic Systems

The extent to which septic systems may pollute groundwater, and the ways in which they may be controlled and monitored, are related to several historical aspects of these systems. In rural America, the septic system, whether merely a rock-filled dug hole (cesspool) or a septic tank with a subsurface percolation field, came into extensive use as electricity and inexpensive pumping systems became available to rural families. The isolated rural dweller, however, represents a rather special case. Normally, he depends for water supply upon his own shallow well equipped with a jet pump and a small pressure tank. Most state and county health departments have dealt with the question of groundwater contamination by specifying some arbitrary minimum horizontal distance (usually 50 or 100 feet) between the well and the percolation system as a prerequisite to approval of the septic tank installation. In terms of groundwater quality, the effect of isolated rural septic systems is basically negligible because only a small amount of pollutant is introduced to the soil, and at widely separated points. Thus, a great degree of dilution is achieved by dispersal of inputs.

The use of septic systems in subdivisions following World War II was attractive to land developers because their objective was to convert land profitably from single ownership of a large parcel to multiple ownership of small plots without retaining any residual responsibility for the whole, especially in the matter of utilities. At that time the design of septic tank systems had been standardized on the basis of erroneous assumptions, codified, and generally regulated by local health departments (McGauhey and Winneberger, 1964; McGauhey and Krone, 1967; Coulter et al., 1960; Bendixen, et al., 1962). The result was that, through inadequate knowledge and control, septic tanks with badly constructed percolation systems were approved for small lots in urban subdivisions, sometimes of 2, 500 or more houses. The effect was to concentrate a far greater amount of wastewater at a local point of infiltration than had previously existed. However, the potential of these seepage systems to pollute was often obscured by the failure of percolation systems.

Failure of systems in many areas was known to occur, but this knowledge was usually confined to the householders or dispersed in the files of thousands of county health departments. Only after a single agency, the FHA, became responsible for home loan insurance did it become known that the failure rate was about 30% within 2 or 3 years. Failure was characterized by the clogging of soil and the consequent appearance of wastewater on the surface of the ground. This converted the groundwater pollution problem to one of surface water during rainy periods.

Environmental Consequences

Two categories of environmental effects which bear upon control measures may be identified:

- Those which lead to restrictions on the use of septic systems.
- Those which are inherent in a properly designed and well-functioning septic system in suitable soil.

Under the first category three situations may be identified. Most common of these is the failure of percolation systems, which creates a hazard to health and an unacceptable nuisance as decomposing sewage effluent appears on the surface of the ground.

The second and more serious situation in the context of groundwater quality is direct discharge of untreated septic tank or cesspool effluent into the groundwater through coarse gravel beds, fractured rock, solution channels, or lava tubes. In some areas of the United States, a local practice is to cut trenches directly in bedrock and then shatter the rock with explosives to create drainage channels. Hawaii was mentioned earlier as an area where cesspools are dug into lava tubes. In all of these cases, the groundwater itself often carries for long distances putrescible sewage solids, bacteria, viruses, and tastes and odors, with consequent danger to health and impairment of the aesthetic acceptability of water.

The third situation is somewhat similar to the second. It occurs when percolation systems are located below the biologically active zone of the soil, which typically is only a meter or so in depth. Such systems may be installed where the frost line is deeper than the biologically active zone, or they may simply be buried too deeply because of lack of understanding of proper construction techniques. (Long Island is perhaps the most publicized case where percolation systems are commonly to be found below the biologically active soil zone.) In such a situation, biodegradation in the system is confined to the partial degradation of organics under anaerobic conditions; the physical phenomena of filtering and adsorption remain effective, but soluble products of partial breakdown of organic matter may enter the groundwater and move with it. Tastes and odors are introduced, and the organic fraction, being biochemically unstable, remains capable of supporting bacterial growth when the groundwater outcrops or is withdrawn through a well.

The second category of environmental effects, those which are inherent in a properly designed and well-functioning septic system in suitable soil, has been the subject of much definitive research and is quite well understood. In any specific situation the effects of septic system effluent on the quality of groundwater depend upon:

- The differences in chemical and physical characteristics between the local groundwater and the water supply utilized by owners of septic systems on the overlying land.
- The range of materials added to the water supply by human use.

- The changes in the nature of the wastewater occurring in the septic system and in the biologically active soil through which it percolates.
- The kind and amounts of material which moves downward with water percolating to the groundwater.
- The rate and degree of mixing of wastewater and groundwater.

Often the water supply (or carrier water) is less highly mineralized than groundwater in a specific situation unless the supply is derived directly from the same local groundwater horizon into which septic system wastewater is to percolate. This is because water supply is often surface water imported especially because of its high quality, or is water subjected to ion-exchange or other softening process. The expectation, therefore, is that the water supply will have essentially the same spectrum of ions as groundwater—nitrates, sulfates, carbonates, chlorides, etc.—but in lesser concentration. Physically it may differ only in temperature.

Normally the septic system involves only domestic wastewater; therefore, materials added by human use will be human body wastes, grease and organic garbage from the kitchen, and detergents from cleansing activities in the household. However, miscellaneous pollutants such as water softener regeneration brines, pesticides, drugs, and solvents may be added to the septic system by the householder.

The changes in quality occurring in septic tank soil systems have been extensively studied by many investigators. Briefly, the results of such studies (McGauhey and Krone, 1967) are as follows:

- Inert and organic particulate matter is effectively removed by the first few centimeters of soil. Clogging of the infiltrative surface rather than the quality of the percolated water is the principal factor in relation to particles.

- Bacteria behave like other particulate matter in soils and are removed by straining, sedimentation, entrapment, and adsorption. They are also subject to die-away in an unfavorable environment.
- Viruses are removed by soil systems, probably principally by adsorption, as effectively as bacteria.
- A considerable fraction of the 300 mg/ℓ total dissolved solids added to water by domestic use appears as anions and cations normally found in groundwater. Thus, an increase in the mineralization of groundwater is to be expected from septic systems. Under normal conditions of soil pH, phosphates are effectively removed, whereas chlorides, nitrates, sulfates, and bicarbonates move freely with percolating water.
- Synthetic detergents are effectively destroyed by biodegradation in an active aerobic soil.

The foregoing findings, it should be noted, apply specifically to systems discharging into the soil mantle of the earth within the biologically active zone where both physical phenomena and aerobic stabilization of degradable organic matter are effective.

It may be said that at best septic systems increase the total dissolved mineral solids in groundwater. At worst, they may introduce bacteria, viruses, and degradable organic compounds as well. The multiple-point nature of septic system inputs tends to minimize the concentration of pollutants in any unit of receiving groundwater. In some local situations the effect may not be measurable by normal analytical tests. In other local situations such as Long Island, New York, and Fresno, California, where numerous septic systems are installed in a single subdivision, the effect on local groundwater has been readily detected (Perlmutter and Guererra, 1970; Schmidt, 1972).

Control Methods

Control of the effects of septic systems on groundwater quality must be considered in three situations:

- Septic tank installations are already in existence.
- New septic tank systems are to be installed.
- No practical alternative to the septic tank is presently feasible.

Of these situations, the first is the most difficult to deal with because design is beyond recall and degradation of groundwater may have already occurred. Of course, if system failure is involved, the situation is largely self-curative. The inability of soils to transmit effluent to groundwater results in its appearance on the land surface and, if the subdivision involved is of any significant size, to an early replacement by conventional sewerage. However, if an existing system is functioning satisfactorily its total contribution of salts to the groundwater can be computed from an analysis of the water supply and the known contribution of salts from domestic use. The actual immediate effect of any installation large enough to produce measurable results may be estimated by monitoring the top of the groundwater body. The control program would then involve mandatory monitoring and judgment of the significance of the results by competent hydrogeologists. Several control procedures are applicable.

- Require any existing subdivision subject to septic system failure or observed by mandatory monitoring to be damaging to groundwater quality to enter into sewerage districts with collection and treatment facilities.
- Require householders to connect to a sewer as urban development fills in the open land that once set the subdivision

apart from an urban center, or as land development extends the populated area beyond the initial subdivision.

- Prohibit the home regeneration of water softeners where septic systems are used for waste disposal.

In a situation where new septic tank installations are proposed, possible measures for control include:

- Require approval of the site and design by competent soil scientists and engineers before septic systems are approved for any proposed subdivision, recognizing that simple percolation tests (USPHS, 1968) and standard codes offer only inadequate criteria for the design of a septic system.

- Construct percolation systems by methods which do not compact the infiltrative surface (McGauhey and Winneberger, 1964), including:
  - -- No heavy equipment upon infiltrative surfaces.
  - -- Trenching, boring, or excavating for percolation systems only when soil moisture is below smearing level.
  - -- Use of trenching equipment which does not compact trench sidewalks.
  - -- Use of classified stone sizes in backfills to produce "clogging in depth" (McGauhey and Winneberger, 1964).
  - -- Utilize level bottom trenches with observation well risers at end of each tile line.

- Operate septic systems effectively by:
  - -- Alternately loading and resting one-half the percolation system; the cycle to be determined by the onset of ponding in the system at the observation well.
  - -- Where size of system makes it practicable, loading the entire infiltrative surface of the system at each cycle

as uniformly and simultaneously as possible by use of a dosing siphon.

-- Inspecting and removing scum and grease from septic tanks annually.

-- Drawing off half of the sludge rather than pumping out the entire contents of tanks.

- Use of zoning and other land management controls to prevent septic system installations in unsuitable soils (i.e., soils too impervious to accept effluents, or too coarse or fractured to maintain a biological and physical treatment system.

In situations where no practical alternative to septic systems is presently feasible, the choices are:

1. Limit use of septic systems to the growing season for vegetation.

2. Permit the use of septic tanks if soil is suitable, and accept the consequences in terms of groundwater quality.

3. Permit use of septic systems but restrict the materials which may be discharged to them; for example, prohibit the installation and use of household water softening units which are regenerated on the site.

4. Permit the use of septic tanks under specific conditions.

5. No discharge.

The first alternative is applicable to such installations as forest camps, summer cottages, and summer camps in remote areas where evapotranspiration and plant growth consume most of the water and nutrients. The subsequent pickup of salts in the root zone is done by relatively large amounts of meteorological water.

The second alternative is essentially necessary in the case of isolated dwellings on relatively large plots of land remote from any sewer.

The fourth alternative is an appropriate control measure where soil is suitable and good design and operating procedures are followed. Specifically, it may require that sewers be provided in the streets of a housing development and that house owners abandon septic systems and connect to the sewer when it is available. A 5- or 10-year maximum permit to use septic tanks can be specified.

In specific instances it might be required that the septic system involve no discharge of liquid to the soil. To accomplish this a holding tank might be required, from which sewage is transported by tank truck to a sewerage system at intervals appropriate to the type of installation used to service the household.

Monitoring Procedures

Assuming that unsatisfactory systems are to be controlled by regulatory action or replaced as a result of failure, monitoring procedures would be confined to analyses of percolating wastewater and of the receiving groundwater, and to requirement of permits and inspection for any non-permissible softener installations or other connections to the household plumbing system.

Technologically, the use of tensiometers for sampling percolating water in both unsaturated and saturated flow conditions is a well-established routine. Questions to be answered in the case of a subdivision based on septic systems are who is to make the installations, where are they to be located, and how continuously are they to be observed and replaced. The most likely method would be to evaluate the percolate on the basis of an analysis of the water supply and of a seasonal analysis of percolate obtained from a short-term field study in one or more septic tank percolation fields. Fundamentally, this procedure yields baseline data but is not in itself a monitoring system. In general, the monitoring of septic system percolate is probably an unnecessary and unrewarding procedure.

If groundwater receiving percolate from overlying septic systems is to be monitored, it is desirable to sample both at the groundwater table and at greater vertical depths. Bacteria, although they should not be present as a result of percolating sewage effluents, tend to concentrate in soil at the water table. Greases and oils which might be discharged by the householder also tend to float on the groundwater.

Pragmatically, monitoring may prove to be necessary in order to verify technological predictions that degradation of groundwater quality will occur because of prolonged and concentrated use of septic systems. In Suffolk and Nassau Counties on Long Island, measurements of the degradation of groundwater quality were a major factor in making decisions to install sewers and treatment plants. (Other factors also enter into the decision, of course; for example, loss of local recharge may cause lowering of the water table or head, when sewers collect effluent and discharge it to a stream or coastal waters.)

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SPRAYING

History

In the 1950's and early 1960's spray irrigation began to be seriously considered as a procedure for disposing of wastewater such as the seasonal discharge from fruit and vegetable canneries, or for irrigation of pasture and forest land and golf courses. Spray irrigation has long been recognized as an effective method of supplemental irrigation of crops. It is applicable to all kinds of soils and to any condition of ground slope, as well as the utilization of small water supplies not practical under other methods of irrigation (USDA Farmers' Bulletin No. 1529, 1927). Its principal drawback was that it required pressure for operation. As relatively cheap electrical energy became widely available, the merits of spray irrigation far outweighed pumping costs and the practice became common on pasture land, alfalfa, sugar cane and other field crops. Research was directed to evapotranspiration rates and to changes in soil quality on which depend the most economical usage of water and the maintenance of optimum soil-water-crop relationships.

The feasibility of disposing of wastewater or producing useful vegetation was the subject of many investigations (Bloodgood, et al, 1964; Drake and Bieri, 1951; Hicks, 1952; Lawton, et al, 1960; Luley, 1963; Miller, 1953; Wilson and Beckett, 1968). Some attention was also directed to the upgrading of water quality via spray irrigation, particularly by the removal of nutrients from wastewater (Foster, et al, 1965; Hanks, et al, 1966; Hunt and Peele, 1968; Law, et al, 1969; Parizek, et al, 1967).

Environmental Consequences

A limited amount of data exist on the quality of percolating water from spray irrigation and on changes in the composition of groundwater where such irrigation has been practiced. At Paris, Texas, where grassland is irrigated with food processing wastes, removals of volatile solids and BOD range from 92 to 99 percent. Total nitrogen is reduced by 86 to 93 percent, while 50 to 65 percent of phosphorus is removed (Anon., 1970; Law, et al, 1969). No groundwater data are available, but samples of applied water taken at a 3-foot depth below the surface are low in nitrogen and phosphorus and show an increase in salinity with time. These data are consistent with those for septic systems and lagoons, based on extensive reported findings (McGauhey and Krone, 1967), with one difference: because spraying rates were adjusted to the water needs of grasses, nitrogen was taken up by plants. Inasmuch as the applied wastewater was similar to strong domestic sewage in terms of BOD, COD, and nutrients, it is evident that the potential of percolate from spray irrigation of vegetation to change groundwater quality is reduced in terms of nitrogen as compared to percolate from bare soil. Of course, if no vegetation were ever harvested, this difference would in the long run become extremely small.

Reduction in nitrogen by field crops and trees occurred also in a demonstration study of spray irrigation with sewage effluent made by the Pennsylvania State University (Parizek, et al, 1967; Pennypacker, et al, 1967).

In an earlier study of spray irrigation of forest land with sewage, most of the nitrogen in the sewage appeared in the groundwater (Larson, 1960; McGauhey, et al, 1963), as indicated in Table 2-13.

The Pennsylvania State study (Parizek, et al, 1967) included both water quality changes and groundwater effects of spray irrigation by a system shown schematically in Figure 2-5. A similar diagram of monitoring installations is shown in Figure 2-6.

Table 2-13. Groundwater composition before and after spray irrigation with sewage (Larson, 1960).

	14 October 1955 Before Spraying	21 November 1958 After Spraying
Total Hardness	300	420
Alkalinity	310	320
Chlorides	9	130
Nitrate Nitrogen	1	31.0
Nitrite Nitrogen	---	---
Ammonia Nitrogen	0.19	---
Organic	1.4	2.2*
Total Nitrogen	2.6	31.0
Total Phosphorus	0.6	2.9
Groundwater Level	11' 10.5" below top of well	8' 9.5" below top of well

*Kjeldahl Nitrogen (Ammonia plus organic)

Twelve inches of soil on the forest floor removed 95-98 percent of the ABS and 99 percent of the phosphorus. An increase in nitrate nitrogen appeared in the percolate. Thus, the results of spray irrigation compare favorably with those of surface ponds or subsurface percolation systems (McGauhey and Krone, 1967); however, a takeup of nitrogen by field crops and forest reduced the concentration of nitrogen moving with percolating water. Water quality measurements from deep wells showed the water at the irrigated site to be as good or better than that in off-site wells.

Existing evidence leads to the conclusions that:

- Spray irrigation of wastewater carrying plant and animal residues in varying degrees of biodegradation may have no measurable effect on nitrogen in groundwater if the system is operated as an evapotranspiration-nutrient stripping procedure.

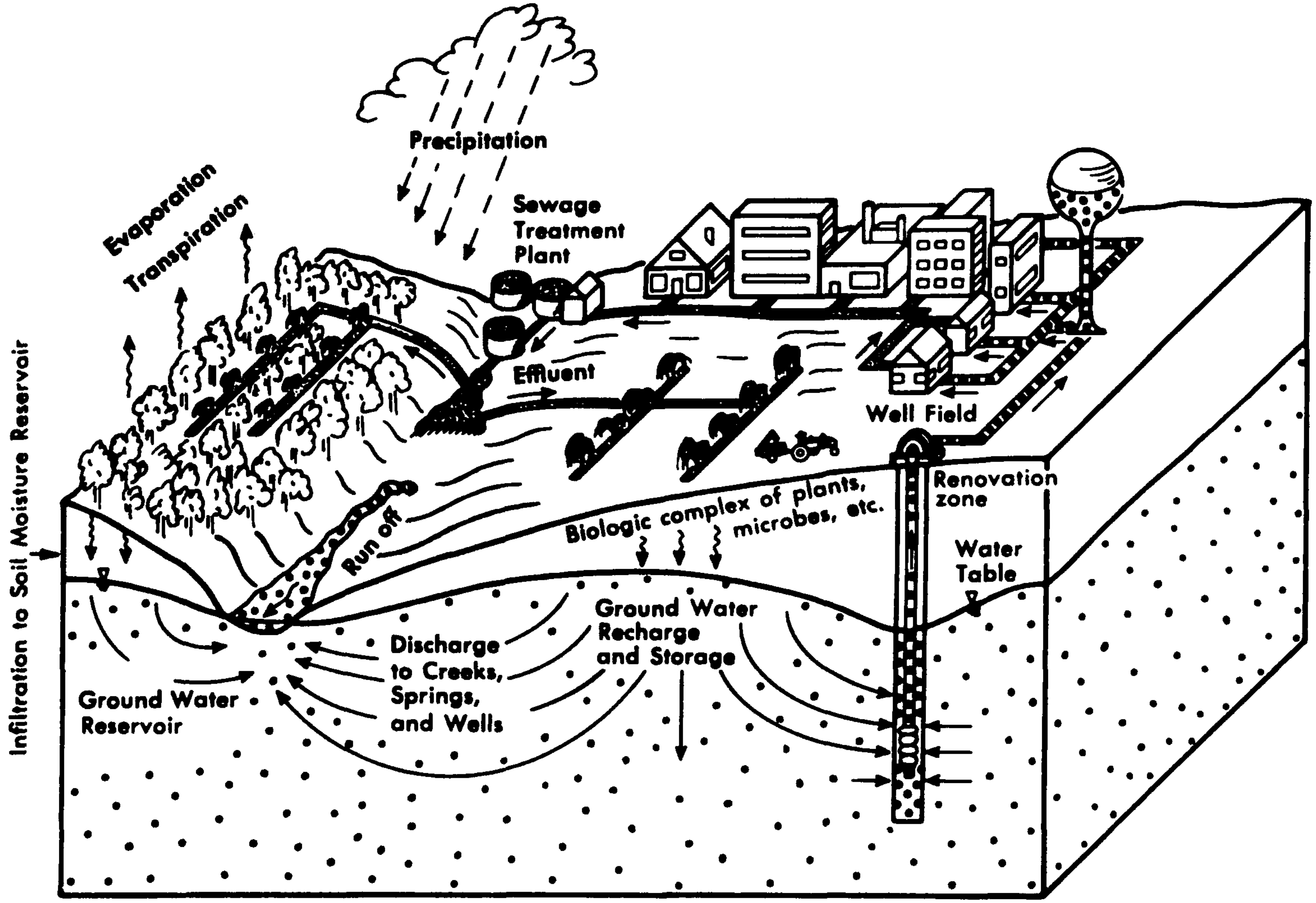
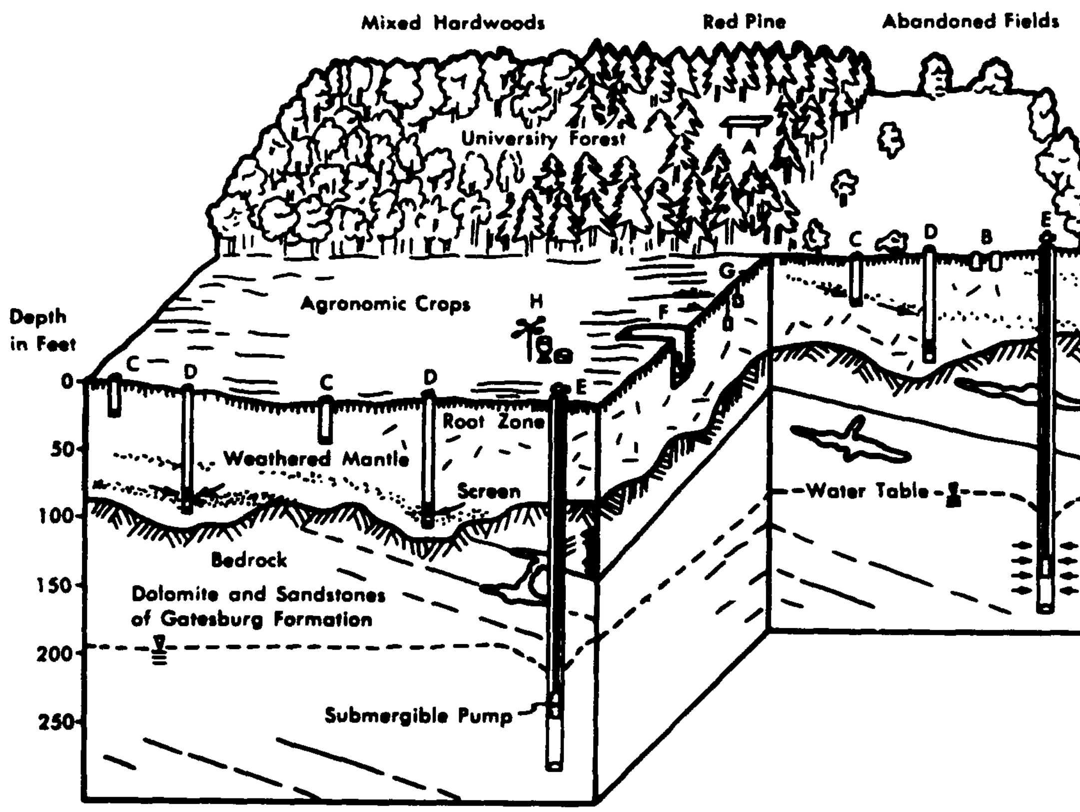


Figure 2-5. The wastewater renovation and conservation cycle (Parizek, et al, 1967).



A. Throughfall gauge

B. Lysimeters (In root zone at depth of 1½ inches to 4 feet).

C. Soil Moisture Access Tubes (To measure changes in soil moisture— 8 to 20 feet deep).

D. Sand-point Wells (completed in the weathered mantle at depths from 6 to 52 feet).

E. Deep Water-table Wells (Contain submergible or piston pumps, 250 to 300 feet deep).

F. Trench with pan lysimeters at one foot intervals to depths 6 and 16 feet.

G. Suction lysimeters, 6 inches to 26 feet in depth

H. Weather Station

Figure 2-6. Schematic of various types of monitoring installations (Parizek, et al, 1967).

- Over a period of time, leaching of salts from the root zone may become necessary. Normally, rainfall will carry such salts down to the groundwater. The effect on groundwater quality then depends upon the quality of the water supply from which the waste derives, and the amount and nature of soluble salts after any pretreatment of the wastewater and passage through the biologically active soil mantle.
- Fundamentally, spray irrigation is but one of several ways of applying wastewater to soil for percolation to the groundwater. It differs from lagoons and underground systems in that it affords a greater opportunity for wastewater to contaminate surface runoff during rainfall periods.

Future Prospects

Spraying as a method of wastewater disposal, nutrient removal, and water reclamation can be expected to increase in the future. Federal objectives envision that all sewage must be treated to at least a secondary level within the next few years. As the quality of treated wastewater increases so does its usefulness to man. There is a growing public mood of resource conservation, and more stringent attempts to achieve a condition of "no pollutant discharge" to surface waters. This leaves the land as the receptor of used water or, at least, of the soluble minerals which differentiate it from meteorological waters. Land disposal of either wastewater or its constituents can only mean that groundwater becomes the sink, unless special precautions to protect it are taken. One such system is to incorporate as many constituents of wastewater as possible into harvestable vegetation, or to tie it up in the soil and return the water directly to the atmosphere by evapotranspiration. Thus, spraying leads to a reduction in the potential of wastewater to affect the quality of groundwater. The potential of spraying to accomplish this result justifies its further practice.

Control Methods

Considering spraying as but one of several methods of applying wastewater to soil, no unique procedures for controlling its contribution to groundwater quality are evident. In the broader sense of minimizing the effects of land disposal of wastewater on groundwater quality, spraying might be recommended instead of surface ponding or subsurface irrigation because of its potential to remove nitrogen during the growing season and, simultaneously, to minimize the amount of water percolating to the groundwater. Offsetting this, however, are two factors:

- The possibility of sprayed water running off to surface waters, especially during storms, and so violating quality requirements established for surface waters.
- The ultimate movement of salts from the root zone to groundwater in amounts essentially the same as from surface spreading except for nitrogen and such other minerals as are taken up by vegetation.

Specific control measures which might be applied directly to wastewater generally serve to reduce the potential of spraying to affect groundwater quality. Eliminating the potential entirely requires a combination of partial demineralization, siting of the spray system, and operation of the system so that the sprayed water closely approximates the native groundwater in chemical constituents.

Specific control measures which might be applied directly to wastewater include:

- Limitation of the type of wastewater which can be applied to land to those which carry products of the natural cycle of growth and decay of organic matter; that is, to domestic sewage effluents and certain food and natural fiber processing wastes as contrasted with industrial wastes carrying chemicals and metal ions.

- Siting the spray operation where soil and geological conditions are favorable to land disposal systems.
- Operating the spray system to maintain a treatment potential of the aerobic soil mantle. This is especially important with cannery wastes because the startup time of any biological treatment system other than the soil system is too long to be useful in treating seasonal cannery wastes alone.

Control measures such as the foregoing confine the quality factors reaching the groundwater to those in the water supply, plus those added by biodegradation, and minus those which may be taken up by vegetation. The result may be a percolating water of better or poorer quality than the native groundwater, depending upon the total dissolved solids content of the groundwater and that of the applied (sprayed) water.

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STREAM BEDS

Scope of the Problem

Disposal of partly treated sewage and industrial wastes in the beds of intermittent and ephemeral streams is practiced mainly in the arid and semi-arid regions of the southwestern United States, particularly in California (Calif. State Water Quality Control Board, 1966; Calif. Dept. of Water Resources, 1966) and Arizona (Bouwer, 1968), where the more conventional method of disposal directly into a flowing stream may be impractical. Stormwater runoff also is discharged into beds of intermittent streams in many parts of the country. A benefit of all these procedures is the replenishment of the groundwater resources.

Effluent usually either percolates into the ground or is evaporated before it travels a great distance down the stream channel. During storms, the channel may contain substantial amounts of runoff, which scour out the bottom materials of the stream bed, carry away accumulated silts from natural and sewage sources, and dilute the contaminated water in and beneath the stream. Wastewater that infiltrates the stream bed in one reach may surface again down-gradient in the stream flow.

The infiltrative capacity of a stream bed varies with the nature of the geologic materials it contains. In reaches where the bottom materials consist of sand and gravel, infiltration is generally at a maximum (McGauhey and Krone, 1967). In other places, where pools and ponds may have previously clogged the bed with organic material and silt, the infiltrative capacity may be substantially reduced. Seasonal stormwater inflow that scours and cleanses the stream bed will restore its infiltrative capacity.

In contrast to the conditions described above, stream beds in the humid eastern part of the country are rarely dry except in the extreme headwater reaches. However, experiments have been planned for recharging tertiary-treated sewage effluent in the headwaters of several streams in southwestern Suffolk County, New York, to maintain the average flow of the streams for aesthetic and recreational purposes. These streams presently are fed by groundwater inflow, but it is anticipated that construction of a major sewer system in the next ten years will eliminate thousands of cesspools whose effluent is now a major source of groundwater recharge. It is expected that this reduction in recharge will result in a decline of the water table and in a substantial, if not a complete, loss of flow in the headwaters of the streams in the area.

Environmental Consequences

Disposal of wastes into stream beds may cause contamination of an underlying shallow aquifer. Generally, stream-bed percolation of wastes tends to increase the overall salinity of shallow groundwater. In those areas that depend partly or totally on groundwater for water supply, the polluted water may eventually arrive at pumping wells whose cones of influence intercept water from beneath the stream. The possibility of pollution is less for wells tapping deeper aquifers than for shallow aquifers, because of separation by confining beds of low permeability.

Even if there are no pumping wells in the vicinity, the wastes will tend to move down-gradient in the main body of groundwater and may eventually enter a stream and reappear as surface water. Such seepage of wastes that contain high concentrations of nutrients can cause excessive algae growth in the stream and thereby render the surface water unsuitable for various uses.

Inadequate pre-treatment or inadequate natural treatment during the movement of the water through the soil zone, or rapid leakage into shallow fractured rock, may introduce bacteria or toxic chemical substances into the aquifer.

A rise of the water table in the stream bed due to recharge may cause formation of pools and swamps containing partly treated wastewater, which may become septic, give off odors, and attract flies, mosquitoes, and miscellaneous vermin.

Nature of the Pollutants

The pollutants that enter an aquifer beneath a stream bed depend on the character of the wastes (domestic, industrial, or both), the type of stream bed material, the depth to the water table, and the type of treatment given to the wastes. In the case of domestic wastes, the potential pollutants include chlorides, organic compounds, nitrogen compounds in various stages of oxidation, phosphates, synthetic detergents, bacteria, viruses, and perhaps pesticides. If industrial or agricultural wastes are included, the spectrum of possible pollutants becomes very broad. From a general standpoint, those of greatest concern include heavy metals such as cadmium and chromium, and organics such as phenolics and polychlorinated biphenyls.

Pollution Movement

The principal route of the contaminated wastes is by downward percolation beneath the stream bed to the water table below the disposal area. From there the contaminated water moves down-gradient in the upper part of the main body of groundwater and may discharge into the stream at and below the start of flow in the channel (Figure 2-7). Where heavy infiltration causes the water table to rise close to the land surface or where a perched water table is created above beds of silt or clay in the unsaturated zone above the main water table, wastewater may emerge at the land surface and form local ponds or swampy areas.

Another possible condition involves a thin overburden containing a shallow water table in highly permeable beds of sand and gravel or a thin overburden underlain by fractured or fissured rock. In these cases, the wastes move down essentially directly into the groundwater with little or no natural treatment and may reach a stream or nearby wells with little

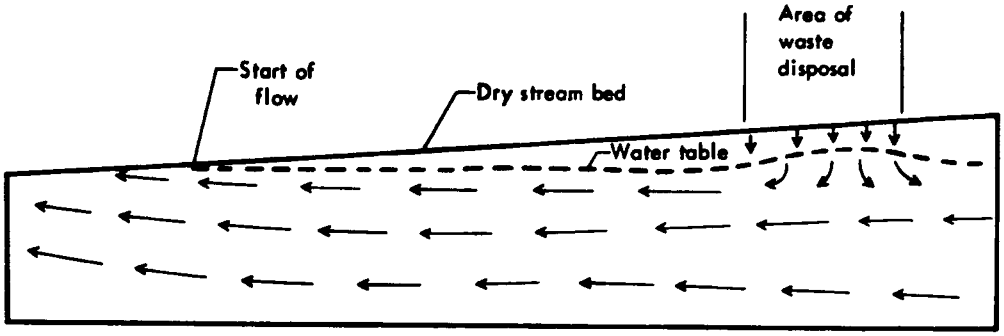

Figure 2-7. Pattern of flow from a liquid-waste disposal area in a dry stream bed. Movement of the contaminated water is along upper set of arrows indicating the direction of groundwater flow.

change other than dilution. This short flow path is particularly hazardous if pathogens are present in the waste. Where the depth to the water table below a stream bed is substantial, bacteria and organic chemicals may be largely removed by biochemical degradation during downward movement through the biologically active zone. However, it is likely that most dissolved inorganic constituents will eventually reach the water table.

Control Methods

To control pollution, most wastes before disposal into dry stream beds should be pre-treated to a level equivalent to secondary treatment or higher. A second line of defense is the natural renovation of wastewater in the ground by a combination of biological, physical, and chemical reactions. Thus, an important consideration for site selection is the ability of the earth materials to treat the wastes properly (Pennsylvania Department of Environmental Resources, 1972).

In unconsolidated materials such as sand and gravel, bacteria are commonly removed by natural phenomena. Viruses are also generally removed by movement through these materials, but the extent and mechanisms are still imperfectly known. In rock aquifers, and especially in some limestones, bacteria and viruses may travel long distances.

Dissolved organic constituents in domestic and some industrial wastes are removed or reduced in concentration by the natural flora of the soil, greatly reducing or eliminating biochemical oxygen demand of the wastes. At the same time, ammonia nitrogen, nitrite, and organic nitrogen are largely oxidized to nitrate, which may be a health hazard where the concentration exceeds 45 mg/ℓ as nitrate. A substantial reduction in total nitrogen may occur, depending upon the site and its operation (Bouwer, 1970).

Phosphates are commonly reduced or removed by direct chemical reaction and by adsorption. Heavy metals may be removed from industrial wastes by ion exchange, but the exchange capacity of individual soils varies widely. Chlorides move through the subsurface environment and often are used as tracers in determining the movement and concentration of wastes in the groundwater.

The selection of suitable waste-disposal sites in stream beds is also a key step in minimizing the pollution opportunity. The major factors in site selection (adapted from Bond and others, 1972) are summarized below:

- Soils. A knowledge of the detailed characteristics and depth of soil is critical in estimating the degree of natural renovation the wastewater will receive before reaching the water table. Deep, well drained, loamy soils are preferable. Clayey soils retard infiltrating water but maximize adsorption, while coarse soils may permit such rapid percolation that renovation is incomplete.

- Hydrology. The basic hydrologic considerations in evaluating a site are the depth of the water table, the direction and rate of movement of the groundwater, the location of induced or natural discharge, and possible changes in groundwater flow that may be caused by the buildup of a recharge mound under the stream bed. Seasonal water table fluctuations and high water tables, regardless of their cause, can lessen the effectiveness of the stream bed as a mechanism for natural treatment of the wastes. A minimum depth to the water table of 10 feet below land surface is commonly recommended (Pennsylvania Department of Environmental Resources, 1972). However, upward mounding in some hydrogeologic environments may require greater initial depths to the water table.

- Geology. The geologic characteristics of the overburden and the underlying rock have a very important bearing upon the suitability of a site. The overburden and the rock must be sufficiently permeable to permit continued downward percolation of the wastewater. Otherwise perched water tables will form, and the aerobic zone will be reduced and possibly eliminated.

- Reaction of the effluent with the overburden. Effluents have different constituents; the chemical reactions that occur between those constituents and the constituents of the overburden should be determined experimentally before disposal operations are started.

- Topography. The effluent should spread freely and should not accumulate in puddles or ponds.

- Rate of infiltration. The infiltrative capacity of the soils to accept wastewater should be determined by testing and experimentation, as this will help to determine the required size of the disposal area. Proper maintenance of the stream bed materials is essential to sustain aerobic conditions.

If retention or stabilization ponds are used, with periodic discharge of effluent, the above listed criteria still should be considered. In addition, the ponds should be designed so that they will provide aerobic conditions. For example, intermittent application of the waste effluent and rotation of the disposal of the wastes from one area to another are essential to reoxygenation of the soil, and hence to the maintenance of an aerobic environment. Application rates must be kept at levels that do not exceed the infiltration capacity of the soil. Vegetative cover will normally improve infiltration, but may require periodic harvesting. Harrowing of the disposal areas may be desirable, should the surface layer become compacted or clogged.

Monitoring Procedures

Monitoring wells installed beneath and near the stream channel may be used to determine the subsurface paths of flow and changes in quality as the water moves down-gradient from the area of infiltration. Monitoring wells also may be installed between the stream channel and nearby supply wells to provide advance warning of possible movement of contaminated water toward the wells.

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LANDFILLS

The Matter of Definition

To evaluate the effects of land disposal of solid wastes in the context of "landfills," it is necessary to recognize an unfortunate lack of distinction between the properly designed and constructed sanitary landfill and the variety of operations that are properly classed as refuse dumps. Therefore, a landfill is herein defined as any land area dedicated or abandoned to the deposit of urban solid waste regardless of how it is operated or whether or not a subsurface excavation is actually involved. Urban, or municipal, solid waste is considered to include household, commercial, and industrial wastes which the public assumes responsibility for collecting. However, commercial solid waste and industrial solid wastes presently collected and hauled privately may be discharged into a public landfill, along with municipal wastes and refuse which the citizen himself delivers.

A survey made by the Glass Container Manufacturers Institute (Environmental News Digest, Nov.-Dec. 1970) reported that only 8 percent of the estimated 250 million tons of municipal solid waste generated each year goes into proper sanitary landfills. About 75 percent goes into refuse dumps which are environmentally unsatisfactory. The remaining 17 percent is incinerated or composted. Only a few citizens, therefore, have ever seen a good landfill, hence the term generally evokes the image of a dump. It is then easy for the individual, and often the public agency, to infer as an article of faith that leachate from landfills is an ever-present environmental evil. As a matter of fact, leaching from a modern well-designed and properly operated sanitary landfill is more fancied than real, whereas leaching from open dumps may be both real and extensive. Therefore, in dealing with the problem of protecting groundwater quality through control of leachate from refuse, a distinction must be made between control measures built into new or existing well-engineered landfills and control measures appropriate to existing dumps and poorly-engineered landfills.

Environmental Consequences

The potential hazard of landfills to groundwater quality via leachate is a function of the total amount of waste generated, its areal distribution, the composition of the waste itself, and the siting, design, and operation of the fill. The US Environmental Protection Agency estimated that in 1969 urban solid waste totaled 250 million tons per year, while industrial solid waste was about 110 million tons. Various estimates of this total for 1972 are about one ton per capita per year — almost 6 pounds per person per day. In 1970 (EPA, 1972) there were some 16,000 authorized land disposal sites, and perhaps 10 times that many unauthorized dumping grounds. Because wastes are generated and disposed of where people are, the pattern of population distribution gives a clue to the location and intensity of landfill practice.

Typical values of components of solid wastes collected in urban communities are shown in Table 2-14. From Table 2-14 it may be concluded that slightly over 70 percent of domestic refuse is biodegradable organic matter of which about three-quarters (50 percent of total waste) is paper and wood. An additional fraction ranging from 1 to 15 percent in the table involves materials which might include some leachate solids such as ashes and certain soils. Studies made in Berkeley, California in 1952 and repeated for the same area in 1967 (Golueke and McGauhey, 1967) verify this conclusion and show that the percentages of individual components changed very little over the 15-year period.

Data on the amount and composition of industrial solid wastes and on its disposal are less extensive. A survey (Manufacturing Chemists Association, 1967) of 991 chemical plants, of which 889 were production facilities is reported in Table 2-15. It shows that 75 percent of waste solids were non-combustible process solids and that 71 percent of the

Table 2-14. Components of domestic solid waste (expressed as percentages of total).

	Santa Clara[a]	Los Angeles[b]	Louis-ville[c]	Quad-Cities N. J.[d]	Purdue Univ.[e]	23 Cities[f]	Madison Wis.[g]	National Avg.[h]
Paper Products	50	41	60	45	42	46	52	50
Food Wastes	12	6	18	[i]	12	17	10	15
Garden Wastes	9	21	--	[i]	12	10	8	5
Plastics	1	2	--	2	1	1	2	3[j]
Cloth, Leather, Rags, Rubber	4	2	--	5	2	4	4	2[k]
Wood	2	2	--	[i]	2	3	2	2
Rocks, Dirt Miscellaneous Unclassified	7	12	3	10	15	1	--	7
Metals	8	6	9	9	8	9	7	8
Glass and Ceramics	7	8	10	6	6	9	15	8

a. EPA, 1970; University of California
b. Bergman, 1972
c. EPA, 1970; University of Louisville
d. US Public Health Service, 1968
e. Bell, 1963
f. Niessen and Chanskey, 1970
g. Ham, 1971
h. Salvato, et al, 1971
i. Total 3 categories ≈ 23 percent
j. Includes rubber
k. Rubber included with plastics

total was disposed of by landfill on company-owned property. No data are at hand on the composition of these wastes but it must be presumed that some fraction of the total was leachable if conditions leading to leaching occurred.

Table 2-15. Landfill disposal of chemical process wastes.

	Total Per Year (Thousands of Tons)	Percent Total
Type of Waste		
Process solids, non-combustible	8,404	75
Process solids, combustible	573	5
Containers, non-combustible	64	1
Containers, combustible	168	1
Fly ash from fuel combustion	1,587	14
Other, or unspecified	466	4
	11,262	
Disposal Method		
Landfill on company property	8,067	71
Landfill away from company property	520	5
Incineration, with heat recovery	92	1
Incineration, without heat recovery	231	2
Open dump burning	109	1
Contracted disposal	1,627	15
Other, or unspecified	616	6
	11,262	

Leaching of Landfills

Leaching of landfills with consequent contributions to underlying groundwater depends upon several factors. These, together with measures for control were summarized in 1971 (Salvato, et al, 1971).

If a landfill is to produce leachate there must be some source of water moving through the fill material. Possible sources include (1) precipitation, (2) moisture content of refuse, (3) surface water infiltrating into the fill, (4) percolating water entering the fill from adjacent land area, or (5) groundwater in contact with the fill. In any event, leachate is not produced in a landfill until at least some significant portion of the fill material reaches field capacity. To accomplish this, 1.62 inches of water per foot of depth of fill is reported to be necessary (Qasim and Burchinall, 1970). This value is far in excess of that which might be produced from a typical mixed refuse. Moisture in refuse is about 20 percent by weight (Kaiser, 1966; Bell, 1963). Because of the high paper content and the relatively inert material shown in the typical analyses, Table 2-14, only a small amount of moisture is released by the decomposition of the organic solids in refuse. A composite sample (Bell, 1963) of an average municipal refuse is shown in Table 2-16.

Table 2-16. Composition of municipal refuse.

	Percent
Moisture	20.73
Cellulose, sugar, starch	46.63
Lipids	4.50
Protein - 6.25N	2.06
Other organics	1.15
Inerts	24.93
	100.00

To induce composting, a moisture content of 50 to 60 percent is required, hence a fill having no source of moisture except that of urban refuse will decompose very slowly and produce little if any leachate. On the other hand, if a fill were made of fruits and vegetables having 80 to 90 percent moisture, anaerobic decomposition would proceed rapidly and leachate would be produced. Thus, landfill is not recommended for cannery wastes alone. In areas such as the Pacific Northwest where rainfall occurs almost daily during the winter season, and in other regions of the nation where summer rains are frequent and intense, it may be difficult to place refuse in a fill without its becoming saturated with water. The normal technique of spreading refuse on a working face and compacting it by running equipment over that face exposes thin strata of refuse to moisture before it is compacted and covered. Thus, special control measures may be required, as hereinafter described, to deal with leachate.

Once unsaturated refuse is incorporated in a finished landfill, properly designed and constructed, percolating water from surrounding land is not likely to enter. Even at the density of 750 to 850 pounds per cubic yard attained in compacting many landfills, the fill material is difficult to saturate. The important factor then is to get the refuse into the fill and compacted and covered without its becoming saturated.

If other sources of water are excluded from a landfill by employing procedures described later, the production of leachate in a well-designed and managed landfill can be effectively eliminated. A proper landfill not intersecting the groundwater will not cause water quality impairment for either domestic or irrigation use. Reports (Sumner, 1972) of test borings around landfills dating back as far as 50 years in England showed no evidence of groundwater pollution as a result of leaching. Similarly, no evidence was found (Stolp, 1972) in Holland that past landfilling has been a source of pollution of groundwater. According to reports from Illinois and Minnesota (Anon., 1973; Saxon's River Conference, 1972) groundwater was not contaminated by two major fills built within the groundwater itself. Compaction of fill material, clogging of fill area walls (McGauhey and Krone, 1967), and balanced hydrostatic pressure cause groundwater to flow around the fill rather than through it.

Absence of leaching as an important problem is characteristic of landfill sites engineered and constructed in accord with best current technology. In this category are most of the sanitary landfills comprising 8 percent of the present land disposal situations, and presumably those yet to be built in the future. The 75 percent of urban refuse placed in dumps which in varying degrees are open to external sources of water are likely to produce leachate in significant amounts. It is estimated (Salvato, et al, 1971) that of 49 inches annual rainfall in New York, 45 percent will infiltrate into an unsealed and unprotected dump. At some seasons of the year up to 70 percent of the infiltrated water may be returned to the atmosphere by evapotranspiration. The remainder, and at times all, of the infiltrate will percolate through the landfill. If the fill is in a subsurface excavation, this percolate will move downward to the groundwater at a rate governed by the degree of clogging of the underlying and surrounding soil. Clogging, however, may reduce permeability at the infiltrative surface (McGauhey and Winneberger, 1964; McGauhey and Krone, 1967); it cannot be assumed that the landfill will long discharge leachate at an appreciable rate. It may tend to become essentially a basin filled with saturated refuse and soil. Further rainfall will then run off the fill surface without coming in contact with refuse. However, if leachate is produced within a fill and soil clogging controls its escape to the groundwater, a large fill area even at a low rate of movement into the underlying strata could with time discharge a significant volume of leachate.

Not all unsatisfactory landfills are built in subsurface excavations. Many are in ravines or above the original land surface. In these cases clogging beneath the fill is not the controlling factor. Infiltrated water outcrops laterally on the surface as leachate. There it flows on the soil surface over such an area as necessary for infiltration, or runs off in the surface stream system.

The amount of water which may pass through an open dump is significant. Once field capacity is reached, 36 inches of rainfall per year upon an open shredded refuse fill would (theoretically) percolate about 1 million gallons of contaminated water per acre (Salvato, et al, 1971). In reality, however, this amount would be significantly reduced by evaporation from the fill surface.

A secondary leaching phenomenon associated with all types of landfills not subjected to specific controls is the result of CO_2 generated in the fill being forced outward into the surrounding soil. When picked up by percolating rain water, this increases the aggressiveness of water to limestones and dolomites and so increases the hardness of groundwater. A refuse of the composition shown in Table 2-16 is theoretically capable of producing 2.7 cubic feet of CO_2 per pound of refuse (Anderson and Callinan, 1969). However, the balance of nutrients, the moisture, and other environmental factors are unlikely to exist over the time span necessary for any such complete destruction of the carbonaceous fraction of refuse.

Despite what is known, or postulated, from existing evidence about the leaching of refuse in landfills, the environmental consequences of landfill practice cannot be fully evaluated. Therefore, an extensive program of research is needed before the relative importance of leachate as a pollutant of groundwater can be assessed.

Nature and Amount of Leachate

Data on the analysis of leachate vary widely. Much of it comes from short-term lysimeter studies in which researchers had to make special efforts to saturate the refuse so as to produce maximum leaching. Thereafter, experiments were often terminated before the leaching rate reached an equilibrium. Data on leachate from several sources are summarized in Table 2-17 (Salvato, et al, 1971).

Table 2-17 indicates what many observers have reported: the initial values of BOD and COD are always high. Studies of operating landfills (Emrich and Landon, 1969; California State Water Pollution Control Board, 1954) show constituents of leachate to include:

Table 2-17. Leachate composition.

Determination (mg/ℓ, except pH)	Source[a]					
	1[b]	2[b]	3[b]	4[c]	5[c]	6[c]
pH	5.6	5.9	8.3			
Total hardness ($CaCO_3$)	8,120	3,260	537		8,700	500
Iron total	305	336	219	1,000		
Sodium	1,805	350	600			
Potassium	1,860	655	no result			
Sulfate	630	1,220	99		940	24
Chloride	2,240	no result	300	2,000	1,000	220
Nitrate	no result	5	18			
Alkalinity as $CaCO_3$	8,100	1,710	1,290			
Ammonia nitrogen	815	141	no result			
Organic nitrogen	550	152	no result			
COD	no result	7,130	no result	750,000		
BOD	32,400	7,050	no result	720,000		
Total dissolved solids	no result	9,190	2,000		11,254	2,075

a. No age of fill specified for Sources 1-3, Source 4 is initial leachate composition, 5 is from 3-year old fill, 6 is from 15-year old fill.
b. Data from Los Angeles County (1968).
c. Data from Emrich and Landon (1969).

COD	~	8,000-10,000 mg/ℓ
BOD	~	2,500 mg/ℓ
Iron	~	600 mg/ℓ
Chloride	~	250 mg/ℓ

Table 2-17 also shows hardness, alkalinity, and some ions to be significantly increased. The California data also show that continuous flow through one acre-foot of newly deposited refuse might leach out during the first year approximately:

Sodium plus potassium	1.5 tons
Calcium plus magnesium	1.0 tons
Chloride	0.91 tons
Sulfate	0.23 tons
Bicarbonates	3.9 tons

Rates for subsequent years were expected to be greatly reduced.

Field studies of the amount and quality of leachate through well-designed fills have been made by the Los Angeles County Sanitation Districts. At their Mission Canyon Landfill, underdrains were installed beneath two large fills to entrap leachate (Dair, 1967; Meichtry, 1971). One was installed in 1963; the other in 1968. At the time of Meichtry's report (1971) the first of these two had produced nothing but odorous gases although the fill was heavily irrigated from 1968 onward. The second, deeper fill produced odorous gases but no leachate until March 1968 when 4.35 inches of rain fell in 24 hours. On that occasion 213 gallons of leachate were collected. Flow then continued at a rate of about 1,500 gallons per month. Periodic analysis of the leachate indicated that a spring in the canyon wall beneath the fill, rather than infiltration of the fill, was the source.

Table 2-18 shows both the initial composition of the leachate and its reduction with time over a 3-year period. The table shows a decrease in concentration of most constituents of the leachate with time. This same phenomenon has been observed in comparing a 27-year old abandoned fill with an active fill (Emrich and Landon, 1969).

Pilot studies were made in 1964 to 1966 (Merz and Stone, 1967; Dair, 1967; and Meichtry, 1971) to study the effects of rainfall and irrigation on landfill leaching. Two cells 50 feet square at the bottom and sloped to the top were filled with a single 19-foot lift of refuse, plus a two-foot earth cover. Devices to collect leachate at various depths were installed. One was subjected to simulated rainfall; the other to irrigation of turf. After 27 months and 130 inches of rainfall no leachate appeared in the rainfall cell. A small amount of water appeared in the topmost cell of the irrigated system at 27 months and 169 inches of applied.

Table 2-18. Change in leachate analysis with time (Meichtry, 1971).

Constituent	Leachate Analysis Mission Canyon Landfill	
	3-18-68	3-24-71
pH	5.75	7.40
Total Solids, mg/ℓ	45,070	13,629
Suspended Solids, mg/ℓ	172	220
Dissolved Solids, mg/ℓ	44,900	13,409
Total Hardness, mg/ℓ $CaCO_3$	22,800	8,930
Calcium, mg/ℓ $CaCO_3$	7,200	216
Magnesium, mg/ℓ $CaCO_3$	15,600	8,714
Total Alkalinity, mg/ℓ $CaCO_3$	9,680	8,677
Ammonia, mg/ℓ N	0.0	270
Organic Nitrogen, mg/ℓ N	104	92.4
BOD, mg/ℓ O	10,900	908
COD, mg/ℓ O	76,800	3,042
Sulfate, mg/ℓ SO_4	1,190	19
Total Phosphate, mg/ℓ PO_4	0.24	0.65
Chloride, mg/ℓ Cl	660	2,355
Sodium, mg/ℓ Na	767	1,160
Potassium, mg/ℓ K	68	440
Boron, mg/ℓ B	1.49	3.76
Iron, mg/ℓ Fe	2,820	4.75

Such experiments as the foregoing support the conclusion previously cited that leachate from well-designed fills is not a significant problem.

The time required to produce leachate from a fill penetrated by rainfall can be predicted by moisture-routing techniques (Remson, 1968). For example, an 8-foot lift of refuse with 2 feet of earth cover will take from one to 2-1/2 years to reach field capacity and produce leachate if 44 inches of rainfall is allowed to infiltrate and percolate into the fill.

The nature of leachate reaching groundwater depends its passage through soil systems. Reduction in BOD of leachate was observed to be 95 percent during travel through 12 feet of soil (Emrich and Landon, 1969). The ability of aerobic soil systems to stabilize organic matter is well known (McGauhey and Krone, 1967); consequently, an increase in dissolved minerals is the effect on groundwater to be expected from leachate infiltrating surface soils. Fills which produce leachate that is not discharged to the soil surface soon develop an underlying anaerobic zone of clogging. Leachate which passes through this zone of clogging may be expected to be high in BOD, COD, and tastes and odors. These quality factors may be little changed in the groundwater except by dilution until the groundwater outcrops or is withdrawn through a well and becomes reseeded with aerobic organisms. In reality it makes little difference whether a leaching landfill is above or in contact with the groundwater because in either case there is no biologically active zone to change the nature of the pollutants. However, if groundwater in contact with refuse is the leaching medium, any rise and fall in the water table may have a surging effect and so accelerate the pickup and mixing of groundwater and leachate. In one field observation (Hassan, 1971) a landfill partly inundated by groundwater was investigated. Well water 325 meters down gradient from the fill showed leachate effects in terms of hardness, alkalinity, Ca, Mg, Na, K, and Cl. At a distance of 1,000 meters the effects were undetectable. Inasmuch as the fill was an old one it might be concluded that the groundwater was not seriously affected. However, similar studies in Germany revealed the presence of leachate effects in groundwater 3,000 meters away.

The nature of leachate can be expected to change as years go by. Present trends toward greater use of garbage grinders can significantly reduce the BOD of leachate. For example, Table 2-14 shows only 6 percent food wastes in Los Angeles, where household garbage grinders are common, as compared to the 15 percent national average. Moreover, the increasing use of plastics increases the content of inerts. Future use of refuse fiber for energy production could eliminate most organic matter and increase the content of leachable ashes in urban refuse.

In the case of industrial wastes disposed of by landfill on company property, little is known of the nature and extent of leachate. Table 2-15 shows that non-combustible solids represent 75 percent and ashes another 14 percent of the total. These data suggest that soluble minerals are the most common materials which might be leached from industrial waste fills. In terms of groundwater pollution oil, process sludges, and salt solutions from lagoons and pits are likely to be the most significant industrial wastes.

Control Methods

In general, procedures for the control of leachate are those which exclude water from the landfill, prevent leachate from percolating to the groundwater, or collect leachate and subject it to biological treatment. Obviously, the possible utilization of these three approaches is maximum in the design phase of a landfill operation and minimal in some types of existing landfills.

In existing situations the potential of a landfill to pollute groundwater can be limited by such procedures as:

- Separating at the source wastes which are unacceptable in a given landfill situation
- Controlling haulers by requiring permits and by enforcing
- Licensing private haulers of industrial wastes.

In the case of a new projected landfill the control measures include:

- Select site to achieve both general regulations and specific objectives. Typical of the general measures for siting control are those of Los Angeles County which recognize three classes of fills:
  - Class I, which may accept all types of solid wastes by reason of its geologic isolation from any contact with the groundwater. This type of site is essentially an impervious bowl, and hence is not common.
  - Class II, which may accept the normal run of mixed municipal solid refuse (no waste oils, or chemical sludges).
  - Class III, which may accept only inert earth-type materials.

  Specific siting involves evaluation of alternate locations by hydrogeologists and engineers to determine such things as:
  - Location and depth of groundwater in the vicinity.
  - Importance of underlying groundwater as a resource, both present and future.
  - Nature of geology of the site.
  - Feasibility of excluding both surface water and groundwater from the finished fill.
- Design landfill to correct deficiencies of best available site:

- Use compacted earth fill to seal walls and bottom of fill site. If the fill is above groundwater, as is most commonly required, this will minimize the rate of escape of leachate from the fill. If the fill is in groundwater the movement of the groundwater into and out of the fill will be minimized.
- Provide underdrainage system to collect leachate and deliver it to a sump.
- Drain sump to surface by a valved pipe or by a vertical well into which a submersible pump may be inserted, if necessary, to collect and deliver leachate for biological treatment.

• Construct fill with purpose of keeping the minimum of refuse surface exposed to rainfall, and the working surface and site well drained. Use dike and fill technique to isolate fill from unfilled area.

• Utilize water for dust control during construction in such amounts that evaporation rather than infiltration is its fate.

• Divert surface water from the fill site during and after fill construction by means of peripheral bypass drains.

• Compact and slope fill cover for good surface drainage; vent gases through the fill cover with j-vents.

• In areas of prolonged rainfall, construct fill with underdrains, sump, and necessary piping for removing leachate which may result from saturation of the refuse during fill construction. In some situations it may be necessary to bale the refuse under cover and to construct the fill of compacted baled refuse which is then promptly covered and surface drained.

In new or existing landfills:

- Provide continuing maintenance of the graded finished fill cover; fill in and regrade surface as shrinkage of the fill causes cracks or depressions which might serve to increase infiltration.
- Seed completed fill surface with a high transpiration cover crop.
- Avoid over irrigation of surface plantings.
- Divert both surface and groundwater around fill site where feasible.
- Reduce the amount of putrescible solid waste by initiating regional reclamation activities under a statewide authority which features energy conversion of the organic fraction of refuse.

In the case of existing landfills and dumps:

- Intercept polluted groundwater at the fill site by well points in or near the fill area if the situation is serious.
- Initiate and implement statewide programs of waste management which feature regional landfills, thus replacing numerous small refuse dumps with landfills on an economic scale, and so phasing out with time the leachate contribution to groundwater.

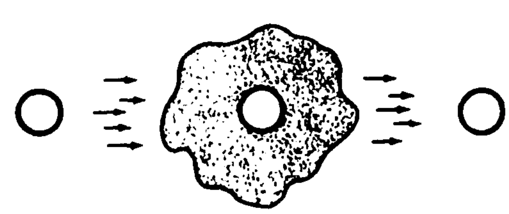
Of the foregoing control measures only those which are applicable to new sanitary landfills have the potential to prevent or essentially to eliminate the possibility of groundwater pollution by leachate. Siting, constructing, operating, and maintaining fills are in this category of control measures. Existing well-engineered landfills, although not usually equipped with underdrains, generally have minimal effects upon groundwater quality and hence are of secondary importance in comparison with dumps. Similarly, old landfills may have contributed the major portion of their leachate already and are now of secondary importance. Reshaping the soil surface and maintaining surface drainage are measures which reduce the effect of leachate from existing fills. The overall effect of dumps may be lessened by a geographical distribution of the volume of wastes they contain. Control measures such as well-point interception reduce rather than prevent or eliminate leachate discharges. Regionalization of new sanitary landfills is a control measure which can reduce and eventually phase out the leachate from existing dumps.

Monitoring Procedures

In new fills, properly engineered and sealed off from underlying and sidewall strata, the drainage system and a pumped well located in or near the fill can be used both for inspection (monitoring) and for control.

A system of three observation wells (Hughes, et al, 1968) is illustrated in Table 2-19 along with the results of groundwater quality observations.

Table 2-19. Groundwater quality.



Groundwater Characteristic	Background (mg/liter)	Fill (mg/liter)	Monitor Well (mg/liter)
Total Dissolved Solids	636	6712	1506
pH	7.2	6.7	7.3
COD	20	1863	71
Total Hardness	570	4960	820
Sodium	30	806	316
Chloride	18	1710	248

It would be feasible to drill and gravel pack a sampling well in a landfill, then seal its bottom and drill through to the groundwater below. Portable submersible pumps could be used to pump these two essentially concentric wells for sampling purposes. An alternative might be to drill a pumped monitoring well downstream from the landfill or directly through the fill. Concentrations of TDS, hardness, and chlorides could be measured and used to surmise the presence of leachate, provided the discharge rate needed to produce a significant drawdown cone under the fill did not obscure the effect of leachate on the groundwater quality.

In any event the best procedure is the use of control measures which minimize the possibility of leaching of landfills and which, consequently, reduce the need to search for underground pollutants and to assess their concentration in groundwater.

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SECTION III

INDIRECT DISPOSAL OF POLLUTANTS

SEWER LEAKAGE

Scope of the Problem

Gravity sewers above the groundwater table and pressure outfalls either above or below that table are common elements of the domestic sewerage system of organized communities. Seasonally, storm sewers involving underground conduits and lined and unlined open channels carry runoff from paved and unpaved land surfaces. Essentially all of these conduits are sited to accomplish drainage objectives.

Many major sewer systems had their beginnings at least a century ago and some of the early sectors of these systems are still in use. Over this long period, construction materials and methods have changed profoundly as the total length of sewers grew to tens of thousands of miles. Joints in many of the gravity sewer systems carrying domestic sewage number from 1,000 to 2,000 per mile. Joining materials have ranged through the years from cement mortar to asphaltic and similar special compounds and to plastic O-rings and heat-shrinkage joint covers.

Causal Factors

The potential of a municipal sewage system to contaminate groundwater is both varied and variable. Conceptually, a sewer is intended to be water-tight and thus to present no hazard to groundwater except when temporarily disrupted by accident. In reality, however, leakage is a common occurrence, especially from older sewers. Leakage in gravity sewers may result from causes such as:

- Poor workmanship, especially at the time cement mortar was applied by hand as a joining material
- Cracked or defective pipe sections incorporated in the sewer.

- Breakage of pipe and joining material by tree roots penetrating or heaving the sewer line
- Displacement or rupture of pipeline by superimposed loads, heavy equipment, or earthfill on pipe laid on a poor foundation
- Rupture of pipe joints or pipe sections by slippage of soil in hilly topography
- Fracture and displacement of pipe by seismic activity; eg, a sewerage system in California still suffers from fractures caused by an earthquake in 1909
- Loss of foundation support due to underground washout
- Poorly constructed manholes or shearing of pipe at manholes due to differential settlement
- Infiltration surcharging the system and causing sewage to back up into abandoned sewer laterals.

Environmental Consequences

Except at times of heavy infiltration during storms, which may surcharge a system, the piezometric pressure inside a gravity sewer laid above groundwater is small. The static head may vary from a maximum equal to the pipe diameter to a minimum of perhaps 20 percent of that diameter. Consequently, the rate of leakage accompanying several of the cited failures is quite small. In fact, some small leaks become stopped through clogging of the opening by suspended solids. Major fractures may release an appreciable amount of sewage which moves along the pipe foundation as the soil clogs, causing the trench locally to function like the percolation system of a septic tank.

Materials escaping from a sewer via leakage is raw sewage, which may be actively decomposing, together with such industrial waste chemicals as may be present in the sewer. Thus, if a sewer is deep underground and close to the groundwater, pollutants may be released below the biologically active zone of the soil and so introduce into the receiving groundwater BOD and COD as well as chlorides and unstable organics productive of tastes and odors. Because this tendency is partly offset by the clogging of soils under anaerobic conditions, the true effect of sewer leakage on groundwater quality is probably far less than the theoretical potential.

If a fractured sewer is below the groundwater table, infiltration rather than leakage is the result. If infiltration is seasonal and leakage occurs part of the year, the effect of the intermittent flow may be to unclog the system and so maintain a higher seasonal leakage rate than that of year-round leakage.

Pressured outfall sewers are normally made of cast iron, steel, transite, or concrete pipe. Except in very large diameters they have fewer joints per mile than gravity sewers, and the joining is less likely to be of poor quality or so readily ruptured. Because of superior construction and engineering attention, the outfall sewer is not often a threat to groundwater quality. Due to the internal pressure when leakage does occur, it is normally outward regardless of whether the pipe is above or below the water table. Small openings may clog but most commonly sewage is injected into soil or groundwater directly. It may appear on the surface of the soil or outcrop on a hillside where it is easily detected by sight and odor.

The effect of storm drains is generally to hasten the flow of surface water to a surface stream. Therefore, it is likely to have less potential than uncontrolled surface runoff to spread the oils and soluble matter from streets, fertilized land, and pesticide-treated gardens over infiltrative surfaces feeding the groundwater.

Looking to the future, it seems certain that sewer leakage will be less of a hazard to groundwater than at present, even though the extent of sewer systems is certain to increase to accommodate the growth and urbanization of population. The principal reasons are improved construction and maintenance practices:

- Both new sewers and replaced old lines are laid with joining materials which are water-tight and also permit some change in pipe alignment without fracturing
- Better construction methods are practiced by contractors
- More rigid specifications and better inspection characterize the larger units of government now responsible for sewerage
- Equipment for photographing or televising the interior of a pipeline is available and increasingly used to locate leaks and fractures in a sewer system
- Municipal public works departments, using their own personnel or private contractors, are increasingly and systematically surveying the condition of sewers within their jurisdictions in a "search and destroy" program of sewer repair and maintenance
- Sewer maintenance has become a special division of public works departments, and both the Water Pollution Control Federation and its member societies conduct annual short courses and training programs in the technology of maintaining sewers.

Control Methods

Procedures for controlling the potential of sewer leakage to degrade groundwaters are implicit in the improved practices listed above. The sewerage system of a large community is an infinite point system of possible leaks. Moreover, the system is underground and hence not subject to control by surface observation and repair. Therefore, the most productive control program has the following features:

- A public policy of maximum protection of groundwater as a part of an overall concern for resource conservation
- An organized and identified responsibility for sewer construction and maintenance in the community
- Formulation and modernization of codes and specifications for sewer construction as a state rather than a city responsibility, together with appropriate inspection procedures
- A program of internal and external inspection of existing sewers at five-year intervals to detect and repair major leaks or to replace unrepairable sectors of the sewer system
- Emphasis on training of sewer maintenance personnel
- Exclusion from discharge to municipal sewers of any materials found to be irretrievably hazardous to groundwater.

<u>Monitoring Procedures</u>

As in the case of lagoons, basins, and pits, monitoring of groundwater quality in relation to sewer leakage is best accomplished by a program of collection and evaluation of groundwater data in each metropolitan area. Similarly, surveillance of the control procedures should be maintained so as to prevent and to correct leakage.

TANK AND PIPELINE LEAKAGE

Scope of the Problem

In the United States underground storage and transmission of a wide variety of fuels and chemicals is a common practice for commercial, industrial, and individual uses. Unfortunately, the pipes and tanks are subject to structural failures from a wide variety of causes and the subsequent leakage then becomes a source of contamination to local groundwaters. European countries also have experienced these problems; their technical literature is well worth consulting.

This section describes the nature and occurrence of tank and pipeline leakage and summarizes the practices that have been found effective in the control and abatement of groundwater pollution. Emphasis in this section is on petroleum products because they are the majority of materials stored or transmitted in subsurface excavations.

Leakage of petroleum and petroleum products from underground pipelines and tanks may be much more pervasive than is generally realized. This is particularly true for small installations such as home fuel oil tanks and gasoline stations, where installation, inspection, and maintenance standards may be low. In Maryland, where standardized investigative procedures have been adopted, some 60 instances of groundwater pollution were reported in a single year from gasoline stations (Matis, 1971). In northern Europe, where most homes are heated by oil stored in subsurface tanks, oil pollution has become the major threat to groundwater quality (Todd, 1973).

Radioactive Wastes

Tanks of solid short-lived radioactive wastes often are buried in underground pits, primarily as a means of storing them in a shielding medium while the radioactivity decays. Five sites are used in the United States, operating under license and regulated by the states in which they are located: Richland, Washington; Beatty, Nevada; Sheffield, Illinois; West Valley, New York; and Moorehead, Kentucky (Atomic Energy Commission, 1969). Under state regulations, the sites are designed and operated so that no leakage should occur; to assure that no leakage is occurring, the states require and perform monitoring of surface water and groundwater in the vicinity of the sites as well as from sumps in the backfilled pits.

History

Underground tanks and pipes have been used for storage and transmission of liquids whenever the need for space or protection so dictated. In the United States the use of underground tanks and pipes has been most heavy in the petroleum industry. Here their use has expanded with the industry to the point where pipelines are now the major mode of transportation for liquids and gases within the continental United States.

Traditionally, pipelines and storage tanks have been buried only when the cost of burial did not exceed the cost of the area they would otherwise occupy, or the cost of the potential damage done to them by weather, vandalism, etc. The present and increasing emphasis on the aesthetic value of burying utilities and other commercial or industrial structures will undoubtedly increase the number of tanks and pipes that will be placed in excavations. Because pipelines are an economical means of shipping, there is an increasing trend toward developing methods for pipelining solids such as coal or ores by powdering the solids and mixing them with water or oil to produce a pumpable slurry.

Leakage in the United States

TANKS. Underground storage tanks are used in the United States by industries, by commercial establishments, and by individual residences. Industrial use is predominantly for fuels, but a wide range of other chemicals are also stored in tanks. Commercial businesses and individual homeowners use underground storage almost exclusively for fuel. The most numerous underground storage tanks are those used by gasoline stations and for fuel oil at residences. These small tanks are usually coated with a protective paint or corrosion resistant material, but they are frequently subject to corrosion-induced leakage. The primary problem associated with such tanks is the fact that their installation and use are not usually well regulated. If any regulation exists concerning such tanks, in most cases it is a local regulation requiring that tank construction and installation be satisfactory, but it is rare that any followup or periodic checks are required to determine whether or not leaks have developed. Because such tanks are small and comparatively inexpensive, cathodic protection is not required even when the tanks are in clay soils, which are known to promote galvanic action.

PIPELINES. Pipelines are used in three forms: for transportation, for collection, and for distribution.

Transportation pipelines are used for a wide number of chemicals such as oil, gas, ammonia, coal, and sulfur. Their heaviest use is for the transportation of petroleum products, natural gas, and water, in that order. The list of commodities lost by accidents during one year from liquid interstate pipelines is shown in Table 3-1.

Many industries employ underground collection pipelines to move process fluids and wastes in-plant or for storage or shipment. In oil fields, collection pipelines are used to bring crude oil from wells to tanks for separation of brines, storage, and shipment.

The only pipelines for which any program of leak prevention and any requirements for decontamination exist are the transportation pipelines, and all of these are not covered. All interstate transportation pipelines and some intrastate pipelines are regulated; on collection and distribution

Table 3-1. Summary of interstate liquid pipeline accidents for 1971 (Office of Pipeline Safety, 1972).

Commodity	No. of Accidents	% of Total	Loss (Barrels)	% of Total
Crude Oil	172	55.9	115,760	47.2
Gasoline	51	16.6	42,001	17.1
L. P. G.	39	12.7	39,887	16.3
Fuel Oil	21	6.8	13,724	5.6
Diesel Fuel	5	1.6	6.953	2.8
Condensate	5	1.6	3,658	1.5
Jet Fuel	4	1.3	2,236	.9
Natural Gasoline	4	1.3	8,743	3.6
Anhydrous Ammonia	3	1.0	9,810	4.0
Kerosene	2	.6	700	.3
Alkylate	2	.6	1,585	.7
Total	308	100.0	245,057	100.0

pipelines there is no regulation other than that of the initial installation. The purpose and intent of the regulations that exist are for preventing the escape of combustible, explosive, or toxic chemicals. Prevention of groundwater pollution has not heretofore been considered.

Because interstate pipelines are a major means of transportation, they are regulated by federal government agencies in the Department of Transportation. Furthermore, because leaks of petroleum products can produce a fire or explosion hazard, these regulated pipelines have been required, for the past 5 years, to report leaks and spills. An analysis of these reports (Office of Hazardous Materials, 1969; Office of Pipeline Safety, 1971; 1972) has been made and is summarized in

Table 3-2. It should be noted that the quantities reported represent only leakage associated with interstate carrier systems. This means that local distribution systems, gas stations, residential storages, and even relatively large intrastate carriers are not included. Therefore, it must be assumed that the leakage reported covers perhaps 10 to 25 percent of the total leakage in the country.

Environmental Consequences

Pipeline and tank leakage into the soil can have several environmental consequences, depending upon the chemical leaked. Oils and petroleum products in even trace quantities will render potable water objectionable because of taste, odor, and effects on vegetation growth.

In sufficiently high concentrations the vapors of lighter fractions of petroleum products, liquified petroleum gas, and natural gas can seep into basements, excavations, tunnels, and other underground structures. These vapors mixed with the air in the cavity constitute a severe explosion or fire hazard in the presence of open flame or sparks.

Table 3-2. Range of annual pipeline leak losses reported on DoT Form 7000-1 for the period 1968 through 1971.

Number of accidents -- 300 to 500
Number of barrels lost -- 250,000 to 500,000
Value of property damage -- $650,000 to $1,300,000
Number of deaths -- 1 to 11
Number of injuries -- 8 to 32
Major cause -- Corrosion
Major commodity lost -- Crude oil

Chemicals such as ammonia and other agricultural or industrial chemicals can have toxic properties. For example, ammonia will add to the nitrification of groundwater, while acids can change the pH of groundwater which, in turn, will accelerate the solution of soil solids and heavy metals.

The leakage of water can produce undesirable effects if the dissolved solids in the water introduce objectionable hardness or if the water is a brine.

Causal Factors

The annual reports of the Office of Pipeline Safety summarize the causes of leakage of interstate pipelines. This list appears to be representative of the causes of leaks for all pipelines and tanks.

Table 3-3 is extracted from Office of Pipeline Safety (1972) to show the relative frequency of causes. Other causes that have been reported in other years but did not occur in 1971 were flood and surge of fluid in the pipeline. Examination of the table indicates that the major cause of leakage is corrosion, which attacks the lines both externally and internally. The second greatest cause can be found by aggregating those related to pipeline component, equipment, personnel failure, or malfunction. The third greatest cause is line rupture as the result of attack by earth moving equipment.

The remaining small number of causes include vandalism (usually bullet holes in exposed sections of pipe, tanks or valves) and acts of God such as cold weather, lightning, floods, earthquakes, forest fires, etc. In general, pipelines are routed to avoid areas with a history of such acts of God or are structurally designed to withstand such problems as cold weather or earthquakes.

Table 3-3. Frequency of causes of pipeline leaks in 1971 (Office of Pipeline Safety, 1972).

Cause	Number	Percent
Corrosion-external	102	33.1
Equipment rupturing line	67	21.8
Defective pipe seam	31	10.1
Corrosion-internal	22	7.1
Incorrect operation by carrier personnel	22	7.1
Miscellaneous	12	3.8
Ruptured or leaking gasket	7	2.3
Ruptured or leaking seal	6	2.0
Defective repair weld	6	2.0
Unknown	6	2.0
Ruptured leaking or malfunction of valve	5	1.6
Rupture of previously damaged pipe	4	1.3
Malfunction of control or relief equipment	3	1.0
Cold weather	3	1.0
Defective girth weld	3	1.0
Threads stripped or broken	3	1.0
Pump packing failure	2	0.6
Vandalism	2	0.6
Lightning	2	0.6
TOTAL	308	100.0

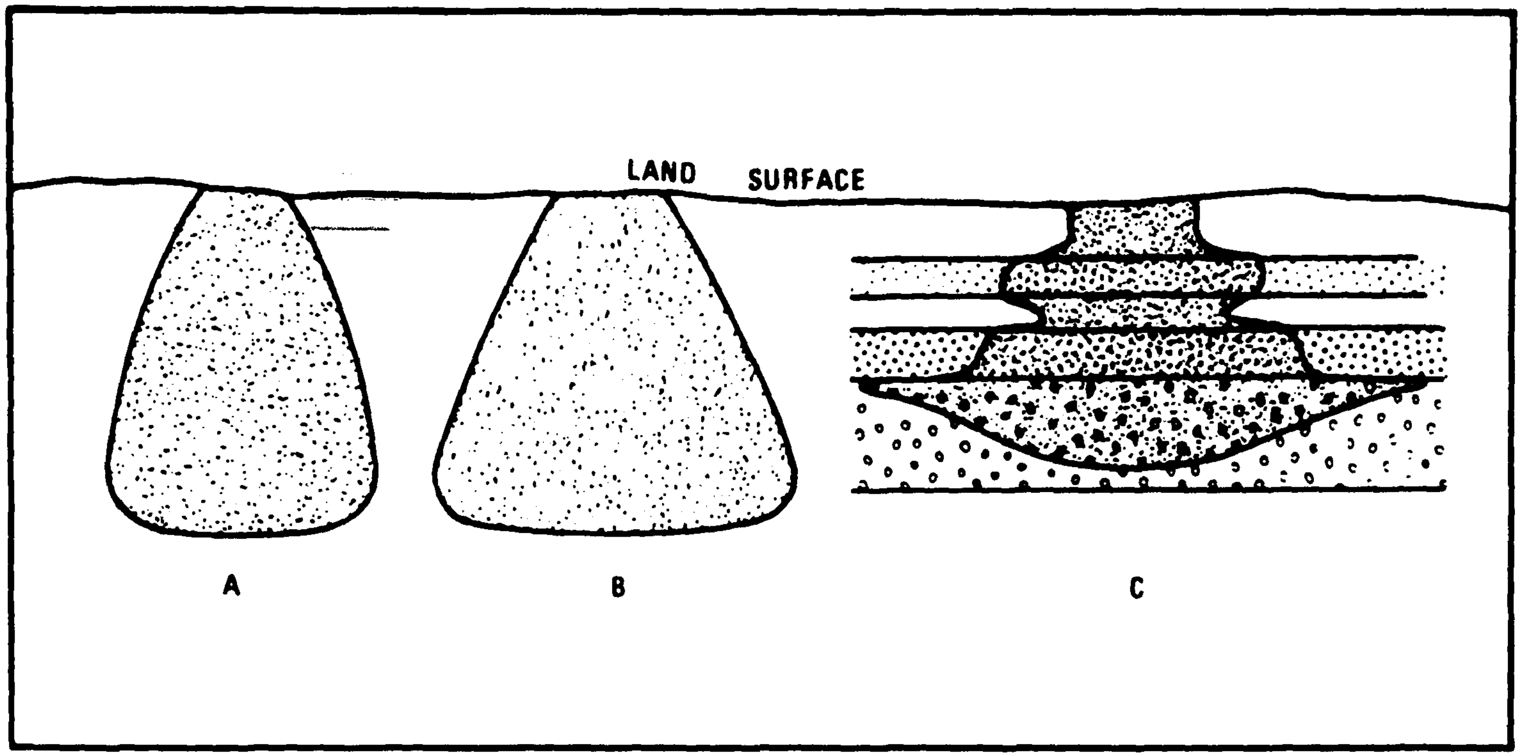
Pollution Movement

A leak into an underground excavation can behave in several ways, depending on the characteristics of the soil and the depth below the leak of the saturated zone. The statements below apply not only to oil but also to all liquid pollutants emanating from underground tanks and pipelines.

If the leak is from a tank of limited horizontal extent or from a pipeline in relatively permeable soil, the liquid will remain in the vicinity of the leak and move downward through the soil under the influence of gravity. On the other hand, if the leak is from a pipeline in relative impermeable soil, the leaked liquid will tend to remain in the trench. In a sloping trench in impermeable soil, the leaked fluid will tend to move through the backfill in the trench along the outside of the pipe in the direction of the slope.

As leaked liquid moves downward through the soil under the influence of gravity, it will coat the soil particles as it advances. This process removes some fluid from the downward moving body. If the quantity of leaked liquid is small enough, it may be exhausted to immobility by this process as shown in Figure 3-1. However, the leaked liquid will not remain immobilized. Subsequent rainfall will wash the pollutant from the soil particles and carry it further downward until eventually it will reach the saturated zone.

If the leakage is large enough to reach the saturated zone before exhaustion, its path of movement will depend upon the density and viscosity of the fluid and whether it is miscible with water. Miscible liquids will tend to mix and thus to dilute slowly with distance and time. Subsequent rainfall will tend to displace oil or other low density fluids lying on the water table, producing a mixture that will extend into the saturated zone. Once in the saturated zone, a pollutant will move downstream in the direction of the water table gradient as shown in Figure 3-2.



A – HIGHLY PERMEABLE, HOMOGENEOUS SOIL
B – LESS PERMEABLE, HOMOGENEOUS SOIL
C – STRATIFIED SOIL WITH VARYING PERMEABILITY

Figure 3-1. Generalized shapes of spreading cones of oil at immobile saturation (Comm. on Environmental Affairs, 1972).

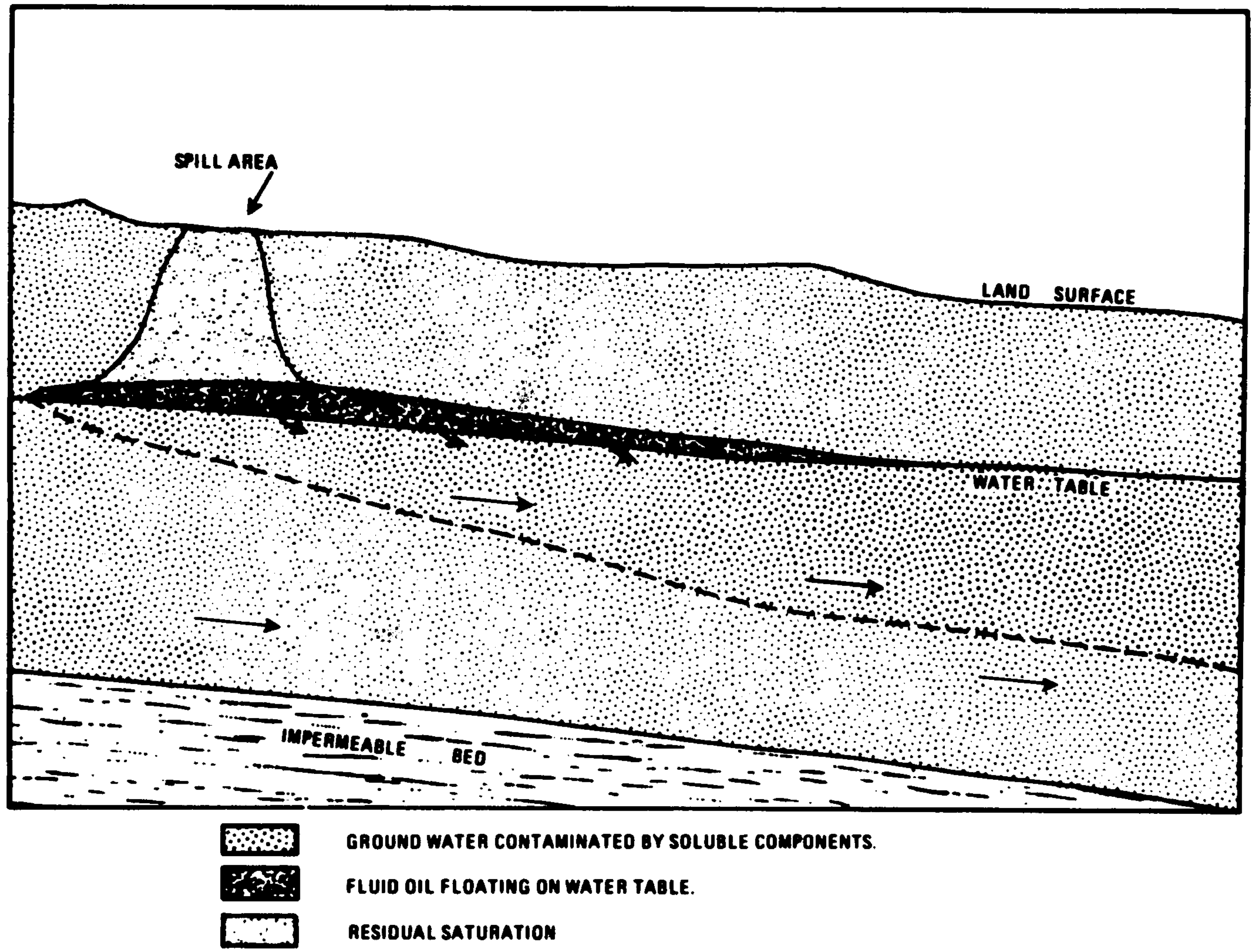


Figure 3-2. Movement of oil away from a spill area under the influence of a water table gradient (Comm. on Environmental Affairs, 1972).

Figure 3-3 shows a plan view of an actual situation involving a large gasoline spill and indicates how the leakage apparently concentrated in a depression in the water table created by pumping wells.

It is quite possible for leaked liquids to move laterally for great distances above the saturated zone. If a spill is large enough or if a leak continues long enough, the fluid can migrate along impermeable layers above the water table as shown in Figure 3-4. The same can happen along a pipeline, as described earlier, until it reaches a permeable region where it can penetrate downward.

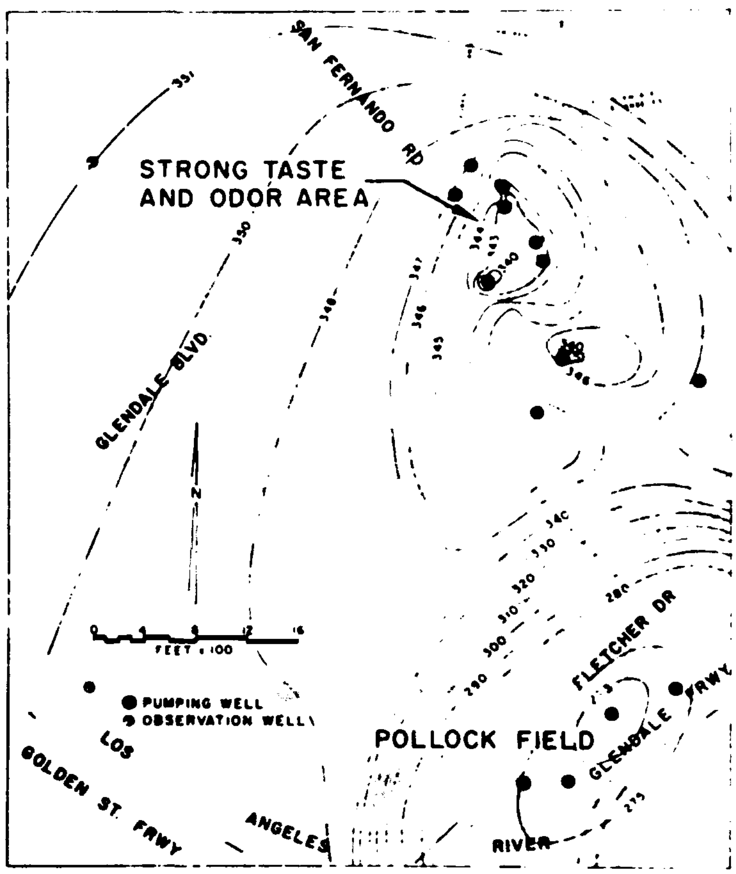


Figure 3-3. Area contaminated by subsurface gasoline leakage and groundwater contours in the vicinity of Forest Lawn Cemetery, Los Angeles County, as of 1971 (Williams and Wilder, 1971).

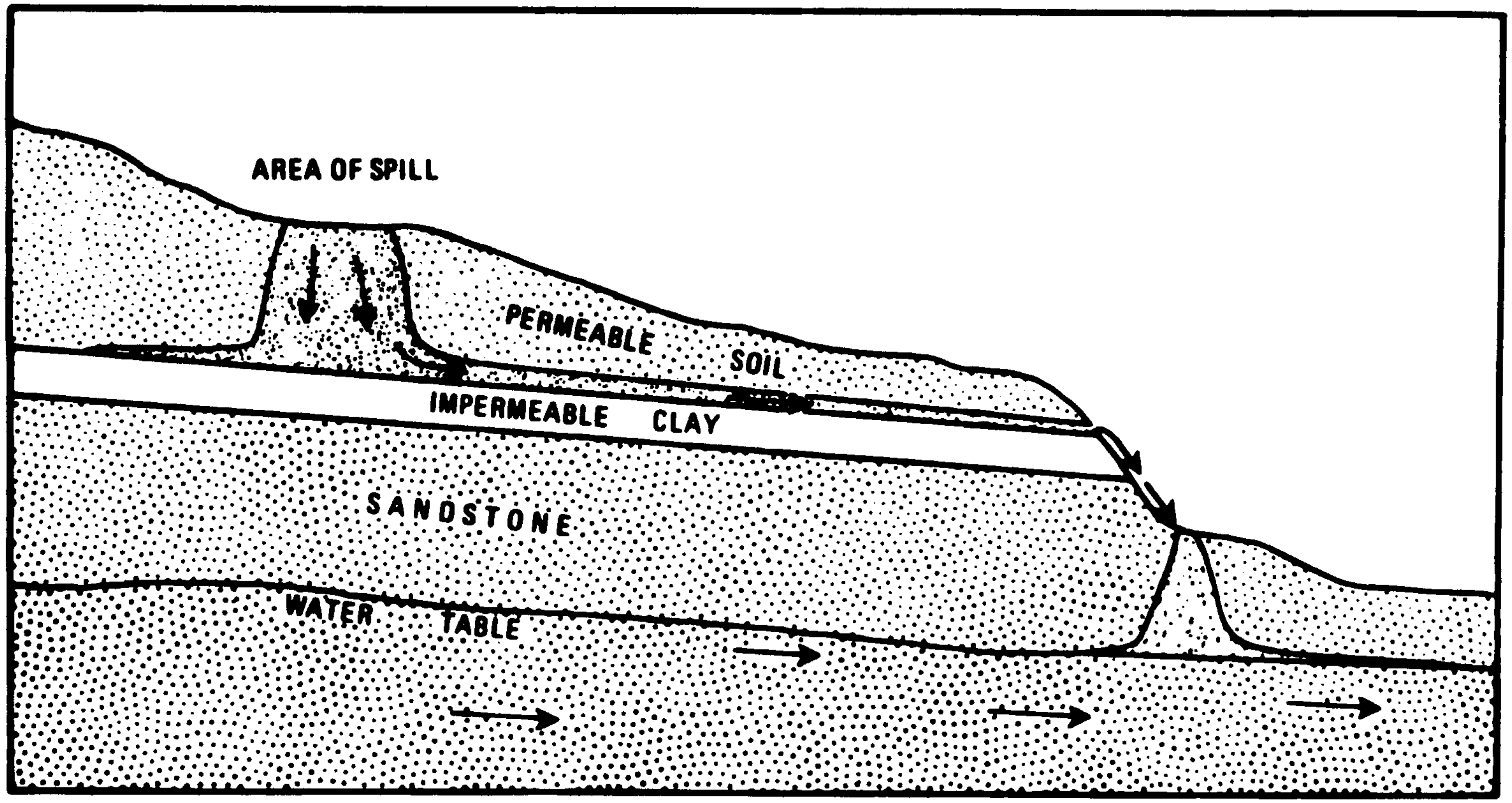


Figure 3-4. Illustration of the possible migration of an oil spillage along an impermeable layer, to an outcrop, and hence to a second spill location (Comm. on Environmental Affairs, 1972).

It should be noted that most chemicals do not move with the velocity of the groundwater. Because of the effects of sorption, varying miscibility and solubility with water, and varying chemical activity with the soils, chemicals usually migrate through the soil in the direction of the groundwater flow but at a slower rate (Comm. on Environmental Affairs, 1972).

Control Methods

At the present time, most of the research and development work on methods for controlling and abating the contamination of groundwater by leakage from tanks and pipelines in underground excavations has been concerned with reducing fire, explosion, and toxicity hazards. Although it would appear that this work is not often aimed toward abating pollution of groundwater, it may be applicable if judiciously applied. Further, many references that describe methods for handling hazardous materials can also be applied for handling leakage materials such as sewage, brines, and agricultural and industrial chemicals not considered to be hazardous.

PREVENTION. Primary control methods emphasize three types of leak prevention:

- Corrosion-preventing coatings such as tar or plastic are used on the outside of tanks and pipelines.
- Cathodic protection is used to minimize corrosion resulting from galvanic action (Dept. of Transportation, 1969, 1970a).
- Internal fibreglass linings, which do not deteriorate, are coming into use for small tanks such as those used for gasoline storage (Matis, 1971).

CONTAINMENT. Storage sites can be designed to contain leaked liquids so that they can be trapped and removed before they get into the soil. These methods are almost exclusively applied to tanks. Lined excavations are sometimes used to enclose a subsurface tank with an impermeable material such as clay, tar, or sealed concrete. These are analogous to the dikes used for containment in oil-tank farms.

Another method has been used in Switzerland (Todd, 1973) for containing liquids that are lighter than water, such as oil. An underground dam is built around the tank. The dam is designed to penetrate the water table to such a depth that the full volume of the tank could leak into the space inside the dam, and the bottom of the pool of leaked fluid would be well above the bottom of the dam.

In pipelines, containment can be accomplished by use of automatic shut-off valves inserted in the pipe at intervals. These valves are designed to close off any section of pipe where a significant drop in line pressure occurs. This method, like containment devices for tanks, tends to limit the spread and the volume of the leak and thereby permit easier cleanup. At the present time this form of protection is required on interstate pipelines but not on most small collection and distribution systems.

ABATEMENT BY REMOVAL OF SOIL. If a leak is discovered and is accessible soon after it occurs, perhaps the best method for preventing groundwater contamination is removal of the soil soaked with the leakage. It is important that this method be applied before rainfall occurs in the region. Normally, without the flushing action of rainfall, liquids move downward very slowly under the influence of gravity.

Figure 3-5 (Todd, 1973) indicates that from several hours up to a day or more may be available before leaked liquids reach depths beyond those that would be reasonable for normal earth removal. This slow migration downward is a characteristic not only of leaks small enough that they will be exhausted to immobility before they reach the saturated zone but also of leaks large enough to eventually reach the saturated zone. Thus,

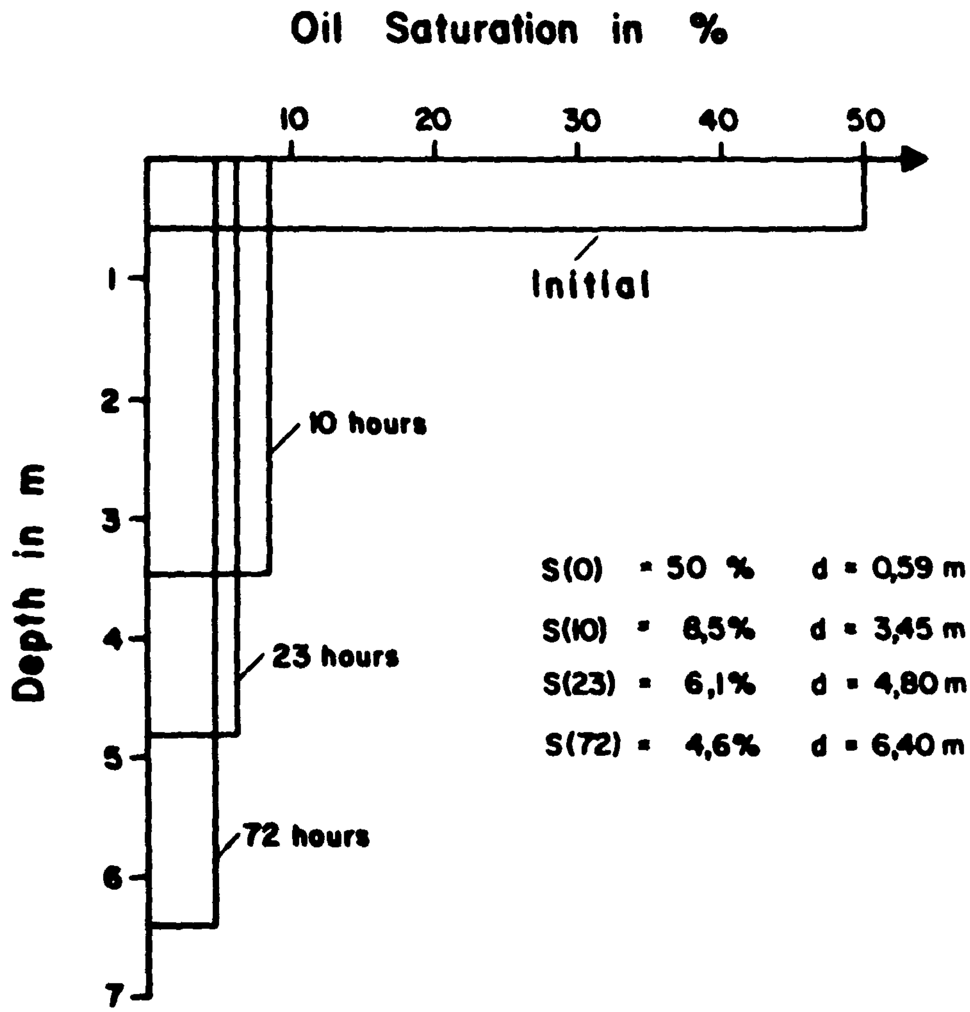


Figure 3-5. Experimental results from Switzerland on the distribution of oil in soil as a function of time (Todd, 1973).

in dealing with the large leaks that are associated with a catastrophic failure, such as a tank or pipe rupture, it is important to initiate cleanup procedures as rapidly as possible.

After the soil has been removed, the problem of how to dispose of it must be addressed. The most suitable method for handling biodegradable materials, such as oil, and many agricultural chemicals such as ammonia, is to spread the contaminated soil in a thin layer, 20 centimeters or less in thickness, and permit the natural aerobic soil bacteria to degrade it. This is usually accomplished within six months. If the liquid is not biodegradable, the soil must be removed to an appropriate industrial waste treatment plant and processed as an industrial waste.

It should be noted that earth removal can be an extensive operation requiring more than simply digging a hole with a bulldozer and hauling the soil away in a truck. In at least one case in an urban area (Geraghty, 1961), such earth removal involved the demolishing of buildings and excavation of an area of approximately the size of a city block.

ABATEMENT BY PUMPING OR DITCHING. In cases where the pollutant has reached the water table but has not yet moved a significant distance from the leakage site, a removal well can be used. This method works best for water-soluble chemicals and for oils that float on the water table; however, it can be expensive and time consuming. With respect to soluble chemicals, the effect of pumping will be to reverse the normal migration or flow away from the site of the leak; with respect to oil, the drawdown cone that the well produces will trap the oil. In the case of oil, two pumping locations are often used—a deep pump inlet to maintain the drawdown cone and a skimming pump with its inlet floating on the surface to remove the oils (Figure 3-6).

If the pollutant has moved so far downstream that recapture by use of a drawdown cone is infeasible, a ditch placed across the contaminated plume can be used to capture the pollutant. Figures 3-7 and 3-8 illustrate this method.

When the water table is far below the surface of the ground, a row of pumping wells may be required. Placed across the contaminated plume, their drawdown cones will merge, producing a trench in the water table. The contaminant cannot escape from the depression and with time will

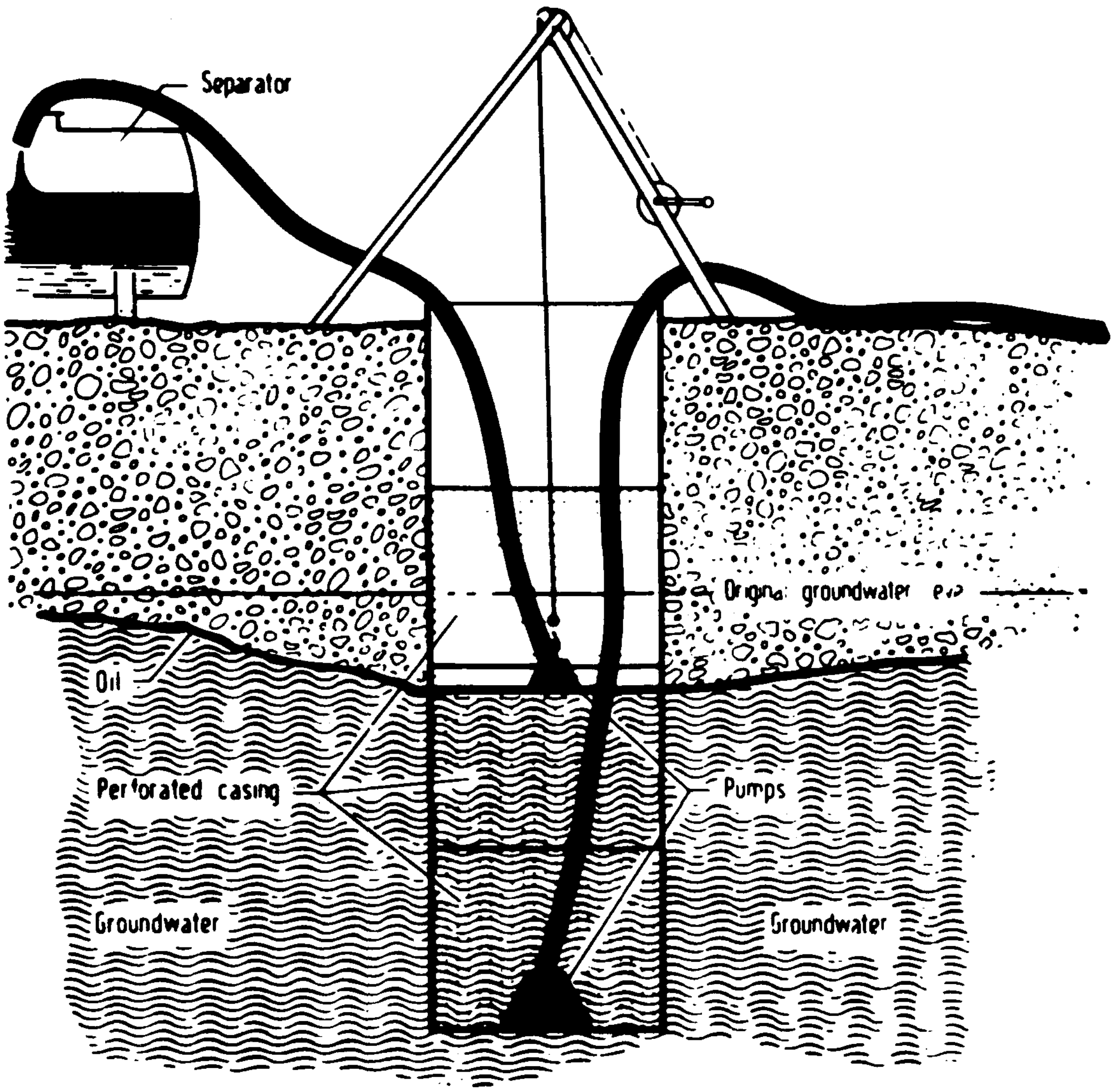


Figure 3-6. Swedish two-pump method for removal of oil pollution from a well (Todd, 1973).

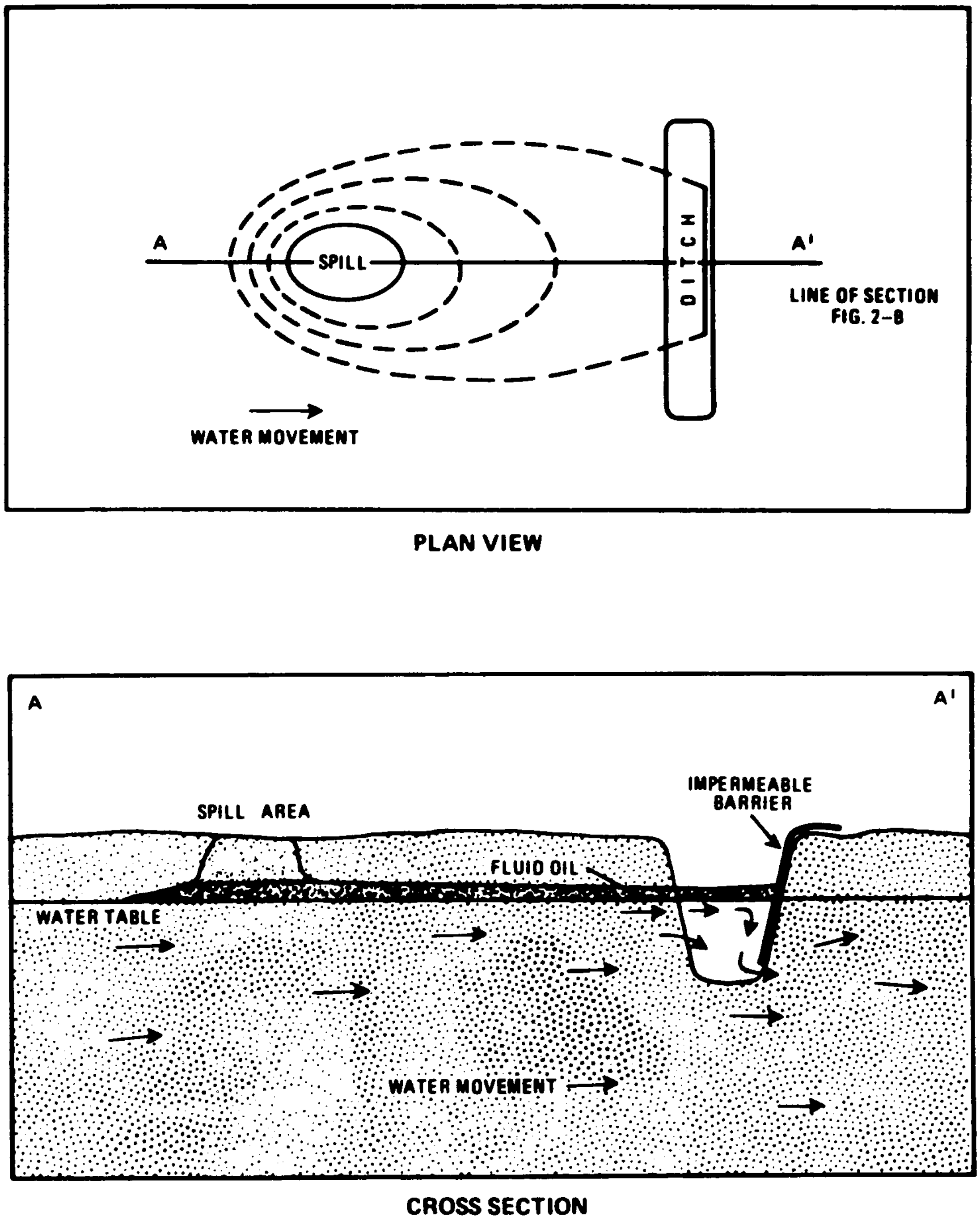
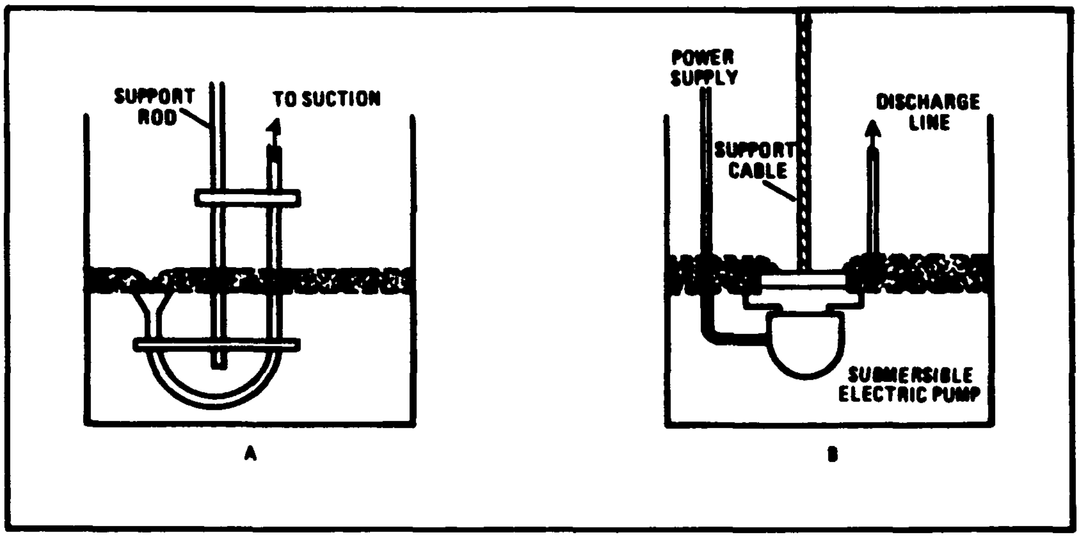


Figure 3-7. Oil moving with shallow groundwater is intercepted by a ditch constructed across migration path (Comm. on Environmental Affairs, 1972).



A FLOATATION DEVICE MAY BE SUBSTITUTED FOR THE HANDLING CABLE OR ROD.

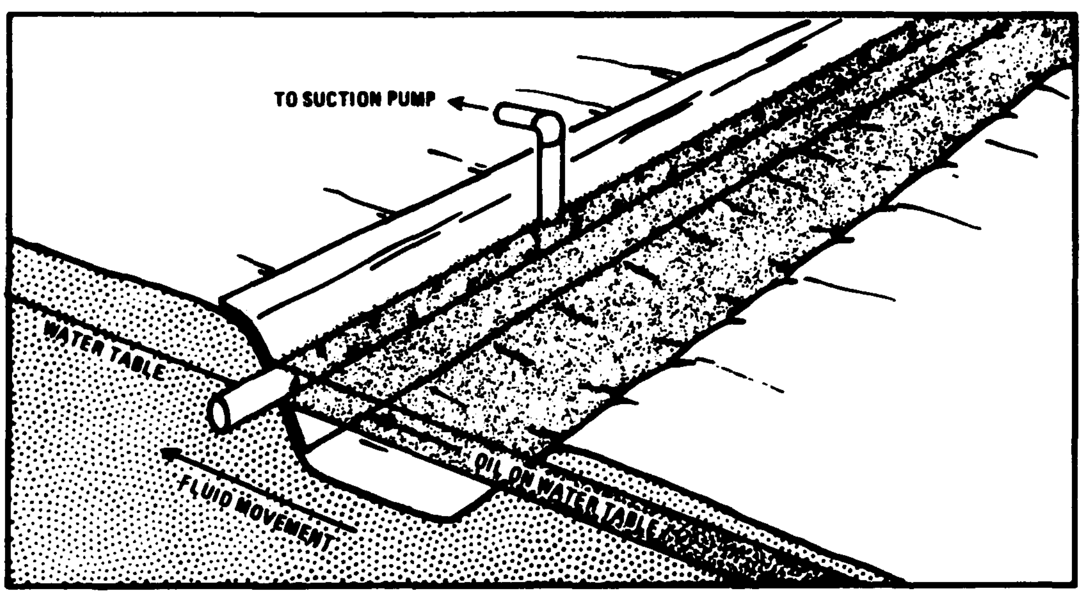


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Figure 3-8. Three systems for skimming oil from a water surface in ditches or wells (Comm. on Environmental Affairs, 1972).

gradually be removed by the wells. After the contaminated water is removed, it must be processed as an industrial wastewater before disposal to a sewage system or return to the aquifer. The appropriate technique will depend upon the nature of the pollutant and upon available wastewater treatment facilities.

ABATEMENT BY BIODEGRADATION. A new method currently under investigation is that of subsurface biodegradation. Many chemicals such as ammonia and petroleum products are biodegradable by aerobic bacteria, but below the surface air transfer is slow and the aerobic bacteria tend to consume the oxygen. At the present time research is being conducted to identify anaerobic bacteria that would also be capable of such biodegradation (McKee, et al., 1972).

ABATEMENT BY CHEMICAL ACTION. The use of chemical reagents or pH changes has been suggested to cause precipitation of pollutants or reactions with the soil to simply immobilize them. So far as is known no experimental results are available. Further research on such methods is required.

Monitoring Procedures

In general the monitoring required for the detection of leaks from tanks and pipelines in excavations is in proportion to the quantity of chemicals handled.

At the level of the household fuel storage tank, gasoline station storage tank, and local collection or distribution system, local monitoring is probably not economically feasible. If local governments regulate such operations at all, they do so by ordinances and codes specifying the materials and methods of installation. The most frequent occurrence of leaks from underground pipes and tanks is from these small systems. Commonly, monitoring for such leaks is by "discovery," when a nearby owner of a water well discovers that his well is contaminated. Other examples occur when an owner or operator discovers that the chemical is disappearing from his tank faster than he is using it, or during the rainy season when the water table rises above the level of a leak in a tank so that the owner or operator discovers that the tank is supplying water (Gilmore, 1973).

Monitoring methods and procedures for interstate carriers are under the control of the Office of Pipeline Safety. To assure that interstate carrier monitoring and pipeline operation are being done satisfactorily, the Office of Pipeline Safety requires detailed reports of all leakages in next excess of 50 barrels of commodities from initiation of the leak to the time of cessation (Department of Transportation, 1969; Office of the Secretary of Transportation, 1970).

Monitoring procedures described below have been developed and implemented by interstate carriers, but they can be applied to any underground tank or pipeline.

Pipelines contain pressure-monitoring devices that automatically close valves to isolate a section of pipe whenever a significant pressure loss occurs (Dept. of Transportation, 1969; 1970). Regular checking of pipelines and tanks is accomplished by throughput monitoring, periodic inspection, and periodic pressure testing (Dept. of Transportation, 1970a; Office of the Secretary of Transportation, 1971; 1972). In all of these monitoring procedures emphasis has been on hazard and on economics; in general, if the leak is so small or so located that it constitutes no hazard (as defined by the Office of Pipeline Safety) and the costs of repairing the leaks are greater than the loss incurred by the leakage, no attempt will be made to detect, locate, or repair the leak.

THROUGHPUT MONITORING. Throughput monitoring compares input and output. This method will detect large leakage rates, but small rates, comparable to the fluctuations in difference between the input and output measurements resulting from temperature changes, inaccuracies in the measuring instruments, etc., will go undetected. Improved instrumentation might permit the detection of such leaks, but usually they are detected by periodic inspections and pressure tests.

PERIODIC INSPECTION. Periodic inspection includes a visit to the site and at least a visual inspection. Often, if volatile chemicals are involved, a length of pipe is inserted into the soil and air samples are drawn through portable gas detectors. The periodic inspection of pipelines usually takes the form of a patrol on foot, by truck, or from aircraft. In all cases the dominant method of detection is visual. In addition to seeking evidence of leaks in the vicinity of the pipelines, inspectors are usually adept at identifying leaks by the effects that the chemicals have on adjoining vegetation.

For tanks in lined excavations, liquid level sensors or vapor sensors (for volatile fluids) can be placed in the space between the lining of the excavation and the tank. These are connected to an alarm located where personnel are on duty.

PRESSURE TESTS. Pressure tests are usually made on both pipelines and tanks after repairs and periodically whenever corrosion may be a problem. A tank or a section of pipeline is filled and pressurized, and the pressure monitored. Allowance is made for temperature change and expansion under pressure, and the degree of tightness is determined. The normal pressure-test duration is 24 hours. A report must be filed with the operator and the Office of Pipeline Safety.

This type of test is more sensitive than throughput monitoring and periodic inspection, but because of the potential variation of many parameters affecting the pressure, small persistent leaks may go undetected and tests may prove inconclusive. An example of the ambiguity of such a test resulted at Forest Lawn Cemetery in Los Angeles County (Williams and Wilder, 1971). A pipeline near the cemetery was suspected as the source of gasoline leakage, shown in Figure 3-3. It was pressure tested, but some experts said that the results indicated that the pipe was tight, while others felt that the results indicated a small leak. As of 1972, 50,000 gallons of gasoline had been recovered at this site, and it is estimated that the total spill amounted to 250,000 gallons.

MONITORING SOLID SHORTLIVED RADIOACTIVE WASTES. The monitoring methods used for tanks of solid shortlived wastes buried in pits include sampling from sumps, wells, and surface water. Laboratory analyses are made for beta and gamma activity and tritium content. In practice, the methods are similar to those for monitoring leachates from sanitary landfills.

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SURFACE WATERS

Scope of the Problem

Pollution by flow from surface water to groundwater is known to be taking place in some parts of the country (Fuhriman and Barton, 1971), and undoubtedly it is occurring in many other places as yet undetected. Water applied during irrigation and water that temporarily covers the surface of the land during floods are common ways in which contaminants can enter the soil to pass downward into aquifers. Less widely appreciated is the fact that surface waters in open bodies such as rivers and lakes can enter shallow aquifers where groundwater levels are lower than surface-water levels. Pumping from shallow wells near a stream, as shown in Figure 3-9, and infiltration from flash runoff in normally dry stream channels are two examples.

Surface runoff in urban areas contains a variety of pollutants; the infiltration and percolation of this water causes gradual local increases in dissolved constituents in groundwater. The kinds of pollutants that can enter aquifers through the mechanism of flow from surface to groundwater include virtually the entire spectrum of inorganic and organic compounds as well as bacteria and viruses.

The reverse problem, that of groundwater polluting surface water, has received relatively little attention. Invariably, flowing groundwater discharges into a surface water body unless it is intercepted by pumping wells. A large fraction of all streamflow is derived from drainage of groundwater. Thus, long-term degradation of surface water can be anticipated in areas where groundwater pollution continues to exist.

Environmental Consequences

Any pollutants entering the groundwater from surface-water sources will gradually disperse with movement underground and may ultimately affect the quality of a relatively large volume of groundwater in

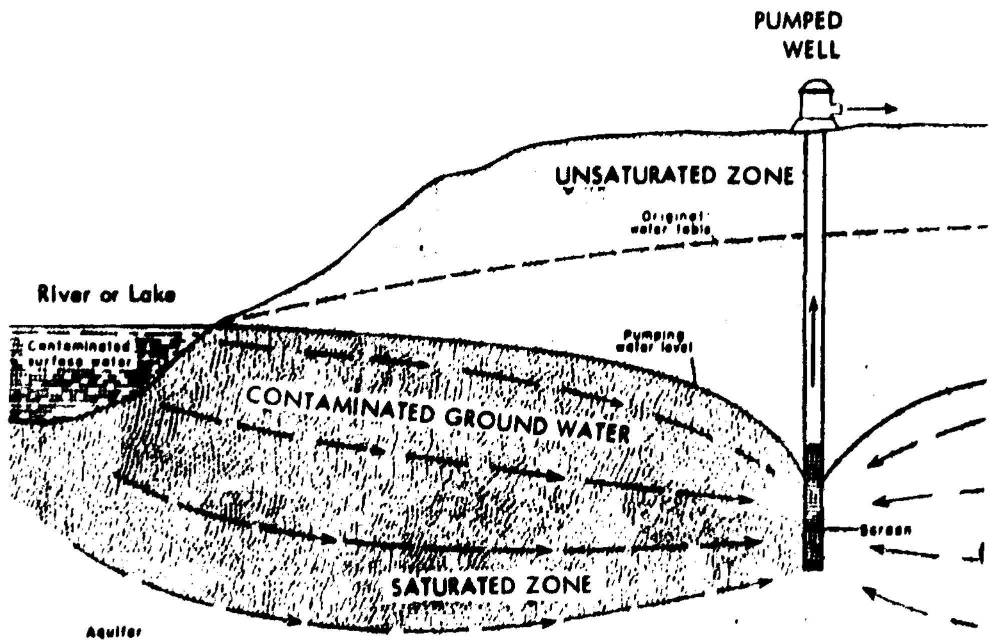


Figure 3-9. Diagram showing how contaminated water is induced to flow from a surface source to a pumped well. Arrows show the direction of groundwater flow (after Deutsch, 1963).

comparison to that initially affected. In general, dissolved solids move farthest with the groundwater and form a plume which may extend thousands of feet downstream from a point source of pollution.

Nature of the Pollutants

Stormwater runoff exhibits a wide range of organic, bacteriological, and chloride contents, as shown in the examples given in Table 3-4. Not shown are other substances such as nitrate, lead, other heavy metals, pesticides, and other organic compounds that have been reported in stormwater runoff, particularly in urban and suburban areas (Sartor and Boyd, 1972). Road salting in parts of the United States is a particularly large contributor of chloride to groundwater (Hanes, et al., 1970).

Table 3-4. Examples of constituents in stormwater runoff (Federal Water Pollution Control Agency, 1969).

City	BOD mg/ℓ	Total Solids mg/ℓ	Suspended Solids mg/ℓ	Coliform per ℓ	Chlorides mg/ℓ	COD mg/ℓ
1. East Bay Sanitary District						
Minimum	3	726	16	4	300	
Maximum	7,700		4,400	70,000	10,260	
Average	87	1,401	613	11,800	5,100	
2. Cincinnati, Ohio						
Maximum seasonal means	12	260				110
Average	17		227			111
3. Los Angeles County						
Average 1962-63	161	2,909			199	
4. Washington, D. C.						
Catch-basin samples during storm						
Minimum	6		26		11	
Maximum	625		36,250		160	
Average	126		2,100		42	
5. Seattle, Washington	10			16,100		
6. Oxney, England	100**	2,045				
7. Moscow, U.S.S.R.	186-285	1,000-3,500**				
8. Leningrad, U.S.S.R.	36	14,541				
9. Stockholm, Sweden	17-80	30-8,000		40-200,000		18-3,100
10. Pretoria, South Africa						
Residential	30			240,000		29
Business	34			230,000		28
11. Detroit, Michigan	96-234	310-914	102-213***	930,000**		
Criteria* for:						
A. Potable water						
(to be filtered)				5,000	600**	10
(not to be filtered)				50		10
B. Body contact water				2,400	NA	

*New York State
**Max.
***Mean

Water in streams consists of a base-flow fraction from seepage of groundwater and an overland runoff fraction that is usually more mineralized than precipitation (Hem, 1970) but less mineralized than groundwater. Generally, the dissolved-solids content of a stream is inversely proportional to the discharge. Other factors affecting the quality of stream waters are geochemical reactions of the water with streambed and suspended materials, evapotranspiration, and the activity of biota in the stream. Superimposed on all these natural processes are pollution from man's activities.

The chemical quality of streamflow ranges widely. For example, the streamflow in many largely undeveloped drainage basins in upstate New York and in New England is very soft and commonly has a dissolved-solids content of less than 30 mg/ℓ. In contrast, the Hudson River in southern New York and many streams in other areas of the country receive large discharges of partly treated sewage and miscellaneous industrial and agricultural wastes, including effluents from chemical and paper manufacturing, fruit and vegetable processing, canneries, and other sources. In addition, large amounts of warm water are returned to streams after use in cooling systems by utilities and other industries. The quality of water pumped from wells near a surface-water source generally reflects an integration of native groundwater and the surface water that has infiltrated during various stages and seasons.

Geraghty & Miller, Inc. (written communication, 1973) reports high iron and manganese content in groundwater pumped from wells near several streams in New England. They attribute this to geochemical reactions involving the infiltrating stream waters and the streambed and aquifer materials. Bacterial activity may also have contributed to the iron and manganese enrichment of the groundwater. Hem (1970) notes briefly the role of bacteria in dissolving and precipitating iron and manganese.

The composition of lake water is affected by many of the same factors influencing streams, and also by incomplete mixing of water within a lake, thermal stratification, evaporation, and the character of the subsurface and surface inflows to a lake. Surface water commonly has a much higher annual range in temperature than groundwater (Rorabaugh, 1956); consequently, induced infiltration from a surface source may cause temperature changes of as much as 5 to 10 degrees C. or more in nearby groundwater (Figure 3-10). There is generally a lag between changes in temperature in a surface-water body and in the hydraulically interconnected groundwater; above-normal groundwater temperatures near a stream or lake reflect summer infiltration, while below-normal temperatures reflect winter infiltration of surface water.

Pollution Movement

In places where a surface-water body is closely connected hydraulically with an underlying aquifer, water will move in the direction of the hydraulic gradient. In different reaches of a stream channel, the stream may have gaining or losing characteristics (i.e., it receives groundwater inflow or loses water to an aquifer). In reaches where the water level in the stream is above the adjacent land surface, as for example during a flood or where levees line the banks, part of the seepage from the stream may become temporary bank storage and return water to the stream.

Figure 3-11 shows a pattern of flow from groundwater carrying hexavalent chromium to surface water (Perlmutter and Lieber, 1970). Figure 3-12 shows the concentration of nitrate (Perlmutter and Koch, 1972) that seeped into gaining streams from an interconnected shallow aquifer.

Flow from surface water to groundwater takes place where wells are installed near a stream or lake and the water pumped from the aquifer

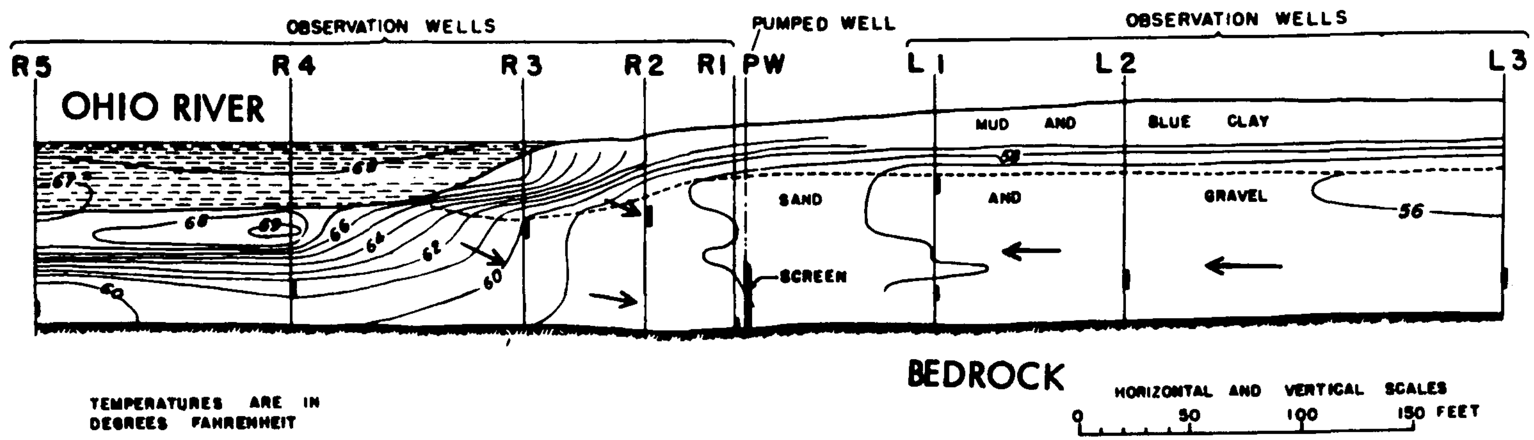
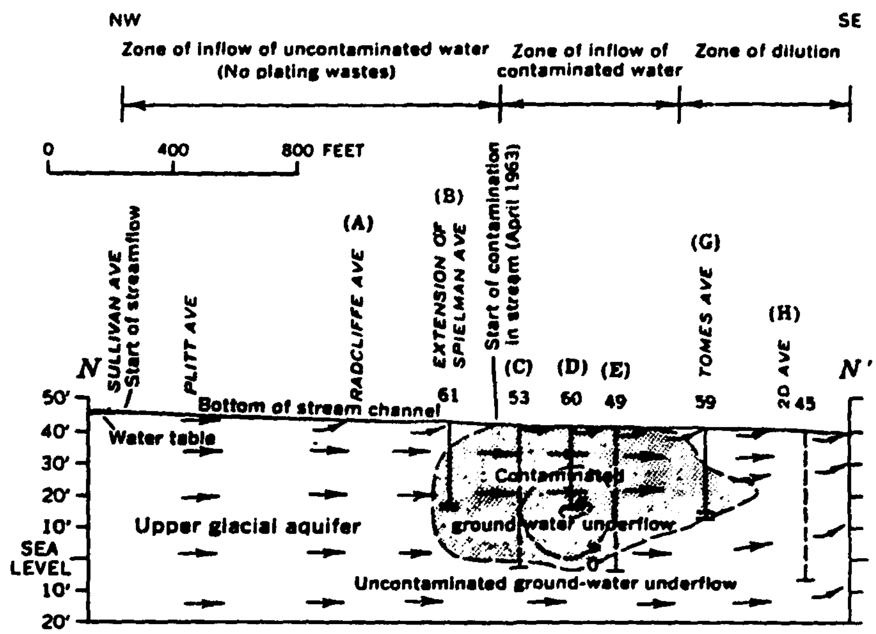
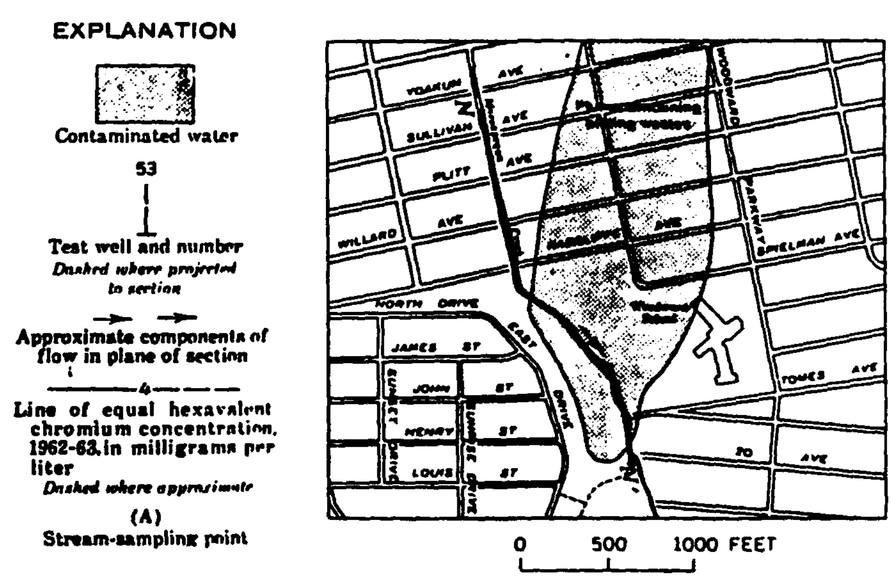


Figure 3-10. Section across the Ohio River near Louisville, Kentucky, showing the distribution of lines of equal temperature of water during a pumping test of a well. Note downward movement of warm water from the river toward the pumped well (Rorabaugh, 1956).



Longitudinal Section N-N' along Massapequa Creek



Location of Section N-N'

Figure 3-11. Relation of the pattern of groundwater flow to the occurrence and dilution of plating wastes in South Farmingdale, Long Island, N. Y. (Perlmutter and Lieber, 1970).

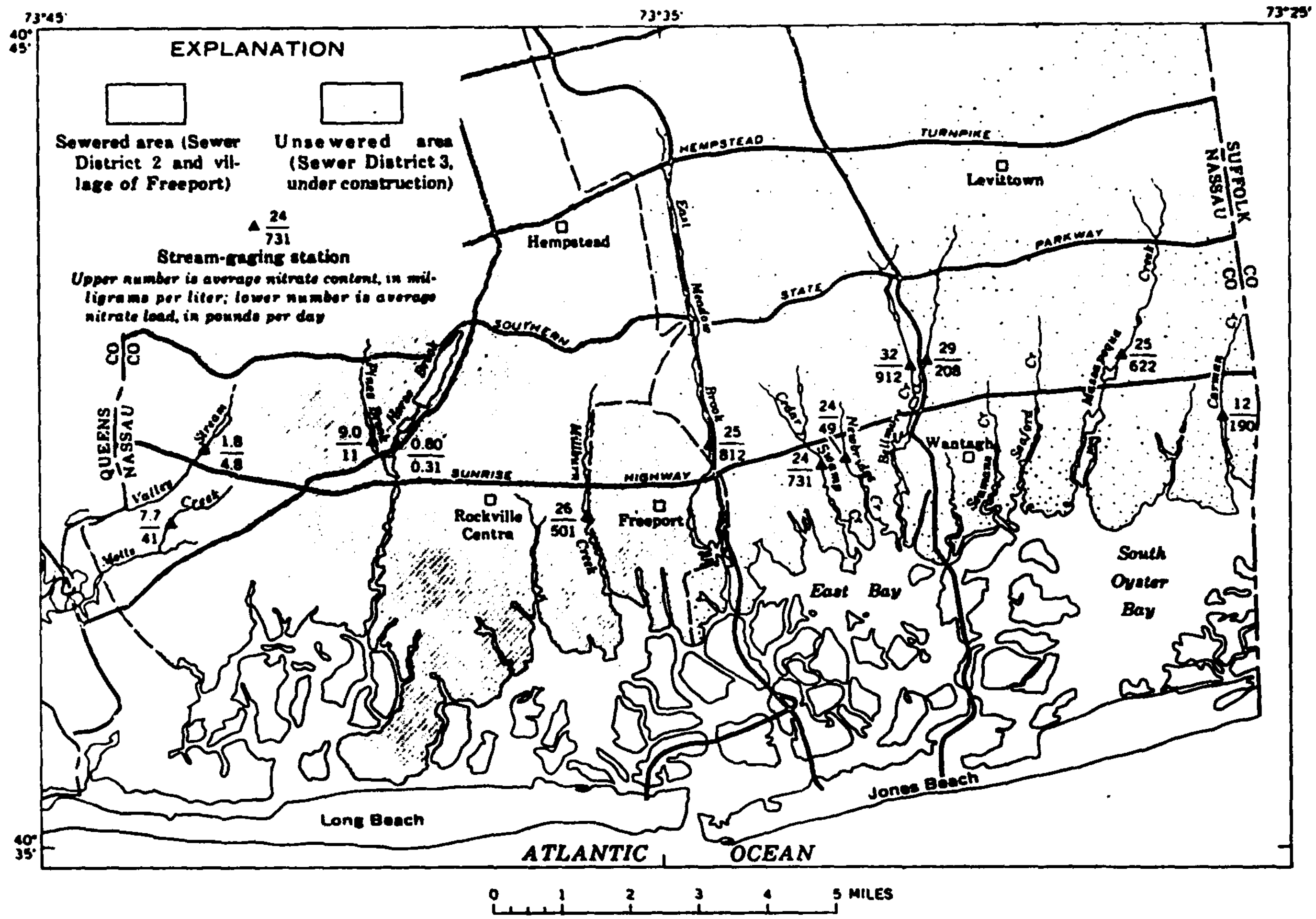


Figure 3-12. Average content and daily load of nitrate in water at gaging stations on selected gaining streams in sewered and unsewered areas, southern Nassau County, Long Island, N. Y., 1966-70 (Perlmutter and Koch, 1972).

is replaced in part by induced infiltration of surface water as shown in Figure 3-9. The hydraulic relations, yields of wells, and methods for calculating stream depletion by pumping wells have been discussed by Jenkins (1970), by Reed and others (1966) on the basis of field tests at Kalamazoo, Michigan, by Rorabaugh (1956) for the Louisville, Kentucky area, and by Kazmann (1948), who investigated horizontal collector wells near Charlestown, Indiana. Under conditions of long-term steady flow, most of the water pumped from a well may be derived from a nearby interconnected surface-water source. The quantity of surface water that moves into an aquifer depends on the transmissivity of the aquifer, the hydraulic conductivity and the area of the bottom of the stream or pond, the pumping rate, and the amount of surface water that is available. The appearance of coliform bacteria in water from a municipal well, located 180 feet from the Susquehanna River in upstate New York, is attributed partly to dredging of the river bed. This may have increased the opportunity for induced infiltration of the polluted river water (Randall, 1970).

Control Methods

Effective programs to improve the quality of water in streams and lakes, through control of waste disposal and storm runoff, will also be effective in improving the quality of groundwater fed by these surface-water bodies.

Control of pumping, and proper siting of wells through aquifer tests and other hydrogeologic evaluation, will help to minimize seepage of polluted surface water into an aquifer.

Monitoring Procedures

Monitoring of the quality of surface water bodies in all reaches where groundwater can be affected will provide the data needed to define areas where surface water may pollute aquifers.

Periodic sampling of existing wells should be programmed where justified by the threat of contamination from nearby surface-water bodies, with chemical analyses tailored to detect the contaminants involved. Special observations wells may be warranted to provide advance warning of flow between the surface and subsurface bodies.

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THE ATMOSPHERE

Scope of the Problem

Raindrops falling through the atmosphere pick up varying concentrations of dissolved solids from particles suspended and carried in the air. Some of the solids originate from natural sources, such as airborne salt particles; generally, their concentration is small. Much higher concentrations of suspended particles and many more constituents result from man's air-polluting activities, including industrial, automotive, and urban sources. Where air pollution exists, raindrops may dissolve enough solids to become a source of groundwater pollution.

Nature of the Pollutants

Precipitation, including rain, snow, and dry fallout of particulate matter, varies in composition from place to place, from storm to storm, and from season to season. The wide range in composition of precipitation has been discussed by Carroll (1962) and Gambell and Fisher (1966). The dissolved and particulate matter in precipitation is of local and transported origin and is derived from the oceans, land masses, vegetation, industrial processes, fertilization and cultivation of the soil in agricultural areas, combustion of fuels, and other sources. The analyses in Table 3-5 show the range in content of major cations and anions in precipitation collected at selected localities in the United States prior to 1962. The concentrations of all the listed constituents are well below recommended limits in drinking water, but even at these low concentrations, the annual fallout from precipitation represents several tons per constituent per square mile. Other minor constituents in precipitation include iodine, bromine, iron, lead, cadmiun, and traces of other heavy metals (Biggs and others, 1972); silica; detergents; nitric and sulfuric acids; and radioactive substances. Precipitation is generally acidic and has a pH averaging about 5 to 6.

Table 3-5. Chemical composition of rainwater at various localities in the United States (Carroll, 1962).

Locality	Distance From Sea (miles)	Average Annual Rainfall (millimeters)	Constituents, ppm						
			Sodium (Na)	Potassium (K)	Calcium (Ca)	Chloride (Cl)	Sulfate (SO_4)	Nitrate (NO_3)	Ammonia (NH_4)
Cape Hatteras, N. C.	0	1,370	4.49	0.24	0.44	6.50	0.88	1.03	0.11
San Diego, Calif.	0	277	2.17	.21	.67	3.31	1.66	3.13	1.15
Brownsville, Tex.	1	635	22.30	1.00	6.50	21.96	5.34	1.76	.28
Akron, Ohio	*27	889	.10	.10	.69	.17	1.62	4.68	.38
Tallahassee, Fla.	37	1,397	.53	.13	.43	.66	.48	.72	.07
Greenville, N. C.	50	1,194	.18	.07	.31	.13	.57	2.97	.14
Tacoma, Wash.	75	2,032	14.50	.59	.73	22.58	1.69	.99	.05
Urbana, Ill.	*85	940	.90	.07	-	.69	1.20	1.27	.09
Washington, D. C.	85	1,052	.23	.18	.23	.35	1.33	2.14	.43
Fresno, Calif.	112	240	.30	1.11	.37	.35	.54	2.94	2.21
Indianapolis, Ind.	*128	995	.26	.12	.69	.18	4.00	2.06	.27
Albany, N. Y.	150	914	.21	.09	.43	.23	.10	4.05	.21
Roanoke, Va.	200	1,270	.22	.13	.32	.23	1.33	3.12	.21
Ely, Nev.	410	381	.60	.14	3.79	.30	1.05	.81	.35
Amarillo, Tex.	540	534	.22	.23	2.17	.14	.03	1.64	.28
Glasgow, Mont.	625	380	.40	.26	1.72	.17	1.30	1.82	.75
Grand Junction, Colo.	650	226	.69	.17	3.41	.28	2.37	2.63	.33
Columbia, Mo.	650	1,016	.33	.31	2.18	.15	1.20	3.81	.44

*Distance from freshwater lake system.

The principal sources, categories, and amounts of certain air pollutants produced by activities of man are given in Table 3-6. Concentrations of selected heavy metals, organics, and radioactive substances as particulate matter in the air are given in Table 3-7. A part of these pollutants is eventually dissolved and reaches streams and groundwater.

Table 3-6. Annual emissions of air pollution constituents in the United States (Federal Water Pollution Control Agency, 1969).

	Carbon Monoxide	Sulfur Oxides	Nitrogen Oxides	Hydro-carbons	Particulate Matter
	(in millions of tons)				
Motor Vehicles	66	1	6	12	1
Industry	2	9	2	4	6
Power Plants	1	12	3	1	3
Space Heating	2	3	1	1	1
Refuse Disposal	1	1	1	1	1

Pollution Movement

That portion of precipitation that infiltrates into the ground and is not subsequently lost by evapotranspiration can be expected to percolate downward to underlying aquifers. Minerals that are left in the soil when rainfall evaporates normally will be carried down to the groundwater by subsequent infiltration of rainfall.

The portion of precipitation that actually reaches the groundwater varies from near zero in arid regions to a major percentage in areas receiving moderate to heavy precipitation on highly permeable soils. Pollutants present in rainwater plus those picked up by the water passage through the soil become groundwater pollutants when the water reaches the main groundwater body. Pollutants in precipitation falling on surface water bodies may later reach the groundwater at some downstream location.

Table 3-7. Concentrations of selected particulate contaminants in the atmosphere in the United States from 1957 to 1961 (Federal Water Pollution Control Agency, 1969).

	(Micrograms per cubic meter)			
	Urban		Nonurban	
	Mean	Maximum	Mean	Maximum
Suspended particulates	104	1706	27	461
Benzene-soluble organics	7.6	123.9	1.5	23.55
Nitrates	1.7	24.8	-	-
Sulfates	9.6	94.0	-	-
Antimony	(a)	0.230	-	-
Bismuth	(a)	0.032	-	-
Cadmium	(a)	0.170	-	-
Chromium	0.020	0.998	-	-
Cobalt	(a)	0.003	-	-
Copper	0.04	2.50	-	-
Iron	1.5	45.0	-	-
Lead	0.6	6.3	-	-
Manganese	0.04	2.60	-	-
Molybdenum	(a)	0.34	-	-
Nickel	0.028	0.830	-	-
Tin	0.03	1.00	-	-
Titanium	0.03	1.14	-	-
Vanadium	(a)	1.200	-	-
Zinc	0.01	8.40	-	-
Radioactivity	b4.6	b5435.0	-	-

a. Less than minimum detectable quantity.
b. Picocuries per cubic meter.

Control Methods

The primary control that can be exerted over pollutants in precipitation is that of improvement of air quality, through regulations and enforcement actions that lead to a reduction in pollutants and to a conformance with emission standards from stationary and non-stationary sources.

Monitoring Procedures

Monitoring of atmospheric and precipitation samples is required to verify the effectiveness of control methods.

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SECTION IV

SALT WATER INTRUSION

SEA WATER IN COASTAL AQUIFERS

Scope of the Problem

Under natural conditions fresh groundwater in coastal aquifers is discharged into the ocean at or seaward of the coastline. If, however, demands by man for groundwater become sufficiently large, the seaward flow of groundwater is decreased or even reversed. This causes the sea water to advance inland within the aquifer, thereby producing sea water intrusion.

This section briefly describes the history of sea water intrusion, occurrence of intrusion in the United States, environmental consequences, causal factors, and movement of sea water in the underground. Thereafter, control methods and monitoring procedures are presented, together with references to sources of additional information.

Emphasis in this section is on control of the lateral movement of sea water underground. Control of vertical flow mechanisms causing intrusion are presented subsequently.

History

Sea water intrusion developed as coastal population centers overdeveloped local groundwater resources to meet their water supply needs. The earliest published reports, dating from mid-19th century in England, describe increasing salinity of well waters in London and Liverpool. As the number of localities experiencing intrusion has grown steadily with time, so has recognition of the problem (Louisiana Water Resources Research Institute, 1968). Today, sea water intrusion exists on all continents as well as on many oceanic islands.

More than 70 years ago two European investigators found that saline water occurred underground near the coast at a depth of about 40 times the height of fresh water above sea level (Todd, 1959). This distribution, known as the Ghyben-Herzberg relation after its discovers, is related to the hydrostatic equilibrium existing between the two fluids of different densities. Although coastal intrusion is a hydrodynamic rather than a hydrostatic situation, the relation is a good first approximation to the sea water depth for nearly-horizontal flow conditions. Where head differences in the two fluids exist, refinements in the relation (Luscynski and Swarzenski, 1966) give improved results.

Intrusion in the United States

Almost all of the coastal states of the United States have some coastal aquifers polluted by the intrusion of sea water (Task Committee on Salt Water Intrusion, 1969; Todd, 1960). Florida is the most seriously affected state, followed by California, Texas, New York, and Hawaii.

The Florida problem stems from a combination of permeable limestone aquifers, a lengthy coastline, and the desire of people to live near the pleasant coastal beaches. Intrusion has been identified in 28 specific locations (Black, 1953). Some 18 municipal water supplies have been adversely affected since 1924. In the Miami area intrusion has long been a problem and was seriously augmented by interior drainage canals which lowered the water table and permitted sea water to advance inland by tidal action (Parker, et al, 1955).

In California, the large urban areas concentrated in the coastal zone have caused sea water intrusion in 12 localities; 7 others are threatened, and 15 others are regarded as potential sites (California Department of Water Resources, 1958). Most of the affected areas contain confined aquifers, and salinity increases can be traced to the lateral movement of sea water induced by overpumping. Major programs to control intrusion have been implemented in Southern California.

In Texas, intrusion is occurring in the Galveston, Texas City, Houston, and Beaumont-Port Arthur areas (Pettit and Winslow, 1957). Saline water is moving up-dip from the Gulf of Mexico in the confined Coastal Plain sediments. The problem in New York is centered around the periphery of the heavily pumped western half of Long Island (Luscynski and Swarzenski, 1966). The Honolulu aquifers of Hawaii have been extensively intruded by sea water due to continued overdraft conditions (Todd and Meyer, 1971; Visher and Mink, 1964).

Environmental Consequences

Because of its salt content, as little as 2 percent of sea water in fresh groundwater will make the water unusable in terms of US Public Health Service drinking water standards. Thus, only a small amount of intrusion can seriously threaten the continued use of an aquifer as a water-supply source.

Once invaded by sea water, an aquifer may remain polluted for decades. Even with application of various control mechanisms, the normal movement of groundwater precludes any rapid displacement of the sea water by fresh water. Prolonged abandonment of the underground resource may be required.

Causal Factors

The usual cause of sea water intrusion in coastal aquifers is over-pumping. Pumping lowers the groundwater level, either water table or piezometric surface, thereby reducing the fresh water flow to the ocean. Thus, even with a seaward gradient, sea water can advance inland. If the pumping is sufficiently great to reverse the gradient, fresh water flow ceases and sea water moves into the entire aquifer.

In flat coastal areas, drainage channels or canals can cause intrusion, in two ways. One is the reduction in water table elevation and its associated decrease in underground fresh water flow. The other is tidal action. If the channels are open to the ocean, tidal action can carry sea water long distances inland through the channels, where it may infiltrate and form fingers of saline water adjoining the channels.

In most oceanic islands fresh water forms a lens overlying sea water. If a well within the fresh water body is pumped at too high a rate, the underlying sea water will rise and pollute the well. Wells can also serve as means of vertical access; sea water in one aquifer may move into a fresh water aquifer lying above or below the saline zone.

Pollution Movement

The interface between underground fresh and saline waters has a parabolic form (Cooper, et al, 1964). The salt water tends to underride the less-dense fresh water. When an equilibrium is established, the sea water is essentially stationary, while the fresh water flows seaward. The length of the intruded wedge of sea water varies inversely with the magnitude of the fresh water flow. Thus, a reduction of fresh water flow is sufficient to cause intrusion; flow reversed is not required.

Because sea water intrusion represents miscible displacement of liquids in porous media, diffusion and hydrodynamic dispersion tend to mix the two fluids. The idealized interfacial surface becomes a transition zone. The thickness of the zone is highly variable; steady flows minimize the thickness, but nonsteady influences such as pumping, recharge, and tides increase the thickness. Measured thicknesses of transition zones range from a few feet in undeveloped sandy aquifers to hundreds of feet in overpumped basalt aquifers (Visher and Mink, 1964).

Flow within the transition zone varies from that of the fresh water body at the upper surface to near-zero at the lower surface. The movement in the transition zone transports salt to the ocean. Continuity considerations suggest that the salt discharge must come from the underlying sea water dispersing upward into the zone. It follows that there must be a landward sea water flow as sketched in Figure 4-1. This circulation has been verified by a field investigation at Miami, Florida (Cooper, et al, 1964).

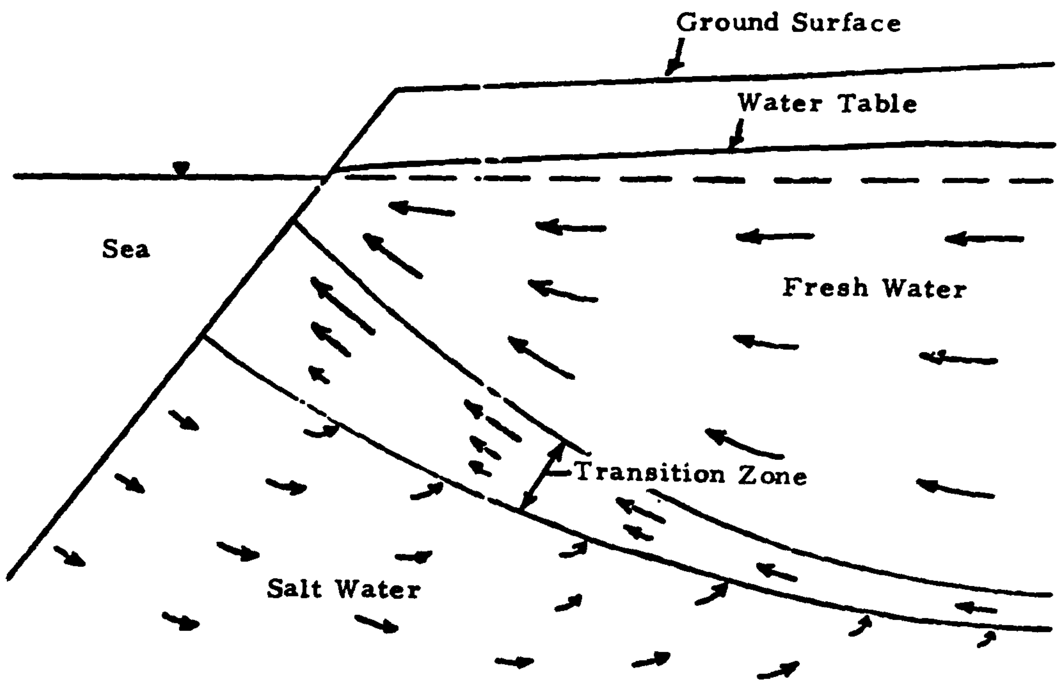

Figure 4-1. Schematic vertical cross section showing fresh water and sea water circulations with a transition zone.

Control Methods

A variety of methods have been proposed or utilized to control sea water intrusion (California Department of Water Resources, 1958; Todd, 1959).

- Control of Pumping Patterns. If pumping from a coastal groundwater basin is reduced or relocated, groundwater levels can be caused to rise. With an increased seaward hydraulic gradient, a partial recovery from sea water intrusion can be expected. Figure 4-2 illustrates the effect of moving pumping wells inland in a coastal confined aquifer.

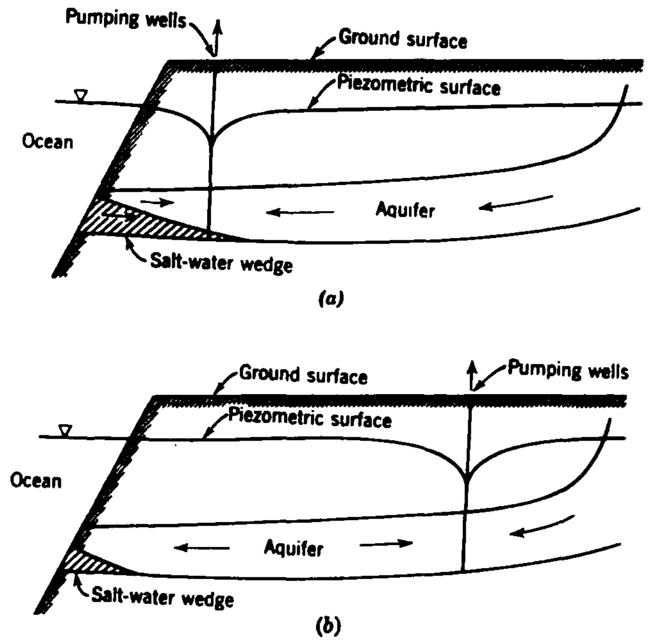

Figure 4-2. Control of sea water intrusion in a confined aquifer by shifting pumping wells from (a) near the coast to (b) an inland location (Todd, 1959).

- Artificial Recharge. Sea water intrusion can be controlled by artificially recharging an intruded aquifer from surface spreading areas or recharge wells. With overdraft eliminated, water levels and gradients can be properly maintained. Spreading areas are most suitable for recharging unconfined aquifers, and recharge wells for confined aquifers.

- Fresh Water Ridge. Maintenance of a fresh water ridge in an aquifer paralleling the coast can create a hydraulic barrier which will prevent the intrusion of sea water. A line of surface spreading areas would be appropriate for an unconfined aquifer, whereas a line of recharge wells would be necessary for a confined aquifer. A schematic cross section of the flow conditions within a confined aquifer is shown in Figure 4-3. With a line of recharge wells paralleling the coast, the ridge would consist of a series of peaks and saddles in the piezometric surface. The required elevation of the saddles above sea level will govern the well spacing and recharge rates required. The ridge should be located inland of a saline front so as to avoid displacing the sea water farther inland. This control method has the advantage of not restricting the usable groundwater storage capacity. The disadvantages are high cost and the need for supplemental water.

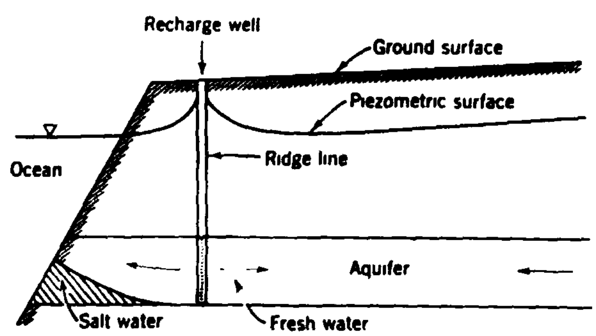

Figure 4-3. Control of sea water intrusion by a line of recharge wells to create a pressure ridge paralleling the coast (Todd, 1959).

Injection wells have been extensively and successfully employed along the Southern California coast (California Department of Water Resources, 1958 and 1966). A new project underway in Orange County, California, will inject a combination of reclaimed wastewaters and desalted sea water (Cofer, 1972). Details of well construction are available in a report on the Los Angeles West Coast Basin barrier (McIlwain, et al, 1970).

- Extraction Barrier. Reversing the ridge method, a line of wells may be constructed adjacent to and paralleling the coast and pumped to form a trough in the groundwater level. Gradients can be created to limit sea water intrusion to a stationary wedge inland of the trough, such as illustrated in Figure 4-4 for a confined aquifer. This method reduces the usable storage capacity of the basin, is expensive, and wastes the mixture of sea and fresh waters pumped from the trough.

  The trough method has been successfully tested at one location on the Southern California coast (California Department of Water Resources, 1970).

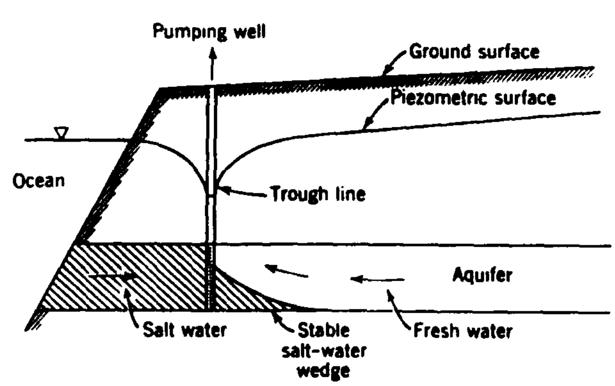

Figure 4-4. Control of sea water intrusion by a line of pumping wells creating a trough paralleling the coast (Todd, 1959).

- Combination Injection-Extraction Barrier. Using the last two methods, a combination injection ridge and pumping trough could be formed by two lines of wells along the coast. Figure 4-5 shows a schematic cross section of the method for a confined aquifer. Both extraction and recharge rates would be somewhat reduced over those required using either single method. The total number of wells required, however, would be substantially increased.

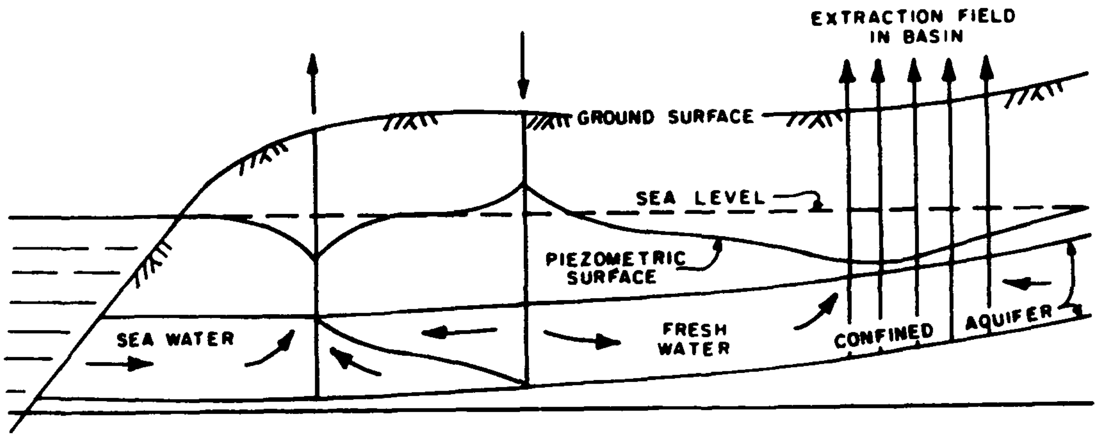

Figure 4-5. Control of sea water intrusion by a combination injection-extraction barrier using parallel lines of pumping and recharge wells (after California Department of Water Resources, 1966).

- Subsurface Barrier. By constructing an impermeable subsurface barrier through an aquifer and parallel to the coast, sea water would be prevented from entering the groundwater basin. Figure 4-6 shows a sketch of such a barrier in a confined aquifer. A barrier could be built using sheet piling, puddled clay, emulsified asphalt, cement grout, bentonite, silica gel, calcium acrylate, or plastics. Leakage due to the corrosive action of sea water or to earthquakes would need to be considered in a barrier design. The method would prove most feasible in a narrow, shallow alluvial canyon connecting with a larger inland aquifer. Although expensive, a barrier would permit full utilization of an aquifer.

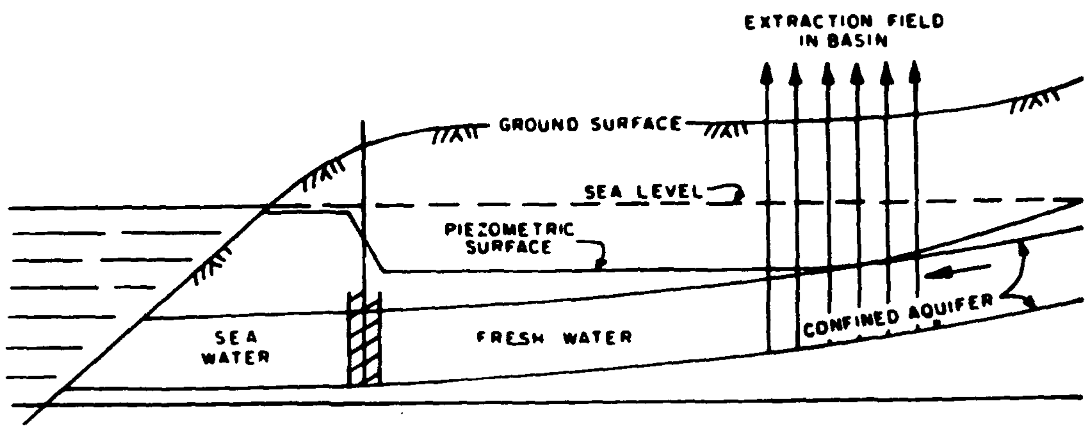

Figure 4-6. Control of sea water intrusion by construction of an impermeable subsurface barrier (after California Department of Water Resources, 1966).

- Tide Gate Control. Wherever drainage channels carry surplus waters from low-lying inland areas to the ocean, there is a danger of sea water penetrating inland during periods of high tides. If the channels are unlined, as is often the case, the sea water immediately invades the adjoining shallow aquifers. To control such intrusion, tide gates should be installed at the outlet of each channel. These will permit drainage water to be discharged to the ocean but prevent sea water from advancing inland. This control method has operated successfully for many years in the Miami, Florida, area (Parker, et al, 1955).

Monitoring Procedures

Whatever the method of sea water intrusion control adopted, a monitoring program will be a necessary part of the system. Conditions both within and outside of the intruded zone should be measured. Data will be required on groundwater levels and chloride concentration. The vertical structure of the transition zone should be measured at a few key locations.

In general, observation wells should be located so as to provide a comprehensive picture of the local intrusion situation: along any line of control, on the seaward side, and on the landward side. The number of wells required can vary with individual circumstances; however, the fact that 30 observation wells were drilled for each mile of recharge line in the West Coast Basin of Los Angeles (McIlwain, et al, 1970) is indicative that a reasonably dense network will be required.

Observation wells should be measured for groundwater levels and chloride (or total dissolved solids) at intervals of one to two months under normal circumstances. Electrical conductivity logs should be run in selected wells on a similar frequency.

Most observation wells for the Los Angeles injection barrier were cased with 4-inch PVC plastic pipe in a gravel-packed and grouted 14-inch diameter hole (McIlwain, et al, 1970). For economic reasons multiple casings into as many as three aquifers were placed in the same drill hole. This required a 22-inch diameter drill hole with each of the gravel-packed casings grouted between the aquifers to prevent communication.

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SALINE WATER IN INLAND AQUIFERS

Scope of the Problem

Hydrologic data accumulated in recent years indicate that large quantities of saline water exist under diverse geologic and hydrologic environments in the United States. Most of the nation's largest inland sources of fresh groundwater are in close proximity to natural bodies of saline groundwater.

Saline water derived from remnants of ancient sea inundations or water contaminated by natural mineral deposits can be found at relatively shallow depths throughout large portions of the United States. Freshwater recharge has tended to flush much of the saline water from aquifers during recent geologic time, but saline water remains at depth or where the movement of groundwater is restricted. Brines occur in almost all areas at the depths explored and developed by the oil industry.

Saline water in inland aquifers may be derived from one or more of the following sources (Task Committee on Salt Water Intrusion, 1969):

- Sea water which entered aquifers during deposition or during a high stand of the sea in past geologic time
- Salt in salt domes, thin beds, or disseminated in the geologic formations
- Slightly saline water concentrated by evaporation in playas or other enclosed areas
- Return flows from irrigated lands
- Man's saline wastes.

When development of an aquifer by acts of man causes saline water from any of these sources to move into the freshwater aquifer, salt-water intrusion results.

Intrusion in the United States

Considerable information exists on the geographic distribution of saline groundwater (here defined as water containing more than 1,000 ppm dissolved solids) (Feth, 1965; Feth, et al, 1965; Task Committee on Salt Water Intrusion, 1969). These reports indicate that approximately two-thirds of the conterminous United States is underlain in part by saline groundwater.

In the Atlantic and Gulf Coastal Plain and in many groundwater basins on the Pacific Coast, saline water occurs because of sea water that was trapped in the sediments during deposition or that invaded the sediments during previous high stands of the sea.

In the Midwest, bedrock aquifers generally contain mineralized water at depths below about 400 feet. Aquifers with saline waters of more than 1,000 ppm dissolved solids underlie fresh-water aquifers throughout most of the Great Plains area from central Texas to Canada. In the mountainous area from the Rocky Mountains to the Pacific Coast, saline water occurs at depth in many groundwater basins.

Environmental Consequences

Intruded fresh-water aquifers typically are locally affected. Because of the relatively slow movement of groundwater, saline water intrusion may produce detrimental effects on groundwater quality that could persist for months under the most favorable circumstances, or many years or decades in other cases.

Causal Factors

Salt water intrusion can result from several mechanisms. One involves the upward movement of saline water through the aquifer as a result of some act of man on the hydrologic regime, such as overpumping. Another occurs by saline water moving vertically through wells into a fresh-water aquifer. Saline water intrusion also can occur where construction of a waterway or channel involves removal of materials which have acted as an impermeable blanket between saline waters and fresh-water aquifers. Destruction of natural barriers may also permit saline water on the surface to be carried past natural geologic barriers, such as faults which previously protected the fresh-water aquifer.

Pumping of an aquifer underlain by saline water will cause the groundwater level to be lowered, which in turn can cause an upconing of the saline water into the aquifer and eventually the well itself (Winslow and Doyel, 1954). Figure 4-7 shows the sequence of upconing to a pumping well in an unconfined aquifer.

Where saline and fresh-water aquifers are connected hydraulically, dewatering operations, as for quarries, roads, or excavations, may cause vertical migration of saline water. Similarly, the deepening or dredging of a gaining stream will cause a lowering of the head in the aquifer near the stream. If the aquifer is hydraulically connected to an underlying saline aquifer, the lowering of head will induce upward movement of saline water. Figure 4-8 illustrates the zone of saline water intrusion produced when a water table is lowered. This indicates that encroachment of saline water can be a potential problem where flood control or other projects modify stream stages.

Extensive pollution of freshwater aquifers has been caused by vertical leakage of saline water through inactive or abandoned wells or test holes. A well is an avenue of nearly infinite vertical permeability through which fluids may move. Pumping from fresh-water aquifers may lower water tables below the piezometric surfaces of lower saline water zones. Examples of saline water moving upward into a fresh-water aquifer through various types of wells are sketched in Figure 4-9.

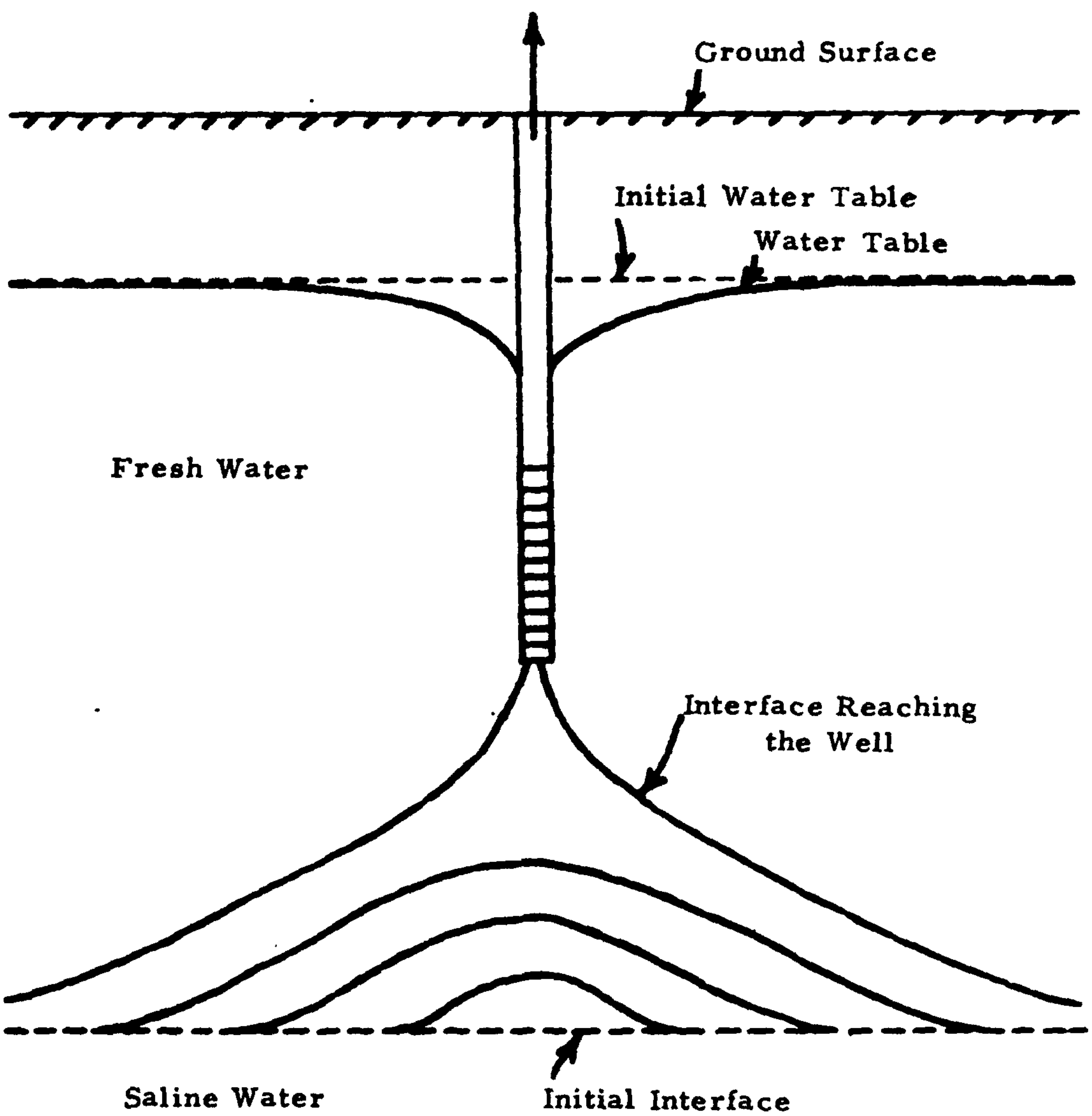


Figure 4-7. Schematic diagram of upconing of underlying saline water to a pumping well.

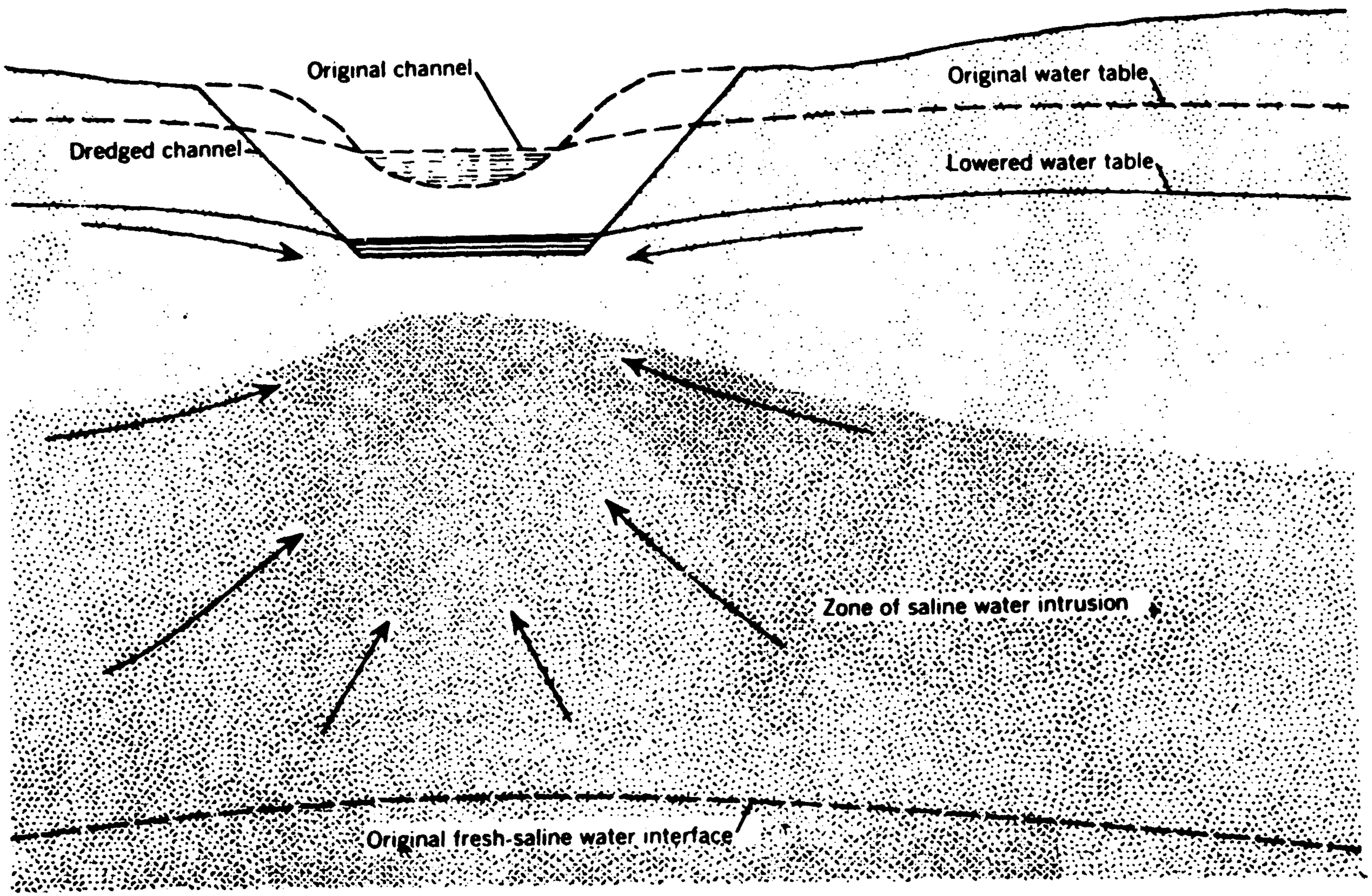


Figure 4-8. Diagram showing upward migration of saline water caused by lowering of water levels in a gaining stream (Deutsch, 1963).

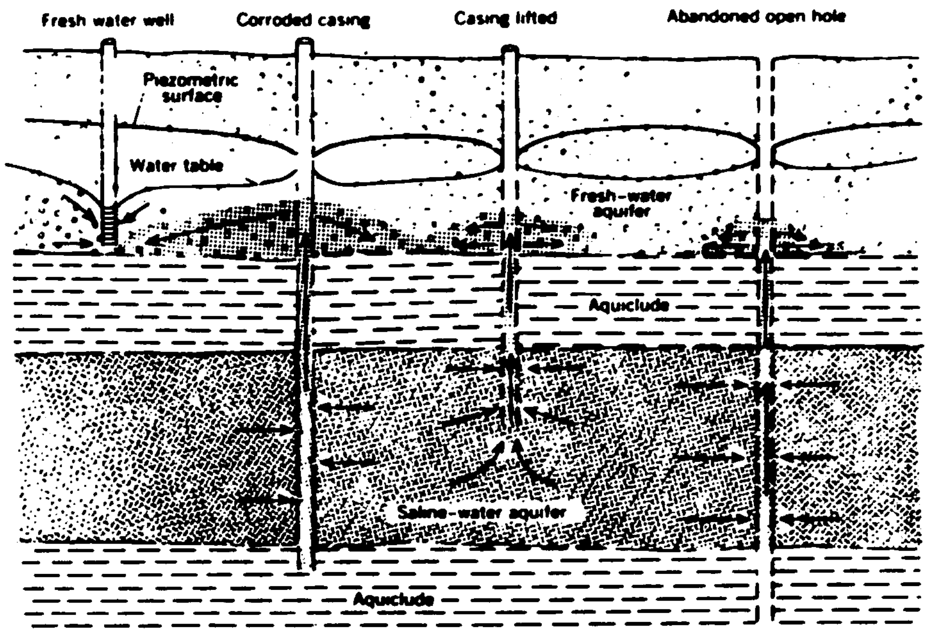
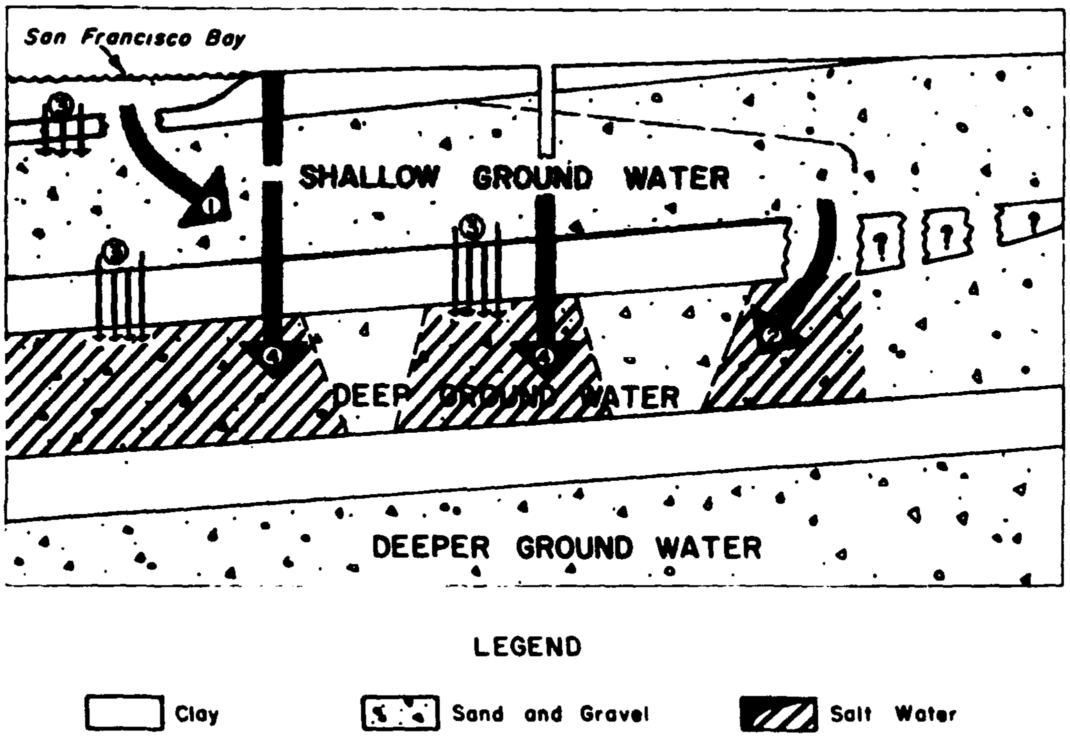


Figure 4-9. Diagram showing interformational leakage by vertical movement of water through wells where the piezometric surface lies above the water table (after Deutsch, 1963).

Indicative of all of the above mechanisms is the intrusion situation in Southern Alameda County, California, shown in Figure 4-10. Here a combination of four causal factors — natural and man-made — has led to intrusion in two distinct aquifers. Although the intruding water shown here is sea water, the mechanisms apply equally to any saline water source. Saline intrusion by downward seepage from surface sources and from brine injection wells is described elsewhere.

Pollution Movement

When an aquifer contains an underlying layer of saline water and is pumped by a well penetrating only the upper fresh water portion, a local rise of the interface below the well occurs. With continued pumping this upconing rises to successively higher levels until eventually it may reach the well. When pumping is stopped, the denser saline water tends to subside to its original position.



NOTE

1. Direct movement of bay waters through natural "windows"
2. Spilling of degraded ground waters.
3. Slow percolation of salt water through reservoir roof.
4. Spilling or cascading of saline surface waters or degraded ground water through wells

Figure 4-10. Illustrative sketch showing four mechanisms producing saline water intrusion in Southern Alameda County, California (after California Department of Water Resources, 1960).

The factors governing upconing include the pumping rate of the well, the distance between the well and the saline water, the duration of pumping, the permeability of the aquifer, and the density difference between the fresh and saline waters.

Upconing is a complex phenomenon. Quantitative criteria have been formulated for the design and operation of wells for skimming fresh water from above saline water (Schmorak and Mercado, 1969). From a water-supply standpoint it is important to determine the optimum location, depth, spacing, pumping rate, and pumping sequence to maximize production of fresh groundwater while minimizing the under-mixing of fresh and saline waters.

The movement of saline water within wells is in the direction of the hydraulic gradient. The flow can occur either upward or downward, depending upon the direction of the head differential. Also, head differences may result from natural geologic causes or from effects of pumping. Typically, a well pumping from a fresh-water zone reduces the head there to a value lower than that of other zones. If the non-pumped zones contain saline water and are connected hydraulically to the well, intrusion into the fresh-water zone will result.

Control Methods

A variety of methods are available to control saline water intrusion in aquifers. The selection of a particular method will depend on the local circumstances responsible for the intrusion. Alternative control methods are briefly described in the following subsections.

- Reduced Pumping. Where pumping of a fresh-water aquifer produces upconing of saline water, reducing pumping is an effective control method. This may take the form of actual termination of pumping, of reduction in the pumping rate from individual wells, or of the decentralization of wells.

The more pumpage is reduced, the greater the tendency for the saline water interface to subside and to form a horizontal surface.

Illustrative of the consequences of pumping rate are data shown in Figure 4-11 from the Honolulu aquifer. Here underlying saline water (actually sea water) in a nearby observation well moves upward and downward in accordance with the pumping rate of a well.

- Increased Groundwater Levels. In situations where surface construction or excavations have lowered groundwater levels and caused underlying saline groundwater to rise (see Figure 4-8), any action which raises the groundwater level will be effective in suppressing intrusion. Artificial recharge of an unconfined aquifer, for example, may have a beneficial effect. Similarly, raising surface water levels, as by regulating stream stages or by releasing water into surface excavations, will cause a corresponding upward adjustment in the adjacent water table.

- Protective Pumping. Because saline water moves into a fresh-water aquifer under the influence of a pressure gradient, an effective control method is to reduce the pressure in the saline water zone. This can be accomplished by drilling and pumping a well perforated only in the saline water portion of the aquifer. Although the water pumped is saline and may present a disposal problem, this method does permit the continued utilization of the underground freshwater resources without increasing intrusion. The method was successfully applied to counteract a growing intrusion problem in Brunswick, Georgia (Gregg, 1971).

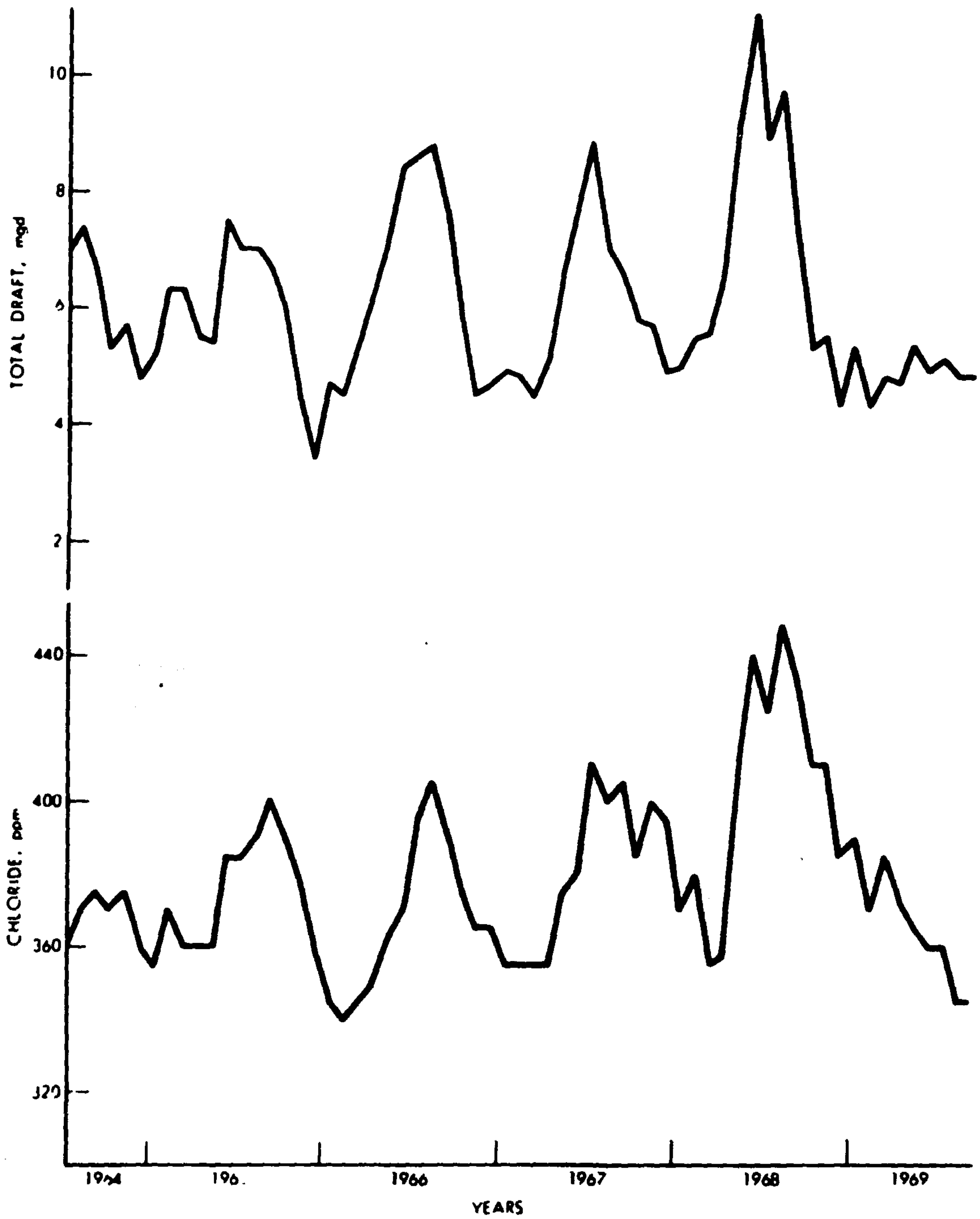


Figure 4-11. Monthly variations of total draft and chloride content in a nearby observation well, Honolulu aquifer (after Todd and Meyer, 1971).

- Sealing Wells. To minimize the vertical movement of saline water in abandoned wells and test holes, these should be completely sealed by backfilling with an impermeable material. Dumping of loose soil into a well seldom provides an effective guarantee of impermeability, particularly in a deep well. Preferably, a clay or cement slurry should be pumped into the well, filling from the bottom upward. When the material solidifies, it will create a void-free column having a lower permeability than that of the surrounding formations.
- Well Construction. To control the movement of saline water within active wells that are either pumping or resting requires careful well construction. During the drilling of a well, one or more zones of saline water may be encountered. When the full depth of the well has been reached, those formations expected to be developed for freshwater production are selected. Perforations should be placed only opposite the fresh-water zones. Unperforated casing should be placed opposite saline water strata, with the annulus outside of the casing carefully sealed to isolate saline zones from the fresh-water zones. The seals may be of bentonite or cement grout. Details of well construction are available in standard references (Campbell and Lehr, 1973; Gibson and Singer, 1971; Todd, 1959).

Monitoring Procedures

When fresh-water aquifers need to be protected against vertical intrusion, a monitoring network to verify the effectiveness of the control method should be installed. In general, the network will consist of observation wells perforated within the fresh-water zone and sampled regularly for total dissolved solids or electrical conductivity. The monitoring wells should be in the deepest portions of the fresh-water zone so as to reveal the first evidence of intrusion, and spaced close enough to pumping wells that upconing will be detected.

Periodic checks should also be made to ascertain that any newly abandoned wells or test holes are properly sealed.

Regular measurements of pumping rates and groundwater level fluctuations, both natural and artifically produced, will help to recognize causal factors responsible for actual or incipient intrusion problems.

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SECTION V

POLLUTION FROM DIVERSION OF FLOW

EFFECTS OF URBAN AREAS

Scope of the Problem

Urbanization is the concentration of people and of domestic, commercial, and industrial structures in a given geographic area. Urban areas commonly include both suburban and central city complexes. The rapid trend toward urbanization is indicated by the fact that more than two-thirds of the nation's population now reside in urban centers that occupy about 7 percent of the land area of the United States. By the year 2000 the urban population may include as much as three-fourths of the population (Thomas and Schneider, 1970).

This concentration of people and their activities will produce an agglomeration both of water supplies and of the wastes produced. Water may be diverted and conveyed to an urban area from sources hundreds of miles away. An example is the Los Angeles-San Diego metropolitan complex which receives water from the Colorado River and from Northern California. Runoff and infiltration in urban areas are markedly different than in the original undeveloped area. Thus, urban areas produce hydrologic and hydraulic problems connected with development of water supplies (Schneider and Spieker, 1969); increases in peak streamflows (Rantz, 1970); and increased mineralization of water resources due to changes in land-use patterns (Leopold, 1968). These urban-area problems are discussed briefly in the material that follows. They are treated in more detail elsewhere in this report.

Seawater intrusion in coastal aquifers is often associated with urban areas due to overpumping, reduction in natural recharge, and sometimes loss of recharge from septic systems that have been replaced by public sewers. Runoff from urban areas is heavily polluted, especially the initial flows (Sartor and Boyd, 1972).

Urban leachate, the source of groundwater pollution, owes its composition to dissolved organic and inorganic chemical constituents derived from a multiplicity of sources such as dirty air and precipitation, leaching of asphalt streets, inefficient methods of waste disposal, and poor housekeeping techniques at innumerable domestic and industrial locations (Hackett, 1969). Urban leachate can be a direct contributor to stream pollution because many urban centers are located in lowlands adjacent to large streams. In reverse, groundwater withdrawals may permit flow of polluted water from streams to hydraulically interconnected aquifers. The expansion of densely populated urban and suburban developments into former rural or heavily fertilized agricultural areas has compounded the problem of groundwater pollution by causing a mingling of the effluent from cesspools and septic tanks with fertilizer-contaminated groundwater. Moreover, in many urban and suburban areas, wastes that are accidentally or intentionally discharged on the land surface often reach shallow aquifers.

The pollutional effects of urbanization change as development proceeds. Initially, large amounts of erosional debris are produced as the original land surface is disturbed by construction. In the mature stage, domestic and industrial sewage, street runoff, garbage and refuse are the principal sources of pollution, which intensify with time.

Pollution from urban areas is not confined to the areas themselves or to the immediately adjacent areas. The effects often extend for considerable distances in groundwaters as well as in surface waters.

Environmental Consequences

Degradation of water quality may occur in both shallow and deep aquifers. Increased mineralization, including increases in the content of nitrogen, chloride, sulfate, and hardness of the water, has resulted in limitations on pumping from some shallow aquifers in California and Long Island.

In scattered places illnesses have resulted from contamination of water by sewage and industrial wastes. The occurrence of nitrate, MBAS (detergent), and phosphate in groundwater in Nassau County, Long Island, New York, has been investigated in detail by Perlmutter and Koch (1971 and 1972). Figure 5-1 shows the location and subsurface extent of MBAS contamination in shallow groundwater beneath an unsewered suburban residential area in southeastern Nassau County, Long Island, New York. The Nassau-Suffolk Research Task Group (1969) has made detailed studies of pollution near individual septic systems in Long Island.

Gaining streams in Long Island also show significant contents of nitrate and MBAS from inflow of contaminated groundwater (Perlmutter and Koch, 1971 and 1972; Cohen and others, 1971). High nitrogen content of groundwater in Kings County, Long Island, New York, is attributed largely to long-term leakage of public sewers (Kimmel, 1972). Contamination of shallow public-supply wells by detergents from cesspoll effluent in Suffolk County, Long Island, New York, has resulted in shutdowns of wells except during periods of peak demand (Perlmutter and Guerrera, 1970). Similar problems occur in California; Nightingale (1970) has analyzed contents and trends in salinity and nitrate in the Fresno-Clovis area.

Urbanization grossly alters the hydrology of an area. In general, this results in a decrease in the natural recharge to underlying groundwater unless compensated by artificial recharge. This, in turn, has an adverse effect on groundwater quality if the quality of the natural recharge was high. The decrease is due to the impervious surfaces of an urban area—houses, streets, sidewalks, and commercial, industrial, and parking areas, which reduce direct infiltration and deep percolation of precipitation (Seaburn, 1969). Peak storm runoff and total runoff is increased but over shorter time periods, resulting in decreased

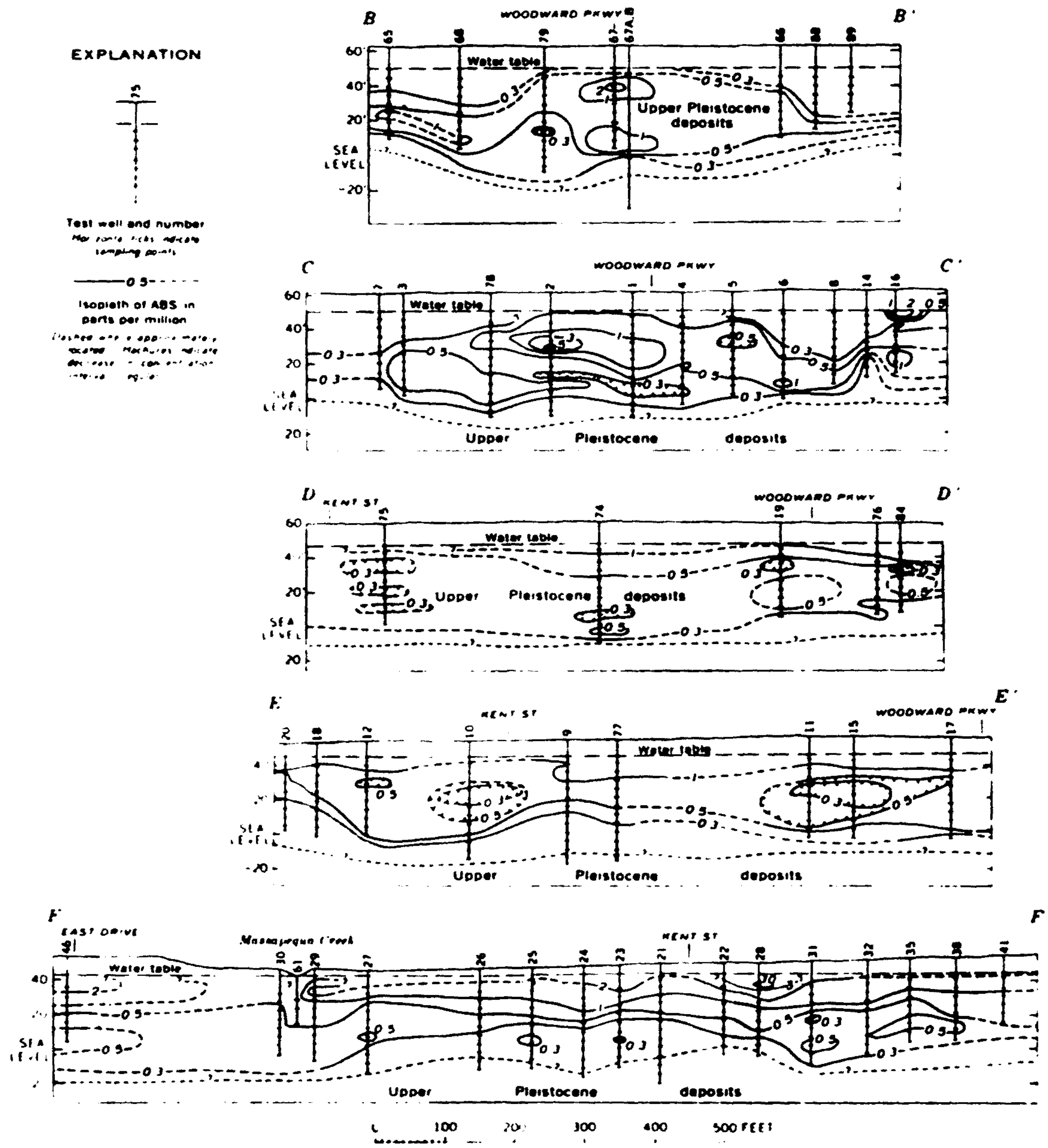

Figure 5-1. Hydrogeochemical sections oblique to the direction of groundwater flow, showing lines of equal concentration of MBAS in Nassau County, Long Island, New York. Contaminated water is shaded; lower limit shown at about 0. 1 mg/liter (Perlmutter, et al, 1964).

streambed percolation. Natural streambed recharge is further decreased by concrete storm drains and the lining of natural channels for flood control purposes.

In the Santa Ana River Basin in Southern California, pollution of groundwater has resulted from the importation by municipalities of Colorado River water, which is high in salinity (750–850 mg/liter total dissolved solids). Pollution has resulted from artificial recharge and also from percolation of water used for irrigation of lawns and parks.

High local groundwater temperatures attributed to recharge of warm water used for air conditioning have been investigated in Manhattan and the Bronx, New York, by Perlmutter and Arnow (1953), and in Brooklyn by Brashears (1941). Pluhowski (1970) attributed a 5- to 8-degree centigrade rise in the summer temperature of water in gaining streams on Long Island to a variety of urban factors such as pond and lake development, cutting of vegetation, increased stormwater runoff into streams, and decreased groundwater inflow.

Wikre (1973) reported several pollution incidents related to urbanization in Minnesota. These included drainage of surface water through wells in sumps which produced discolored and turbid water as well as positive coliform determinations, pollution from leachate in poorly designed landfills, and pollution from solvents disposed of in pits and basins. Poor housekeeping practices at an 80-acre industrial site resulted in the saturation of the area with creosote and other petroleum products over a long period of time. The severity of the creosote leaching problem was recognized when the water from a nearby municipal well developed an unpleasant taste.

Road Salts

A relatively recent and unique problem that has attracted considerable attention is the pollution of groundwater resulting from application of deicing salts to streets and highways in winter. The region affected is largely the Northeast and the North-Central states (Hanes and others, 1970). The salt appears to reach the groundwater both from storage stockpiles (Figure 5-2) and from solution of salt that has been spread on roadways.

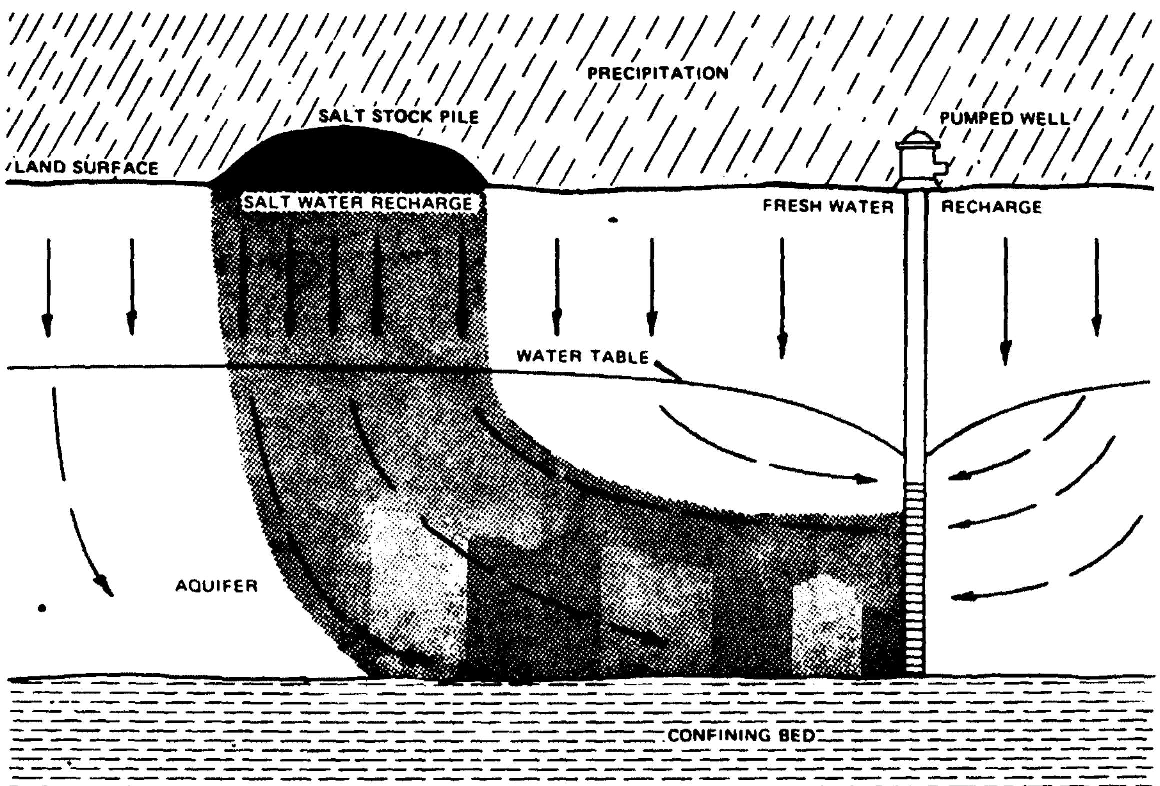

Figure 5-2. Flow pattern showing downward leaching of contaminants from a salt stockpile and movement toward a pumped well (Deutsch, 1963).

Long-term degradation of groundwater quality has been the experience of the New Hampshire Highway Department with highway deicing salts (Hanes and other, 1970). Year after year, chloride contents of water in certain shallow wells rose, to concentrations of 3800 mg/liter. Not only was the groundwater quality degraded, but also the casings and screens of the wells were badly corroded, so that 37 wells had to be replaced. Deutsch (1963) reported a similar situation in Michigan where water from wells was found to contain as much as 4400 mg/liter of chloride due to infiltration of highway salts.

An analysis of the steady-state concentration of road salt added to groundwater was made for east-central Massachusetts (Huling and Hollocher, 1972). Assuming an application rate of 20 metric tons of salt per lane mile per year, and taking into account local rainfall and infiltration values, a chloride concentration of 100 mg/liter was obtained for the gross area. Local deviations from this regional average could easily be from two to four times this figure, especially near major highways. Wells in at least 15 communities in eastern Massachusetts produce water containing more than 100 mg of chloride per liter.

The problem is widespread, litigation on the matter is not uncommon, and research on alternative non-polluting substances is underway (Little, 1973).

Sources and Nature of Pollutants

Groundwater in an urban environmenta may contain almost every conceivable inorganic and organic pollutant. A brief summary by source of the principal potential urban pollutants is given in Table 5-1.

Pollution Movement

The principal mechanisms of groundwater pollution in urban areas are infiltration of fluids placed at or near the land surface and leaching of soluble materials on the surface. The sources of fluids include

Table 5-1. Summary of urban groundwater pollutants

Source	Principal Potential Pollutants
Atmosphere	Particulate matter, heavy metals, salts
Precipitation	Particulate matter, salts, dissolved gases
Seawater encroachment	High dissolved solids, particularly sodium and chloride
Industrial lagoons	Heavy metals, acids, solvents, other inorganic and organic substances
Cesspool, septic tank, and sewage lagoon effluents	Sewage contaminants including high dissolved solids, chloride, sulfate, nitrogen, phosphate, detergents, bacteria
Leaky pipelines and storage tanks	Gasoline, fuel oil, solvents, and other chemicals
Spills of liquid chemicals	Heavy metals, salt, other inorganic and organic chemicals
Urban runoff	Salt, fertilizer chemicals, nitrogen, and petroleum products
Landfills	Soluble organics, iron, manganese, methane, caron dioxide, exotic industrial wastes, nitrogen, other dissolved constituents, bacteria
Leaky sewers	Sewage contaminants, industrial chemicals, and miscellaneous highway pollutants
Stockpiles of solid raw materials	Heavy metals, salt, other inorganic and organic chemicals
Surface storage of solid wastes	Heavy metals, salt, other inorganic and organic chemicals
Deicing salts for roads	Salts

deliberate disposal through wells, pits, and basins, and seepage from hundreds or thousands of miles of leaky storm water and sanitary sewers, water mains, gas mains, steam pipes, industrial pipelines, cesspools, septic tanks, and other subsurface facilities. Some natural treatment of the fluid occurs as it seeps downward through the soil zone; however, large quantities of pollutants, particularly the mineral constituents, may reach the water table in the uppermost aquifer. From there, the polluted water may move laterally toward natural discharge areas or toward pumping wells.

Control Methods

The following list suggests procedures that can prevent, reduce, or eliminate pollution in urban and suburban areas. The applicability of any particular method depends, of course, on local circumstances.

- Pre-treatment of industrial and sewage wastes before disposal into lagoons and pits.
- Lining of disposal basins where the intent is to prevent leaching into groundwater.
- Collection, by means of drains and wells, and treatment of leachate derived from landfills, industrial basins, and sewage lagoons.
- Proper management of groundwater pumping to prevent or retard seawater encroachment in coastal aquifers.
- Creation, by means of wells, of injection ridges or pumping troughs to retard seawater encroachment.
- Abandonment or prohibition of cesspool and septic tank systems in densely populated areas and replacement by sanitary sewer systems.
- Proper construction of new wells and plugging of abandoned wells.
- Implementation of better housekeeping practices for land storage of wastes, and monitoring of potential industrial polluters through permits and on-site inspection.

- Reduction in use of road deicing salts.
- Storage of stockpiles of chemicals under cover and on impermeable platforms to prevent leaching; recovery and treatment of leachate which has occurred.
- Publicizing procedures for optimal applications of lawn fertilizers and garden chemicals to minimize potential leaching.
- Frequent and adequate cleaning of streets.
- Provision for artificial recharge with high quality water to compensate for reduction in natural recharge.
- Use of high-quality water for municipal and industrial purposes where return flow from those uses will contribute to groundwater; alternatively, desalination of wastewaters before discharge.
- Provision for adequate treatment of runoff from urban areas prior to discharge into streams which recharge groundwater.

Monitoring Procedures

Where urban areas use groundwater from local wells, the wells should be monitored for pollutants that are associated with urban activities but may not be included in standard water analyses; for example, heavy metals. When specific threats to groundwater quality from past or present practices of waste disposal (accidental or deliberate) can be identified, special monitor wells may be warranted to provide advance warning of pollutants approaching water-supply wells.

Even though local groundwater may not be a presently important source of supply in many communities, monitoring of its ambient quality is highly desirable in order to detect degradation and take action to reduce or prevent further pollution.

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EFFECTS OF WATER CONTROL STRUCTURES

The construction and operation of structures to control surface water, such as dams, levees, channels, floodways, causeways, and flow diversion facilities, may in most cases have little influence on groundwater quality. However, adverse effects are possible and an awareness of them is important. Control measures are sometimes required. The following subsections briefly describe some of these effects together with suggested methods for controlling the possible resulting groundwater pollution.

Dams

The most important effect of a dam on groundwater quality occurs where the foundation of the structure provides a substantial or complete cutoff of groundwater flow in an aquifer. For example, Prado Dam on the Santa Ana River in southern California, a US Corps of Engineers flood control structure, is located at the upper end of a narrow, V-shaped canyon which forms the natural outlet for both surface and groundwaters from the Upper Santa Ana Valley, an extensively developed region. The cutoff wall extends to bedrock and blocks subsurface flow out of the upstream groundwater basins. Such a stoppage reduces the hydraulic gradient of the groundwater upstream of the dam. This causes an increased accumulation of pollutants in the groundwater, because of slower movement or complete stoppage; the natural disposal of salinity from the basin or aquifer is reduced or eliminated. Under these circumstances the resulting accumulation of salts from natural or man-made sources, such as irrigation return flows, may markedly increase the groundwater salinity.

A second and related effect is due to the higher water table created back of a dam. This brings the groundwater closer to the ground surface where the opportunity for pollution from agricultural and septic system sources, for example, may be increased. Marshy areas, swamps, and pools may be created; evapotranspiration losses then concentrate salinity in the groundwater. There may also be adverse effects on surface-water quality.

Even in situations where the dam and its foundations do not substantially alter the total groundwater flow through the underlying aquifers, the localized effects on groundwater levels and on the original pattern of groundwater flow may have significant adverse impacts on groundwater quality.

The reservoir created by the dam may have somewhat similar effects on the groundwater of the area. If water is stored in the reservoir for significant periods of time, the effects may be more pronounced than those resulting from the dam itself. Seepage losses from the reservoir also contribute to the groundwater. If the quality of the water in the reservoir is better than that of the groundwater, improvement in groundwater quality results. Conversely, seepage losses from a reservoir storing poorer quality water (eg, reclaimed water) degrade the groundwater.

Methods to control groundwater pollution by dams could include use of one or more of the following alternatives.

- Design the dam and its foundation so that there is a minimum restriction to the down-valley flow of groundwater. The feasibility of this approach will depend, of course, on the size and type of dam as well as the geologic conditions of the dam-site.

- Make provision for controlled releases past the dam.

- Lower the water table upstream from the dam by appropriately placed pumping wells. This would reduce the opportunity for pollution from ground surface sources and would reduce the residence time of stored groundwater. In general, water pumped from the wells would be of satisfactory quality for any available local beneficial uses; if none existed, the water could simply be released downstream of the dam. This would increase the outflow of salts from the basin, minimizing accumulation.

- Minimize potential sources of pollution in the area upstream from the dam. This could involve changes in land use, reduction in application of agricultural fertilizers, or removal of cattle from the area.
- If the reservoir is to store poor-quality water, a site should be selected where seepage losses will be minimal. If such a site does not exist, it may be necessary to wholly or partially line the reservoir bottom using, for example, compacted clay.

Levees

Levees are generally low structures located along the edges of surface water bodies such as rivers, reservoirs, lakes, and the sea to prevent inundation of land behind the levees during periods of high water levels resulting from floods, storms, or tides. Levees may be constructed to form a controlled channel. Only in rare instances do levees have a subsurface vertical extent sufficient to form a barrier to groundwater flow.

In coastal areas levees prevent the flooding of land by seawater. As a result, the quality of groundwater in the aquifers behind these levees is protected. The principal harmful effect of levees on groundwater quality occurs in floodplains of rivers. The mineral quality of most floodwaters, neglecting their suspended sediment, is higher than that of groundwater. During periodic inundations of floodplains, some of the water infiltrates to the groundwater and acts to improve its quality by dilution. Where levees prevent this action and thus reduce the natural recharge, the mineral quality of the groundwater will tend to deteriorate with time.

To counteract this effect which tends to degrade groundwater, two possibilities deserve consideration. One would be to pump groundwater from the aquifer behind the levee so as to increase the circulation of groundwater and to remove accumulations of salinity. The other approach would be to divert fresh water to the land behind the levee. By overirrigation or other means of artificial recharge with water of a quality equal to or better than that of the existing recharge, a dilution of the groundwater similar to that produced by natural floodwaters could be maintained.

Channels

Artificial channels are generally constructed to alter the alignment or configuration of natural river or stream channels for some purpose such as navigation or flood protection. In some situations, entirely new channels are constructed. Any artificial channel will tend to alter the natural circulation of the groundwater. Natural recharge to the groundwater may be increased or decreased depending upon location, depth, and other characteristics of the new channel. Thorough investigation of possible effects upon both quantity and quality of groundwater should be made before undertaking a channelization project.

An important distinction in terms of their effect on groundwater quality is whether channels are lined or unlined. A lined channel, constructed of an impermeable material such as concrete, prevents in many reaches the natural recharge of streamflow to groundwater. The water table may be lowered, and groundwater circulation and dilution reduced, so that quality is impaired.

To control this situation water needs to be artificially recharged to the groundwater. This can be done by installation of ditches or basins for artificial recharge in the vicinity of the lined channel. High-quality water diverted from the stream or derived from some other source and released into these structures would infiltrate to the groundwater and thus compensate for the loss of natural streambed recharge. This is extensively practiced in California.

In unlined channels, a primary effect is that produced by changing the water table elevation. If a channel is dredged in an area where the water table is close to the ground surface, the new channel acts as a drain and lowers the water table. If the groundwater body is underlain by saline water, the reduction in freshwater head may cause the saline water to rise and pollute the fresh groundwater.

Methods to control this effect include:

- Install pumping wells in the underlying saline water. Removal of a portion of the saline water by pumping will counteract its upward movement and protect the overlying freshwater. Means for the disposal of the saline water must be provided, as by evaporation from lined basins, disposal to the ocean, or desalting and use.

- Line the channel with an impermeable material. This will prevent dewatering of the upper portion of the aquifer and hence maintain the original natural conditions of groundwater quality. Some drainage to prevent uplift of the channel lining would be necessary.

There may be some loss in streambed recharge even with unlined channels if the hydraulic characteristics are improved and the gradient steepened, resulting in higher velocities. The effects on groundwater quality are the same as for lined channels. Artificial recharge can be used to compensate for the loss.

Unlined channels may allow polluted water to enter the groundwater if the groundwater is below the bottom of the channel and if there is no impermeable layer above the groundwater body.

In some coastal areas (eg, Florida and California) natural channels have been deepened or new channels excavated. These have sometimes cut deeply into or through the underlying clay formation which originally acted as a natural barrier and prevented the downward movement of saline water into the underlying freshwater aquifers. Serious groundwater pollution has resulted, as from the Los Cerritos Creek flood channel near Seal Beach, California. Such channels should be located, designed, and constructed with care so that the natural barriers to saline water intrusion will not be impaired. If this is not possible, the channels should be lined with impervious material. In some flood control channels it may be possible to install inflatable rubber dams to prevent the movement of saline water from the sea or bay into the channel.

Floodways or Bypass Channels

These are usually wide artificial channels constructed to carry floodwaters that exceed the capacity of natural river channels. As such, these are invariably unlined, and the bottom elevation is at or close to the natural ground surface level.

The effect of most such channels on groundwater quality is minimal, particularly as they typically carry water for only a small fraction of each year. If anything, floodwater flowing in a bypass channel and infiltrating into the ground would tend to improve the local groundwater quality.

Because of the negligible effect in degrading groundwater quality, no specific control measures are suggested.

Causeways

A causeway is a raised highway or railway across low or wet ground, frequently made of earthen embankments with bridged openings at intervals. The principal effect on groundwater quality might be some interference with the flow of surface water which could impair groundwater recharge, or, through ponding, increase the percolation of polluted water. Otherwise, the effects are considered to be minimal. Proper drainage should be provided to eliminate ponding.

Flow Diversion Facilities

Flow diversion facilities may consist of gates, locks, or weirs to regulate the distribution and the levels of surface water. In general, these are smaller structures than dams; consequently, the influence of their foundations on local groundwater flows is usually minor.

Effects of the structure on groundwater quality are analogous to those previously described for dams. Similarly, control measures, if required to protect groundwater quality, would be modifications of the procedures outlined for dams.

The principal effects of operation of such structures on groundwater quality results from the diversion of water away from its original course for use elsewhere, thus decreasing local recharge to the groundwater. Controlled releases past the diversion structure may be required, sufficient in amount to provide the same volume of recharge, or artificial recharge may be practiced to compensate for the loss.

Sewers

Sewers can pollute groundwater directly by leakage of sewage into the ground. In addition, the reverse situation where groundwater leaks into sewers can indirectly contribute to quality degradation. Substantial drainage of water can occur at or just below the water table, so that recently-infiltrated, high-quality groundwater is lost. This leaves the poorer-quality deeper groundwater; the average quality of the water body is lowered. Furthermore, a lower freshwater head encourages the upward movement of any underlying saline groundwater (see "Saline Water in Inland Aquifers").

Because most sewers leak, especially older ones, the opportunity for groundwater drainage into sewers exists wherever water tables are high enough to intercept sewers. Increases in sewage flows of 20 to 25 percent after rainfalls are not uncommon. A portion of such increases may be due to storm drains connected illegally to sanitary sewers, but some portion is undoubtedly related to groundwater contributions.

Control methods depend upon improving the water-tightness of sewers and are identical to those described in the section on "Sewer Leakage."

SPILLS OF LIQUID POLLUTANTS

Scope of the Problem

Degradation of groundwater quality can result from discharge of liquid wastes on the land surface. Some discharges are inadvertent spillages such as motor oil dripping from automobiles and trucks, fluids released by careless handling, and tank truck accidents. Others are deliberate releases of waste liquids onto the ground as a disposal mechanism. Tank trucks may habitually dump liquid wastes in open fields; this practice may be far more prevalent than is recognized. Adequate local regulatory authority and enforcement action to halt such incidents are often lacking.

Even in the absence of specific field evidence, general considerations of hydrogeology and climate make it logical to assume that groundwater quality beneath most industrial and urbanized areas is being gradually degraded by spills of various types of liquids on the land surface. However, few investigations have been undertaken to determine the scope of this problem so that little is known regarding the areal extent or severity of such pollution. Chemical analyses of well waters that might reveal such problems are made too infrequently. The standard chemical analysis of water covers only a few of the common troublesome constituents; other constituents that would be indicative of particular sources of pollution, such as organics and heavy metals, are generally not included.

Pollution stemming from liquid spills is quite variable. One example is the degradation of groundwater quality, due to fuel spills and washing of airplanes with various types of cleaning agents, which has been detected at the Miami International Airport; petroleum-derived contaminants are floating on the water table. A second example is the widespread contamination of groundwater resources in Maryland that has been traced to the disposal on the land surface of crankcase oils drained from cars and to oil spills from trucks, railroad tank cars, and oil drums.

The overall problem is believed to be more severe in the humid portions of the East than in the arid regions of the country, where low precipitation, low rates of groundwater recharge, and high rates of evaporation result in less opportunity for the percolation of liquid contaminants. Nevertheless, some notable cases of pollution of groundwaters from surface spilling have also been reported in the West.

Environmental Consequences

Toxic chemicals spilled from trucks in road accidents or from tank railroad cars in detailments can enter aquifers and then begin to move toward points of discharge such as pumping wells or nearby surface-water bodies. A derailment of tank cars in Missouri, for example, resulted in toxic liquids entering the ground, leading to contamination of a spring used for public water supply and a fish kill in a nearby stream (Missouri Mineral News, 1973).

Contaminated water or other liquids entering certain fractured rock such as shales and granites, or rocks having large solution openings such as limestones and dolomites, can move much more rapidly than in other hydrogeologic environments. As a consequence, adverse effects on water supplies some distance away from the source of the contamination sometimes can take place before the existence of the threat is even recognized. Municipal and private wells have been contaminated by pickling brines and milk wastes discharged on the land surface in Michigan (Deutsch, 1961). Sulfuric acid wastes from copper processing plants have moved from the land surface to the water table in a large industrial area near Baltimore, Maryland (Bennett and Meyer, 1952). Not only was a shallow aquifer extensively contaminated, but corrosion of the upper part of the casings in many deep wells also allowed the acid to move down into deeper aquifers. A nearby municipal well showed the effects of the pollution.

Once an aquifer has been contaminated by substances derived from spills, the groundwater quality can remain affected for many decades even if the source of the pollution is stopped. Thus, expensive control measures must be implemented if the groundwater reservoir is to be purged of the contaminant, or the use of the aquifer and perhaps of any surface water body into which the polluted groundwater discharges must be restricted.

Pollution Movement

In the case of a one-time spill, a large slug of liquid spread on the land surface can seep into the ground and move as a more or less intact body of limited size into an underlying aquifer. In the case of long-term infiltration, on the other hand, the contaminated fluid moves continuously downward to the water table and then may become an elongated plume or filament stretching out from the source along the direction of the prevailing groundwater gradient. This progressively degrades the subsurface water quality with time.

The composition, grain size, and thickness of the soil materials in the unsaturated zone govern the movement of a contaminated fluid traveling downward toward the water table. In many areas the materials in a thick unsaturated zone will filter some pollutants before they reach the water table, and biodegradation will stabilize some organics. Where there is an overall deficiency of moisture, the contaminated fluid may evaporate from the soil or may adhere on rock particles as thin films without descending to the water table. But where the unsaturated zone is thin, there may be little retarding or adsorptive action or biodegradation, so that the pollutant arrives virtually unchanged at the saturated zone.

Once the contaminant enters the saturated zone, its direction and rate of travel are largely determined by the local groundwater flow pattern. The pollutant may penetrate into the groundwater body or float on top of the saturated zone, depending upon its density. The polluted groundwater will move toward a natural discharge point or toward a nearby pumping well. If the rate of movement of groundwater is slow, the pollution may remain in the vicinity of the source of contamination for a number of years or decades.

Control Methods

Deliberate spills of liquid pollutants can be controlled by regulation, inspection, and enforcement action regarding the release of waste fluids on the land surface. Such wastes can be treated by the generating organization, or they can be collected and processed by regional treatment centers especially established for this purpose. Centers for handling industrial wastes are increasingly available in most large urban areas.

Accidental spills cannot be wholly prevented; however, spills and their effects on groundwater can be minimized.

- Industries handling and transporting hazardous liquids should be required to maintain emergency facilities and trained personnel ready to respond in case of accidents.

- Some regulatory action may be needed. In England, the Poisonous Waste Act of 1972 requires that notice be given to governmental agencies three days before hazardous substances are to be transported; approval is not required but the agency may object. Both information on movements of waste and some control over these movements result (Todd, 1973, p. 52).

- Municipalities should inform police, firemen, and emergency crews as to the dangers to groundwater inherent in accidental spills and should provide instruction so as to reduce the possibility of spills and the degree of pollution if spills do occur.

Methods for intercepting and removing oil and oil products from groundwater are described by the American Petroleum Institute (1972) and also under the section "Tank and Pipeline Leakage." Methods for limiting and eliminating pollutants dispersed within a groundwater body are described under the section "Sea Water in Coastal Aquifers."

Monitoring Procedures

One approach for locating potential pollution sources from liquid spills is to investigate areas where spills of noxious liquids are known to have taken place. As a follow-up, monitoring wells could be installed to verify control methods and to locate the extent of any polluted groundwater body.

Another monitoring approach is to expand the existing networks of wells that are periodically sampled by public agencies and to substantially improve the analytical procedures so that more determinations are made of constituents that are indicators of contamination. Anomalous concentrations and long-term trends of such constituents would be noted and investigated.

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LAND SURFACE CHANGES

Introduction

Changes in land surface elevation produced by overpumping of groundwater can have unfavorable repercussions on groundwater quality. Two mechanisms can contribute to the problem. One is subsidence, which is a gradual lowering of the land surface. The other is collapse, which is the abrupt failure of the land surface due to the movement of material into underlying cavities. The effects of these physical changes on groundwater quality are described in the two following subsections.

Collapse — The Sinkhole Problem

SCOPE OF THE PROBLEM. Sinkhole collapses serve as entry points for groundwater pollution into soluble rock aquifers. Limestone terranes are most prone to sinkhole collapses, and once pollution is introduced into such formations the extent of its travel can be large.

CAUSAL FACTORS. The formation of sinkholes most often results from collapse of cavities in residual clay through solution openings in underlaying carbonate rocks. The cavities may be caused by a lowering of the water table, resulting in a loss of support to clay overlying openings in bedrock. Other causes which are postulated include fluctuation of the water table against the base of residual clay, downward movement of surface water through openings in the clay, or an increase in water velocity in cones of depression to points of discharge. The geologic conditions responsible for collapses have been enumerated by Foose (1968).

Limestone terranes are the most common locations for sinkhole collapses. Occurrences have been reported in Alabama, Florida, Missouri, Pennsylvania, and South Africa (Aley, et al, 1972). Dewatering for mining has been held responsible for several collapses

(Foose, 1967). In Missouri the construction of sewage lagoons and small surface water reservoirs has triggered collapses, either due to the excessive load applied to the ground surface or to the increased leakage of surface water into underground openings through the bottom of the impoundments (Aley, et al, 1972). Some collapses are apparently unrelated to man's activities, such as those associated with earthquakes.

In December 1972, in Shelby County, Alabama, one of the largest sinkholes in the United States suddenly developed (LaMoreaux and Warren, 1973). The crater is about 140 meters long, 115 meters wide, and 50 meters deep. The collapse may have resulted from extensive groundwater withdrawals, but the history of water levels in the area is unknown.

ENVIRONMENTAL CONSEQUENCES. Only recently has attention been focused on groundwater pollution caused by collapses in limestone terranes (Aley, et al, 1972). Two aspects deserve mention. The first concerns the increases in organic matter, bacteria, and colloidal material in suspension released into an aquifer after the impact of a collapse. The second is the artificial introduction of poor-quality water into the underground through the depressed sinkholes. In particular, the drainage of sewage lagoons into aquifers with numerous large solution openings can pose a serious pollutional threat. Groundwater tracer tests using Lycopodium spores, which have a mean diameter of 33 microns, were made in limestone aquifers in Missouri (Aley, et al, 1972). Recovery of spores in springs revealed subsurface water movements of as much as 40 miles in 13 days. Considering that these spores are 10 to 15 times larger than most bacteria, the potential pollution hazard is clear.

CONTROL METHODS. To minimize the danger of sinkhole collapses:

- Pumping of water from limestone terranes should be carefully regulated so as to stabilize groundwater levels and to avoid extensive areas of dewatering

- Thorough hydrogeologic investigations should be undertaken of any proposed sites for surface water reservoirs in limestone terranes.

Subsidence — The Arsenic Problem

SCOPE OF THE PROBLEM. High arsenic concentrations found in groundwater from deep confined aquifers in the San Joaquin Valley of California are believed to be associated with land subsidence areas (Fuhriman and Barton, 1971). The subsidence results from overpumping of groundwater, which causes compaction of fine-grained confining strata. At present, the phenomenon appears to be limited to one area in California; no evidence is available of its occurrence in other land-subsidence areas.

LOCATIONS OF LAND SUBSIDENCE. Land subsidence can occur from a variety of causes; discussion here is limited to that produced by excessive pumping of groundwater from deep confined aquifers.

The phenomenon of land subsidence from groundwater pumping has been identified at several locations in the United States as well as in Japan, Mexico, and Taiwan. Table 5-2 lists, for land subsidence locations in the United States, the depth of compacting beds, maximum subsidence, area of subsidence, and time of occurrence. Piezometric head declines in the confining aquifers responsible for the subsidence range from 30 to 150 meters.

The land-subsidence problem has been extensively studied for affected areas in California by the US Geological Survey (Green, 1964; Lofgren and Klausing, 1969; Poland and Green, 1962).

Table 5-2. Description of areas of major land subsidence due to groundwater extraction in the United States (International Association of Scientific Hydrology, 1970).

Location	Depth range of compacting beds below land surface, m	Maximum subsidence, m	Area of subsidence, sq km	Time of principal occurrence
Arizona, Central	100-300	2.3	?	1952–67+
California, Santa Clara Valley	50-300	4	600	1920–67+
California, San Joaquin Valley (3 areas)	90-900	8	9,000	1935–66+
Nevada, Las Vegas	60-300	1	500	1935–63+
Texas, Houston-Galveston area	50-600	1-2	10,000	1943–64+
Louisiana, Baton Rouge	40-900	0.3	500	1934–65+

ENVIRONMENTAL CONSEQUENCES. Neglecting the serious consequences of land subsidence on surface structures, the concern here is the increase in arsenic content of groundwater. The US Public Health Service drinking water standards recommend a limit of 0.01 mg/liter for arsenic in domestic water, while concentrations in excess of 0.05 mg/liter are grounds for rejection of a water supply. If, as was found in California, a number of wells in an area show concentrations of arsenic exceeding 0.05 mg/liter, rejection of all domestic use of groundwater in the area could follow.

CAUSAL FACTORS. Land subsidence results from withdrawal of water from wells at a sufficient rate to produce a substantial decline in the piezometric surface elevation. The decline reduces the hydrostatic pressure within the aquifer and increases by a corresponding amount the effective overburden pressure. This pressure creates an increased grain-to-grain load. With time, water within a fine-grained (clayey) confining bed adjusts to the new equilibrium conditions of the adjacent aquifer. This produces a reduction in porosity and a migration of water from the confining bed to the nearest aquifer. The consequent compaction of the confining bed is evidenced by an equal decline in land surface elevation. Figure 5-3 shows by a schematic diagram water movement from a clayey confining layer to an aquifer and the resulting land subsidence when the piezometric surface is lowered.

Although a causal relationship between arsenic in groundwater and land subsidence has not yet been established, circumstantial field evidence in California suggests that the hypothesis has validity.

The Tulare-Wasco area in the San Joaquin Valley of California is one of the principal land subsidence regions within the State (Lofgren and Klausing, 1969). The Allensworth-Alpaugh area, located midway between Fresno and Bakersfield in Tulare County, lies within this large subsidence area. Here the Corcoran Clay at a depth of about 475 feet is one of the principal confining beds. Of 37 wells sampled in the Allensworth-Alpaugh area, 16 were found to pump groundwater containing arsenic in concentrations greater than 0.05 mg/liter. High arsenic values were identified as coming from wells perforated both above and below the Corcoran Clay; however, insufficient sampling points and well information precluded determining the exact source of the high arsenic vertically within the groundwater basin.

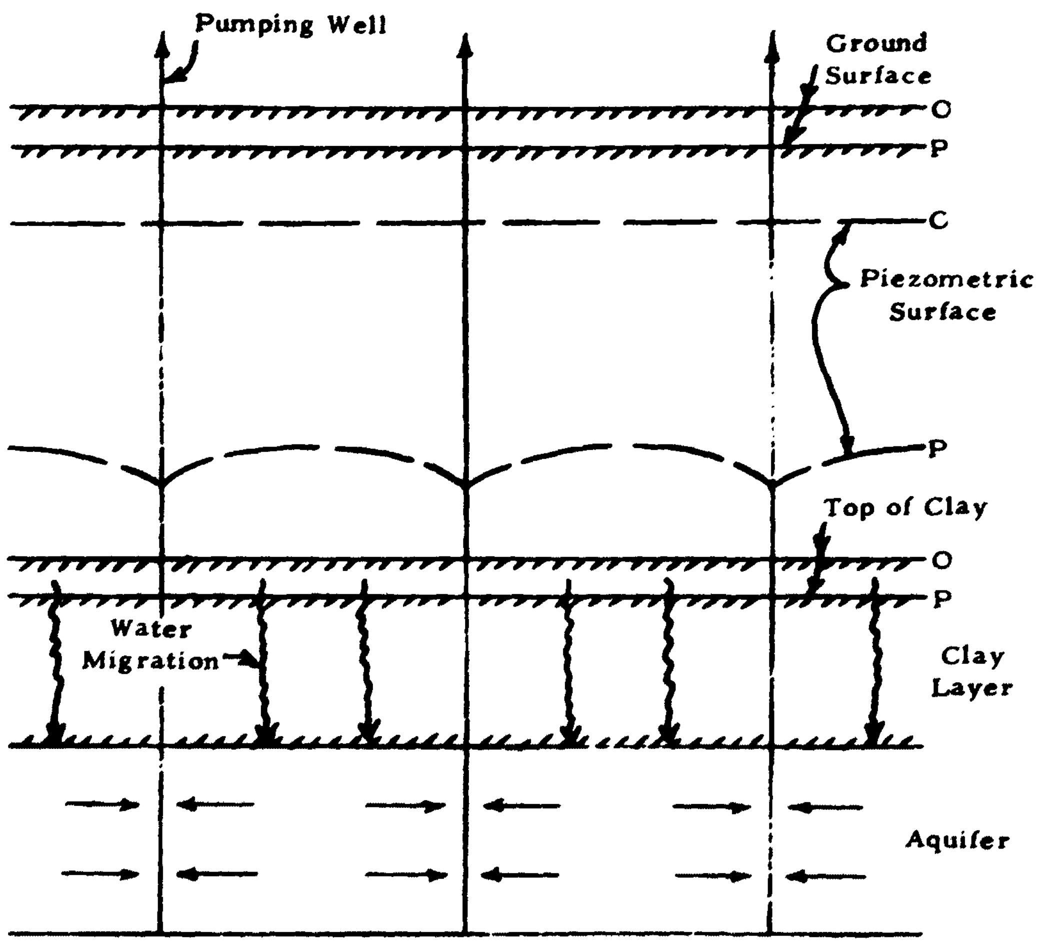

Figure 5-3. Schematic diagram of water movement and land subsidence when the piezometric surface of an aquifer confined by a clay layer is lowered. The letter "O" refers to the original position and "P" to the present position.

Later a test well was drilled in the same area. During drilling the drilling mud was changed regularly and samples of the mud were analyzed for arsenic. Results indicated that high arsenic tended to occur in clayey layers. It follows that if the clay contains arsenic and is compacted, the arsenic will move with the displaced water into the aquifer.

Further research on the subject is needed.

CONTROL METHODS. As any release of arsenic into groundwater is believed to be associated with heavily overpumped confined aquifers, the only feasible control method is a reduction in pumping. This could take the form of reduced pumping rates in existing wells or of reduction in the number of wells operating in a subsiding area. Either procedure would aid in halting the piezometric surface decline, which in turn would terminate subsidence and the movement of arsenic into an aquifer.

MONITORING PROCEDURES. Detection of arsenic in deep confined aquifers would require installation and periodic sampling of observation wells. Locations of these should be in the central portions of known or anticipated land subsidence areas. Perforations should be placed at aquifer depths and relatively close to thick clayey confining beds.

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UPSTREAM ACTIVITIES

Scope of the Problem

The conditions governing lateral subsurface inflow, natural and artificial outflow, recharge from the surface, and hydraulic movement of water within a water-bearing formation will largely determine the quality of water that may be produced from the formation. These conditions are—to varying degrees—amenable to controls designed to protect or improve groundwater quality. The other principal influence on quality within the formation, the native mineral character of the formation itself, is not susceptible to control; mineral constituents that enter the groundwater through natural solution processes must be accepted as dictating the base-line water quality.

Man's activities in areas upstream from the recharge area of a ground-water basin may influence the quality of the underground water. Such influences include changing the lateral inflow, altering downward percolation, introducing pollutants directly into the inflow or recharge water, and reducing the infiltration capability of aquifer recharge areas. Some results of upstream activities benefit the quality of a downstream aquifer; for example, regulation by upstream reservoirs and controlled releases downstream. However, the preponderance of effects are deleterious.

Adverse effects of upstream activities are not often identifiable in a down-stream groundwater basin as a separable influence. Rather, a rational program for control and abatement of the causes of deteriorating ground-water quality must be formulated both from direct evidential data and from an informed evaluation of indirect influences produced by an upstream activity.

Causal Factors

The causal factors and their results are not unique to any part of the United States. Some problems are commonly associated with mountainous areas; others relate to humid areas, or to intensely urbanized areas.

Control of groundwater pollution caused by upstream activities should be formulated with an understanding of two significant geographic categories:

- Those activities occurring at the surface overlying essentially non-water bearing formations where the effects on downstream groundwater basins are wholly related to the surface recharge areas of those basins. For example, in California and other parts of the west, mountainous areas are the source for runoff supplying the principal natural recharge to downstream groundwater basins.

- Those activities occurring on the surface overlying an upstream groundwater basin where hydraulic interdependencies with downstream aquifers are related to either lateral inflow or surface recharge. In Texas, for example, there are intimate and immediate hydraulic relationships between the Edwards-Trinity (Plateau) Aquifer, the Edwards (Balcones Fault Zone) Aquifer, the Carrizo-Wilcox Aquifer, and the surface streams rising from or cutting through these water-bearing formations.

In these two areas, California and Texas, very different conditions prevail. Understanding the hydraulic distinction between them is essential if measures to control activities causing adverse quality effects are to be instituted. Some of the upstream activities with a potential for affecting quality in downstream groundwater basins are common to both categories; these are discussed first, followed by those activities whose effects are unique to one category.

Environmental Consequences

Increased upstream use of surface water, with resultant evapotranspiration losses from streams contributing recharge to downstream groundwater basins, reduces the flow available for recharge and increases salt concentrations. Generally, any sustained reduction in recharge rate will cause gradual deterioration of quality as a result of the relatively higher concentration of the mineral and organic content in the remaining groundwater. A similar adverse effect occurs with intrusion of poor-quality water as diminished recharge reduces the static head in the groundwater basin.

Urbanization in upstream areas causes significant changes in the streamflow—both quantitatively and qualitatively. Runoff from urban areas, and from agricultural lands under certain conditions, will carry very heavy loadings of pollutants during small storms and in the initial phases of large storms. While much of the urban runoff will be collected in storm drainage systems, the effects of sheet runoff will reflect high concentrations of certain types of pollutants. These pollutants may enter a downstream groundwater basin directly from surface recharge, or indirectly by polluting shallow wells in alluvium near streams and thence into groundwater by lateral flow and deep percolation.

The regimen of runoff from developed upstream areas, particularly urban, is generally substantially different from undeveloped areas. It is characterized by higher peak discharges, greater volumes, and shorter runoff times. This tends to reduce downstream percolation and to make artificial recharge difficult.

Diversion structures for certain types of drainage works may cause agricultural runoff carrying high concentrations of agricultural pollutants to enter streams in upstream areas, thence downstream into groundwater basins as recharge from increased streamflow. Such levee works are commonly constructed to reclaim marshlands for agricultural use. Thus, the runoff from the drained lands may carry initially both heavy organic loads and high levels of herbicide/pesticide residues.

Direct discharges of wastes upstream from the recharge area of a groundwater basin are perhaps the most obvious sources of pollutants entering the basin as recharge. These discharges include the entire range of waste-generating activities—municipal sewage, industrial wastes, sawmill and mining discharges, and some agricultural activities such as feedlots.

Storm intensity and channel characteristics will have significant effects on the recharge to downstream basins where upstream flood control is not provided. In the Texas situation, as much as 10 cubic feet per second of the baseflow, and ungaged but very significant percentages of the flood flows of the Nueces River, enter the Carrizo-Wilcox Aquifer as recharge. Generally speaking, surface floodflow (after an initial surge of flushed pollutants picked up from land runoff) and controlled releases from reservoirs will be of better quality than stream baseflows. Thus, flood-control reservoirs may improve the quality of water recharging downstream groundwater basins by trapping sediment and providing sustained regulated flow. In mountainous terrain, on the other hand, conservation reservoirs impounding streamflow for the purpose of firming an out-of-basin export may decrease available downstream recharge to a significant extent.

Watershed management practices (Sopper, 1971) involving changes in ground cover overlying a groundwater basin may result in significant elevation of water tables with high concentrations of leached near-surface pollutants—both man-made and native—entering the streams as baseflow and causing adverse quality effects in downstream aquifers. Nitrate pollution of shallow groundwater basins in Runnels County and other sections of West Central Texas are believed to have resulted from extensive changes in watershed management practices, causing rising water tables with consequent leaching of near-surface rocks. Other types of watershed management activities may cause a decrease in recharge by causing higher surface losses from evapotranspiration. Farm ponds and stock-watering ponds which have been constructed in some watersheds have significantly impaired downstream runoff, as in Texas. Some watershed management practices, such as selective cutting and snowpack management in mountainous areas, may be beneficial to downstream groundwater basins, as in Arizona.

Fire, caused either by man or natural phenomena, often has major and catastrophic upstream effects that impact directly and over long periods on quality in downstream aquifers. Fire changes the regimen of the surface runoff and increases sediment production, transportation, and deposition. The increased silt load deposited in the recharge area of downstream groundwater basins causes a decrease in infiltration capacity, making subsequent efforts at artificial recharge more difficult and costly. A marked increase in organic loadings in streams is a usual result of fire. The gradual decomposition of these organic materials, and their percolation in recharge to groundwater basins, results in continuing and long-term deterioration of groundwater quality. In 1934, a major flood followed a few months after a disastrous fire on the Arroyo Seco watershed in the San Gabriel Mountains near Pasadena, California. The flood deposited large amounts of sediment and organic debris in Devil's Gate reservoir, a flood control facility overlying the recharge area of the Raymond groundwater basin. Subsequent decomposition of the organic matter and movement of the decomposition products into the underlying groundwater resulted in drastic quality deterioration and forced abandonment of several wells.

The erosional debris produced in upstream areas tends to seal the beds of downstream channels, reducing infiltration of runoff and recharge of the groundwater. If the runoff is unpolluted, this has an adverse effect on groundwater quality.

In the case of interdependent groundwater basins, effects of activities overlying an upstream basin may have either beneficial or adverse effects upon a downstream basin. Where the quality of water in the upstream basin is superior to that in the downstream basin, pumpage from the tributary basin will have an adverse effect on downstream basin quality by reducing the high-quality water entering the lower basin as subsurface inflow. On the other hand, if quality in the upstream basin in inferior to that of the downstream basin, the converse will be true.

Effective pollution control in upstream areas will alleviate many of the adverse quality effects in downstream basins.

Control Methods

Specific control measures to reduce the potential for groundwater pollution from activities in upstream areas include the following:

- Adequate fire control in tributary watersheds; prompt mitigative measures, such as re-seeding immediately after a fire.
- Forest management practices, in tributary watersheds, that will increase high quality runoff.
- Land resource management and land use controls in upstream areas to minimize threats to downstream groundwater quality; new institutional arrangements would be required.
- Management of an inter-related group of groundwater basins or aquifers as an integrated system with quality protection and maintenance as a principal objective.
- Artificial recharge with high-quality water to replace reduced natural streambed percolation due to upstream use.
- Mandatory controlled releases from upstream conservation reservoirs to maintain downstream groundwater recharge.
- Treatment of urban runoff.

- Weather modification to increase high quality runoff for recharge; this is probably of limited applicability.
- Regulation of tributary runoff by storage to facilitate recharge.
- Scarification of streambeds to maintain infiltration capacity.

Reference

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GROUNDWATER BASIN MANAGEMENT

Concept

The concept of managing a groundwater basin is analogous to the operation of a surface water reservoir. By regulating the releases of water from a dam, the reservoir can be made to serve various beneficial purposes, and with planning the benefits can be optimized. In general, the benefits depend not on maintaining the reservoir full or empty at all time but rather on varying the water level to meet predetermined supply and demand criteria.

Groundwater basins are increasingly being recognized as important resources for water storage and distribution. Groundwater reservoirs have numerous advantages over surface reservoirs (Comm. on Ground Water, 1972):

- Initial costs for storage are essentially zero.
- Siltation is not a problem.
- Eutrophication is not a problem.
- Water temperatures and mineral quality are relatively uniform.
- Evaporation losses are negligible.
- Turbidity is generally insignificant.
- No land surface area is required.
- Useful lives are often indefinite.

The objective of groundwater basin management is generally to provide an optimal continuing supply of groundwater of satisfactory quality at least cost (Mack, 1971). To reach this objective requires comprehensive geologic and hydrologic investigations, development of a mathematical model to simulate the aquifers, economic analyses of alternative operational schemes, and finally—based on this management study—

regulation of the basin. In most cases conjunctive use of surface water and groundwater systems is considered in seeking a maximum water supply at minimum cost (Todd, 1959).

Procedure

The management study leading to a basin operation consists of the components listed in Table 5-3. These are arranged to indicate the usual sequential order employed.

Table 5-3. Outline of a groundwater basin management study (Comm. on Ground Water, 1972).

Geologic Phase
Data collection and water level maps
Storage capacity and change; transmission characteristics
Water quality analysis
Hydrologic Phase
Data coilection
Base period determination
Water demand
Water supply and consumptive use
Hydrologic balance
Mathematical Model
Programming and parameter development
Validation
Operation—Economic Phase
Future water demand and deep-percolation criteria
Analysis of cost of facilities
Cost-of-water study
Plans of operation
Cost comparison of plans
Preparation of Report

Physically, the management of a basin involves regulating the patterns and schedules of recharge and extractions of water. This would include specifying the number and location of wells together with their pumping rates and annual limitations on total extractions. The upper and lower groundwater levels would be defined. Water quality objectives would be set, and sources and causes of pollution carefully controlled. The artificial recharge of storm flows, imported water, or reclaimed water could be involved. In some instances, measures to limit seawater intrusion and land subsidence would be included.

Because of the dynamic nature of groundwater resource systems, a continuing data collection program is essential. Management parameters and criteria must be re-evaluated at intervals of five to ten years.

Detailed management studies for several basins in California have been undertaken (Calif. Dept. of Water Resources, 1968).

Sources of Basin Pollution

Within a groundwater basin the potential sources of pollution may include all of the possibilities described in other sections.

A pollution source unique to basin management may be artificial recharge of groundwater. In order to increase the available groundwater supply, a basin may be heavily pumped so as to lower groundwater levels. Thereafter, water can be artificially and naturally recharged to fill the available underground storage space. Recharging is usually accomplished by surface spreading in which water is released for infiltration into the ground from basins, ditches, streambeds, or irrigated lands (Muckel, 1959). Water can also be recharged into confined aquifers through injection wells. If the quality of the recharged water is inferior to that of the existing groundwater, pollution will result.

An excellent illustration is the situation in Orange County, California (Moreland and Singer, 1969). To compensate for extensive overdraft of the groundwater basin during the 1940's, large quantities of imported Colorado River water were subsequently recharged underground along the Santa Ana River channel. Because of the high salt content of the imported water, the salinity of a substantial portion of Orange County's groundwater has been significantly increased.

On a long-range basis, maintenance of salt balance in a basin, i.e., prevention of accumulation of salts, must be achieved. This is the most difficult quality-maintenance problem.

Control Methods

Proper management of a groundwater basin requires an appropriate institutional structure (Corker, 1971), embracing the basin to insure that the water quality is not adversely affected. Control methods could include the following:

- Maintaining groundwater levels below some shallow depth so as to minimize the opportunity for pollution from surface sources.
- Maintaining groundwater levels above some greater depth in order to avoid upward movement of more saline and warmer water into the aquifer.
- Regulating the quality of water artificially recharged to the aquifers. Storm runoff collected in upstream reservoirs and then released into spreading areas is usually of higher quality than groundwater, but imported and reclaimed waters may not be.
- Preventing seawater intrusion and the inflow of poor-quality natural waters from adjacent surface and subsurface sources. Poor-quality water from underground sources can usually be excluded by lines of pumping or recharge wells, while surface

waters can be intercepted by drainage ditches and diverted from the basin.

- Regulating the drilling, completion, and operation of all types of wells.
- Regulating land use over the basin to prevent the development of sources of groundwater pollution.
- Reducing salt loads by exporting saline groundwaters, wastewaters, or brines from desalted water supplies.
- Monitoring the quality of groundwater throughout the basin to identify and to locate any pollution sources and to verify corrective measures.

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16. Abstract

Consultants Harvey O. Banks, James J. Geraghty, P. H. McGauhey, Nathaniel M. Perlmutter, David Keith Todd, and Don L. Warner, and TEMPO staff members Charles F. Meyer and Edward J. Tschupp, formed a team which prepared information for EPA's use in developing guidelines and reports in compliance with the Federal Water Pollution Control Act Amendments of 1972. Groundwater pollution aspects of the following topics are discussed: institutional and legal constraints; injection wells into saline and freshwater aquifers; lagoons, basins, and pits; septic systems; sewer leakage; spraying; land fills; surface-groundwater relationships; saltwater intrusion; land subsidence and collapse; effects of urbanization and of flow diversion, including wells and surface structures; spills of liquid pollutants; tank and pipeline leakage; and groundwater basin management, including related surface activities. (Meyer - TEMPO)

17a. Descriptors

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