GROUND WATER POLLUTION FROM SUBSURFACE EXCAVATIONS

UNITED STATES
ENVIRONMENTAL PROTECTION AGENCY
Washington, D. C. 20460

1973

PREFACE

The Federal Water Pollution Control Act, as amended (33 U.S.C. 1251 et seq.; 86 et seq.; P.L. 92-500) instructs the Administrator of the Environmental Protection Agency to issue information including processes, procedures, and methods to control pollution resulting from the disposal of pollutants in wells or in subsurface excavations (Section 304(e)(D)).

This report is issued pursuant to that legislative mandate in an attempt to shed some light on the problems of the pollution of underground water.

Russell E. Train

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Administrator

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Water Programs
Water Quality and Non-Point Source Control Division
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FOREWORD - WATER QUALITY

In order to avoid undesirable changes in ground water quality, that quality must first be established. Consider the discussion of the term "quality" 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 *know* 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."

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 that 20,000 people and caused several deaths, was traced to a new comer (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

1. McGauhey, P.H., "Folklore in Water Quality Standards," Civil Engineering, Vol. 3, No. 6, New York, June (1965).

2. McGauhey, P.H., "Quality - Water's Fourth Dimension," Proceedings of the Water Quality Conference, University of California, Davis, California, January 11-13 (1961).

3. McGauhey, P.H., Engineering Management of Water Quality, McGraw-Hill Series in Sanitary Science and Water Resources Engineering, McGraw-Hill, Inc., New York, New York (1968).

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PART ONE

SOURCE IDENTIFICATION AND EVALUATION

INTRODUCTION

"Ground water quality" is the name of the game in a discussion of subsurface excavations as sources of pollution. In rare instances pollution from subsurface excavations moves directly to surface water bodies without entering the ground water domain. To the extent that ground water moves to the surface, which is considerable, polluted ground water causes surface water pollution, but it is the alteration of the chemical, physical, biological and radiological integrity of ground water that is the overriding concern.

Identification of the nature of polluting excavations starts from the premise that every hole in the ground, whether natural or man-made, is a potential source of ground water contamination. A "well" is a particular type of subsurface excavation rather than merely, "a place from which water issues forth" as it was described in ancient England where the word originated.

Pollution Mechanisms

There are three basic mechanisms by which ground water becomes polluted:

1) The natural filtering system of vegetation, soil, silt, sand, gravel and rocks that protects ground water is bypassed by polluting substances.

2) The natural filtering system is overwhelmed by a concentration of polluting substances beyond its capacity to handle them, or by substances that are unfilterable.

3) The hydraulic or chemical balance in the subsurface is altered so that polluting substances move to, within or between aquifers to change water quality.

Case 1: System bypassed

Whether a hole is natural, dug by hand, drilled, blasted, mined or otherwise excavated; and whether a hole is intended for the production of a resource, the emplacement of a waste, the storage of a product, the collection of information or the emplacement of hardware; it penetrates at least a portion of the surface filtering system, thus providing a possible avenue for contaminants to bypass that system. The polluting substances that can and do enter aquifers as a result of these activities include most of the elements in the periodic table in nearly every combination known to man.

Subsurface excavations may be grouped into categories based on a description of the excavation:

- Wells and vertical, drilled holes:
  Includes water wells, oil wells, gas wells, dry holes, core holes, shot holes, stratigraphic tests, waste injection wells, product injection wells, secondary recovery injection wells, solution mining wells, dewatering wells and observation wells.

- Sanitary facilities:
  Includes septic tanks, cess pools, latrines and dry wells.

- Underground mines and tunnels:

Includes highway, railroad and storage tunnels.

- Construction excavations:
  Includes piling holes, basement excavations, river and harbor dredging, and sand drains.

- Quarries and strip-mines:
  Includes rock quarries, sand pits, gravel pits, strip mines and natural sinkholes.

- Burial vaults:
  Includes buried pipe lines and buried tanks.

- Pit silos and land fills.

A broader grouping, based on the intended use of the excavations, is also useful in terms of ground water pollution considerations.

- Extraction:
  Producing wells, mines, quarries, and sand and gravel pits.

- Injection:
  Waste disposal, mineral recovery, secondary mineral recovery and product storage.

- Other:
  Dry holes, stratigraphic tests, shot holes, core holes, construction excavations, burial vaults, sink holes etc.

The evaluation of the extent of the occurrence of potential sources is a matter of a thorough physical inventory, bearing in mind that subsurface pollution is a four dimensional problem involving three dimensional space, and time. As an example, a waste injection well may introduce, through a twenty centimeter diameter hole in the ground, highly toxic materials into several subsurface reservoirs that are more than a kilometer apart vertically but are directly beneath that twenty centimeter surface area. The waste may be directed into a useless, salty aquifer at a depth of 3800 meters below the land surface where it will cause pollution in the strict sense of the word, as defined in P.L. 92-500, but may cause no environmental problems and never again be detected in the biosphere. However an excessive injection rate (volume divided by time) can cause pressures that will fracture the overlying rock, or the cement around the well casing, or the casing itself and permit the wastes to enter a fresh-water aquifer only two hundred meters below the land surface. Additional pollution problems can result from the corrosive deterioration of the well casing near the surface where water-table aquifers can be polluted at depths of fifteen meters or less. The measurable effects of the change in water quality of the 3800 meter aquifer may last for centuries but may have no adverse effects and never be known. The pollution of the 200 meter aquifer, or the 15 meter aquifer, may occur at any time during the waste injection, may be detected at anytime from a few days to many years after the injection commences, and may last for many decades, moving at a rate of less than 30 centimeters a year.

It is useful to establish priorities of consideration in the initial stages of an inventory program so that aquifers are dealt with in the order of their importance and sources of massive pollution receive first consideration with the effect on human health as the leading criterion.

The nature of the sources of ground water pollution may be established in any political, geographic, administrative or hydrologic region by an inventory of: the regional activities that make or use holes in the ground; the types of holes used or made; their design and construction; and their location. The regional extent of such sources may then be determined by an inventory, by category, of these holes and the use made of them, followed by an analysis of the data thus obtained.

The location of the hole in three dimensional space is critical in that the likelihood and magnitude of ground water pollution resulting from a properly constructed subsurface excavation is largely dependent on the amount and type of material between the aquifers and the contaminant at its point of release.

Much relevant information must be developed to aid in assessing the pollution potential of the most sophisticated type of injection well injecting large volumes of various hazardous materials. It is unlikely that all of the information considered to be relevant for the sophisticated case would be required for many particular subsurface excavations, but the minimum location information required for all the general cases would include the name and address of the party responsible for the generation of the contaminant, the location of the excavation in terms of surface geography (State, County, Survey, Section, Township, Range, latitude, longitude and surface elevation with respect to sea level) the location of the contaminant in terms of subsurface geology (depth of excavation, depth to top and bottom of aquifers, depth to bedrock, depth to top and bottom of aquicludes, depth to top and bottom of injection zone and types of rocks involved).

Design and construction details are necessary to evaluate the excavations pollution potential. These may range from knowing whether or not an excavation is lined with a low permeability material (in the case of an evaporation pond), to the case of a waste injection well which would require design and construction information such as specifications for all strings of casing and tubing, cement, pumps, pressure monitoring equipment, injection rate monitoring equipment, contingency equipment, and surface valves and piping plus details of hole diameters, casing types, casing lengths, casing seats, cementing program, contingency program, monitoring program, testing and completion programs and geologic formations penetrated.

Case 2: System overwhelmed

A hole in the ground is not required for this type of pollution to occur, but the collection of pollutants in a subsurface excavation does provide the ultimate concentration of materials and can cause the filtering system to fail (in the case of materials that would ordinarily be filtered out by the soil), or can cause a concentration of unfilterable pollutants (such as phenols) to move into aquifers. Settling ponds, evaporation ponds and waste lagoons are among the offenders in this category.

Case 3: Hydraulic or chemical balance altered

Any subsurface excavation that is used to move fluids into or out of the ground will have an effect on the hydraulic balance of the aquifers involved. The effect may be so slight as to be immeasurable or may be so great as to cause the fluid in a porous formation to break out into other porous formations or to the surface.

Injected fluid need not be a pollutant to cause serious ground water pollution. For example, cooling water of excellent chemical quality may be injected into an aquifer containing salt water at its lower end in order to avoid causing a damaging temperature rise in a surface stream. The resulting pressure change can:

- Cause the salt water to move into fresh-water portions of the same aquifer and into water wells.
- Cause the salt water to move into other fresh-water aquifers and into water wells.
- Cause the salt water to move into surface-water bodies.

The extraction of fluid also alters the hydraulic balance and can cause the movement of subsurface pollutants in and between aquifers and surface waters. For example, a municipal water-well field pumping many millions of liters per day may cause seawater to move inland in an aquifer several kilometers further than it normally appears and thus pollute municipal wells and other wells in the vicinity.

Likewise, an industrial well pumping high quality process water from the top 15 meters of an aquifer can cause the upward coning of deeper salt water in the same aquifer, resulting in the pollution of the well supply. These effects are treated more fully in the discussion of "Salt-Water Intrusion."[7] Pollution may also result from a similar lowering of pressure in a confined aquifer, causing the compression of an overlying confining bed and resulting in the "wringing out" of highly mineralized water from the confining bed into the aquifer. Arsenic pollution is known to have resulted from just such a situation.

Instances of ground water pollution have been noted that were attributed to a waste injection-caused change in pH and temperature (chemical balance alternation). The pollution resulted, not from concentrations in the aquifer of the injected material, but from an "unloading effect" that occurred when the sorptive characteristics of a formation that had trapped a toxic waste constituent from some other source were changed by exposure to the injected material and the toxic constituent was released into the ground water.

Current Involvement

An inventory of the disposal of wastes into holes in the ground can be commenced by investigating federal waste disposal practices. A 1960 inventory[1] covering waste water disposal practices, under the category "ground disposal," reports more than 11,000 such activities, most of which involve subsurface excavations (septic tanks, cesspools, subsurface disposal fields, privy vaults, chemical toilets, sewage lagoons and wells).

Other government entities in the subsurface disposal business include the State equivalents of the Federal departments as well as the various regional, county, township and city organizations that generate wastes.

The private sector also warrants consideration with special attention being paid to the industries that use well injection as a means of disposing of large volumes of noxious and obnoxious wastes[2]. These include power plants, steel mills, metal plating establishments, waste treatment plants, pharmaceutical laboratories, food processing plants, paper mills, and the petroleum industry and its exploration, production, refining and chemical manufacturing operations.

Other private sector sources include real estate developments, agricultural units, the operators of large buildings and countless rural and vacation home sanitary facilities.

Current Practices

The uses made of wells and other subsurface excavations for the disposal of wastes range in terms of volume from nearly 27,000 kiloliters a day to less than 200 liters, and in terms of health hazard, from dangerous (e.g., certain radioactive materials) to benign (air conditioning cooling water).

The subsurface disposal of radioactive materials has occurred on an operating or experimental basis in several states. The methods used or considered include pit burial, well injection into high porosity, well injection into low porosity formations and salt-mine entombment.

Brines produced in association with crude oil, natural gas and steam are normally disposed of by well injection, often into the rock formation and zone from which they were extracted, but more often either into a deeper, nonproductive portion of the formation from which they were extracted or into some other rock formation. There are tens of thousands of these wells in the oil producing states. Man made-brines are also handled in a similar manner though of course they, being produced at surface sources, do not have a partially depleted underground reservoir to which to return[3].

Raw sewage, treated sewage and hot water resulting from various cooling processes are also being disposed of by well injection. Much material of all kinds is thrown, spilled, dumped, leaked or merely left "lying around" in rock quarries, sand and gravel pits, and construction excavations.

Sources of Contaminants

Vast areas of the United States that produce crude oil and natural gas are underlain by huge volumes of contaminated ground water. The exploration for and the exploitation of fluid hydrocarbons involve multiple sources of contaminants[4]. The pre-drilling exploration activities frequently include seismic surveys that make many holes in the ground. Exploration and production drilling make larger and deeper holes. Secondary and tertiary recovery activities require the use of injection wells, as does the disposal of brines.

The nations petrochemical industry in its production phase also utilizes waste injection wells and settling pits, as do steel mills, metal plating establishments, pharmaceutical laboratories, food processing plants, paper mills, oil refineries, sewage-treatment plants, water-treatment plants, certain agricultural cooperatives and geothermal power producers.

Types of Contaminants

Natural brines produced in association with crude oil and natural gas are a type of contaminant with a varied and complex chemistry[4] that most commonly includes greater than trace amounts of sodium, calcium, magnesium, potassium, barium, strontium, iron, sulphur, bromine and dissolved gasses such as carbon dioxide, hydrogen sulfide and methane.

Natural brines produced in geothermal exploitation are similarly constituted but often contain much more lithium, flourine, silica, arsenic and radioisotopes.

Man-made pollutants that are regularly introduced into the subsurface through well injection or other means include acids, chromates, phosphates, alcohols, sulphates, nitrates, bromine, chlorine, tin, aldehydes, pyrrolidone, ketones, phenols, potassium, acetates, benzene, cyclohexane, hydrogen cyanide[2] and many others (identified and unidentified) that are being pumped, dumped and spilled into the earth.
Sewage, with the associated bacteria and viruses, is also on the list.

Methods of Pollutant Transport

Pollutants in solution move away from wells and other subsurface excavations into aquifers, or to the surface, along the paths of least resistance. Commonly, the zone of fluid movement from a well or other subsurface excavation is a naturally occurring unconsolidated sand or gravel[5] in which fluid moves between the grains in a characteristic manner that lends itself to rather precise mathematical modeling which yields reasonably straightforward predictive information.

Consolidated rocks usually exhibit more complex types of porosity with fluid movement through solution-caused pores or channels, or stress-caused joints and fractures. In some instances the movement is uniform and therefore predictable, but in many instances it is not. The same is true of man-made fractures and channels (the result of high pressure fluid injections, the injection of solvents and subsurface explosions).

Subsurface excavations are, in themselves, potential paths for the vertical movement of fluids. Uncased and poorly cased holes provide direct avenues for the movement of pollutants from the surface to aquifers, from waste injection zones to the surface, and from waste injection zones to other aquifers. Excessive injection pressures aggravate any tendency for fluid to escape through casing-thread leaks, pinhole leaks or channels in the casing cement.

Magnitude of Pollution

Studies of the magnitude of ground water pollution have been made by governmental and private groups including the Envrionmental Protection Agency, the U.S. Geological Survey and other Department of the Interior groups, the Atomic Energy Commission, the American Association of Petroleum Geologists, the American Institute of Mining Engineers, the Interstate Oil Compact Commission and many others. The EPA's "Subsurface Water Pollution - A Selective Annotated Bibliography," Part I, II and III lists hundreds and is available from the EPA's Office of Water Program Operations, Washington, D. C. 20460 .

Prediction Methods

The problems of designing, constructing and operating subsurface waste-disposal facilities properly are quite complex, requiring consideration of the interacting physical and chemical character of: the construction and operating materials, the wastes involved, the geologic formations that will receive them, and the fluids naturally present in those formations.

Various predictive techniques are useful in attacking the problems that result from subsurface waste disposal and, as with other subsurface problems, no one method will provide a complete answer.

The basic tools for predicting the location and extent of subsurface pollution are waste surveys and hydrogeological studies, the former to determine the volume and nature of the materials being introduced into the subsurface, and the latter to assist in assessing the results; for example, the existence of an operating steel mill guarantees the accumulation of a certain amount of used pickling liquor which, if it finds its way into a good quality surface or subsurface water, is a pollutant. The liquor may be recycled for the removal of usable materials to the extent that it is acceptable as a component of an authorized effluent discharge to a surface stream. It also may be piped, untreated, to an injection well and placed underground. A waste survey indicating the existence of the steel mill will thus alert investigators to a pollution threat. Such a survey will also establish similar threats from a high concentration of septic tanks, brine injection wells, food processing plants, and other waste generating activities.

Existing hydrogeological studies made by private, municipal, county, state or federal groups will often yield enough information to establish the areas of likely ground water contamination resulting from waste disposal activities. Additional empirical evidence will come via complaints from well and spring users whose water supplies have developed taste, odor, sediment or color problems. Local health records may also indicate ground water pollution. A ground water quality monitoring system may exist in the area and yield precise information on the results of the disposal of the waste. Mathematical and analog modeling of the subsurface excavation and the aquifers involved may contribute quite reliable data on the fate of the wastes and indicate where to look for ground water pollution. Various geophysical investigations (e.g., seismic surveys and well logging) are often the most convenient way to reinforce both empirical and theoretical investigations.

SUMMARY AND CONCLUSIONS

Ground water supplies a significant proportion of the total amount of fresh water withdrawn[6] for use in the United States (21.4% in 1970); it supplies more than 34% of the nation's public water supply needs, more than 36% of the crop-irrigation water withdrawn, and from 47% to 83% of the total water withdrawals in eleven of our larger states.

As the control of discharges of pollutants into surface waters becomes more effective, the temptation to go to subsurface discharges becomes stronger. An increased and continuing awareness of what is being placed, intentionally or inadvertently, in wells and other subsurface excavations, and where it is going, is essential if we are to prevent the widespread pollution of our ground water resources.

The use of subsurface excavations for the disposal of wastes is growing, the types of materials so disposed of are legion, and the placement and isolation of these materials so as to avoid adverse environmental impacts (particularly ground water quality degradation) is a difficult and complicated problem.

The states, in order to avoid the long-term pollution of huge quantities of usable water, must continue to devote careful and expert attention to the protection of the subsurface environment to assure their citizens of a continuing supply of good quality ground water at the least cost.

References

1. U.S. Department of Health, Education, and Welfare, Waste Water Disposal Practices at Federal Installations as of December 31, 1960, Vol. 54, 55, 56, 57, 58.

2. Warner, Don. L., Survey of Industrial Waste Injection Wells, U.S. Geological Survey (1972).

3. Research Committee, Interstate Oil Compact Commission, Production and Disposal of Oilfield Brines in the United States and Canada, Interstate Oil Compact Commission, Oklahoma City, Ok., (1960).

4. Collins, A. Gene, Oil and Gas Wells - Potential Polluters of the Environment? Water Pollution Control Federation Journal, Washington, D. C. 20016, Vol. 43, No. 12, pp 2383-2393 (Dec. 1971).

5. Walton, William C., Groundwater Resource Evaluation, McGraw-Hill, (1970).

6. Murray, Richard C. and Reeves, Estimated Use of Water in the United States in 1970, U.S. Geological Survey, Washington, D. C., 20242 (1972).

7. Environmental Protection Agency, Identification and Control of Pollution from Salt Water Intrusion, Washington, D.C. 20460 (1973).

PART TWO
CONTROL METHODS, PROCESSES, AND PROCEDURES

SECTION I - INTRODUCTION

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 nonpoint sources of pollutants, and (2) processes, procedures, and methods to control pollution resulting from (D) the disposal of pollutants in wells or in subsurface excavations.

The treatment of this 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.

GROUND WATER QUALITY AND POLLUTION

The quality of ground water refers to its chemical, physical, and biological characteristics. All ground water contains dissolved solids and possesses characteristics such as temperature, taste, and odor. Some contain pathogens such as bacteria and viruses. The natural quality of ground water depends upon its environment, movement, and source; and in different localities, major contrasts in natural quality can be noted. Ground water temperatures may range from a few degrees above freezing in cold climates to considerably above the boiling point in thermal-spring sources, 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, ground water pollution is defined as the man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of ground water. Such pollution is caused, as we would expect, by the introduction into aquifers of pollutants. Pollutants are defined in Public Law 92-500 to include, among other things, all industrial wastes except, "water, gas, or other material which is injected into a well to facilitate production of oil or gas, or water derived in association with oil or gas production and disposed of in a well, if the well used either to facilitate production or for disposal purposes is approved by authority of the State in which the well is located, and if such State determines that such injection or disposal will not result in the degradation of ground or surface water resources." The particular use to which a ground water can be put depends, of course, upon its quality. However, the various criteria defining the suitability of a ground water for municipal, industrial or agricultural use are not considered in describing pollution. Instead, the measure of pollution is the measure of the detrimental change in the given natural quality of ground water. This may take the form, for example, of an increase in chloride content, of a rise in temperature, or of the addition of pathogens.

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

Occurrence of Ground Water

Ground water forms a part of the hydrologic cycle. It originates as precipitation or surface water before penetrating below the ground surface. Ground water 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.

An aquifer is a formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs (USGS 1972). The most common aquifers are those consisting of unconsolidated alluvial materials such as gravel, sand, silt, and clay. Other important aquifers occur in coal, sandstones, limestones, volcanic rocks and other igneous rocks.

The water table is that surface in an unconfined water body at which the pressure is atmospheric (USGS 1972). Below the water table the permeable soil or rock is saturated with water. Unconfined ground water is water in an aquifer that has a water table, whereas confined ground water is under pressure significantly greater than atmospheric, and its upper limit is the bottom of a bed of distinctly lower hydraulic conductivity than that of the material in which the confined water occurs (USGS 1972).

Ground water typically flows at rates of from 20 centimeters 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 ground water body, the movement is lateral 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 incorporated ground water and at a velocity equal to or less than that of the ground water. Pressure changes, in contrast, travel at or near sonic speed. With time and distance traveled, pollutants decrease in concentration, resulting from dilution, filtration, adsorption, precipitation, decay (e.g., radioactive isotopes), and death (e.g., bacteria). From a point source of pollution, plumes of various shapes are often detected extending downgradient within the aquifer and gradually dissipating with distance.

Control by Elimination of Pollution Sources

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 thus 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. These may include, for example:

- Installing sewer systems to replace septic tanks -- economically infeasible in many rural areas.
- Replacing septic tanks with individual home waste treatment and desalination plants -- technically and economically infeasible at the present time.
- Moving people to sewered areas -- socially, legally, and politically infeasible.

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 ground water pollution, will reduce it and will 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.

In situations involving the intentional placement of pollutants in subsurface excavations, control methods involve measures to assure the isolation of the pollutants from the biosphere. The six steps essential to this end, which are developed in this report, are:

- Siting
- Design
- Construction
- Operation
- Monitoring
- Abandonment

SECTION II - POLLUTION FROM WELLS

This section considers ground water pollution resulting from the injection of fluids into the earth, the extraction of fluids from the earth, and other aspects of ground water pollution resulting from the construction and use of wells. Primary emphasis is placed on the subsurface emplacement of industrial wastes by well injection. Wells for this purpose, commonly referred to as "waste disposal wells," are a relatively recent development and are becoming increasingly popular as restrictions on the discharge of noxious and obnoxious fluids to surface waters become more stringent.

INDUSTRIAL WASTE INJECTION WELLS

The potential of wells for the subsurface disposition of industrial wastes was recognized and exploited by at least one company as early as 1928. The extent of such use outside the oil industry was small until the 1960's when increasing emphasis on surface water polluton control prompted companies to seek other alternatives for waste water releases, one of which was well injection.

As of mid 1972 at least 246 such wells had been constructed in the United States (Warner, 1972). This number is relatively small, but the volume of waste involved, and its potency, has caused considerable concern to be expressed about the use of injection wells. The technical reasons for this concern include the following:

- Some of the wastes 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 ground water 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? If the alternatives are examined that are available for ultimate disposition of waste waters containing dissolved inorganic chemicals, relatively nondegradable dissolved organic chemicals, or combinations of these, it is found that they 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 the ultimate disposition of such waste waters may become even more pressing as a result of the goals stated in P.L. 92-500, the Federal Water Pollution Control Act Amendments of 1972.

We will discuss trends in usage of industrial waste-injection wells in the United States, the environmental impacts of such wells, and methods for preventing ground water pollution from such wells.

Current Situation

An inventory of industrial waste-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 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 1 through 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 the 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 success ratio of such wells is very high.

- About 75 percent of existing wells are between 800 and 1800 meters deep. Less than 10 percent are shallower than 300 meters. This fact provides some assurance of protection to usable ground water resources.

- About 70 percent of present wells inject less than 15 liters per second (200 gpm) and 86 percent less than 30 liters per second (400 gpm). This suggests the rate that can be expected for most wells and reduces the need to consider waste-water streams that exceed these amounts.

Oil-field-brine injection wells are discussed in a later section.

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 1 Distribution of existing industrial wastewater injection wells among the 22 states having such wells in 1972 (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 Distribution of injection wells by industry type (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 3 Operational status of industrial injection wells (Warner, 1972).

Total Well Depth (meters)	Percent of Wells	
	1967	1972
0 – 300m	7	8
300 – 600	29	16
600 – 1,200	22	29
1,200 – 1,800	31	34
1,800 – 3,700	9	12
Over 3,700	2	1

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

Injection Rate (liters per second)	Percent of Wells	
	1967	1972
0 – 3 lps	27	36
3 – 6	17	13
6 – 13	25	20
13 – 25	26	17
25 – 50	4	7
Over 50	1	7

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

Injection Pressure (kilograms per square centimeter)	Percent of Wells	
	1967	1972
Gravity flow	14	27
Gravity – 10 ksc	29	22
10 – 20	27	14
20 – 40	9	16
40 – 100	20	18
Over 100	1	3

Table 6 Pressure at which waste is injected in 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 7 Type of rock used for injection by industrial wells (Warner, 1972).

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

Table 8 Age of injection zone of industrial wells (Warner, 1972).

- Only about 3 percent of existing wells are injecting at well-head pressures exceeding 100 kg/cm^2. This information, in conjunction with the range of depths of wells previously mentioned, is reassuring; it suggests that presently-operating wells are generally using pressures compatible with well depth and that waste waters are generally being injected into naturally-occurring porosity, rather than into continuously induced fractures.

Tables 7 and 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 province, 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 waste injection that can be predicted to occur in every case are:

- Modification of the ground water 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 ground water quality.
- Contamination of other subsurface resources, such as petroleum, coal, or chemical brines.
- Stimulation of earthquakes.
- Chemical reaction between waste water and natural water.

- Chemical reaction between waste water 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 should not occur. Unfortunately some permitted wells are known to exist that:

- Do not have standby facilities.
- Have fractured the receiving rocks.
- Are injecting into fresh water aquifers.
- Have other deficiencies.

Contamination of Fresh Ground Water

The impact of greatest concern to most regulatory agencies is the contamination of potable ground water. This could occur where a well injects into a saline-water aquifer by:

- Escape of waste water through the well bore into an aquifer containing usable water because of insufficient casing or failure of the injection well casing due to corrosion, excessive injection pressure, etc.

- Vertical escape of injected waste water, outside of the well casing, from the injection zone into a useable aquifer.

- Vertical escape of injected waste water 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 waste water from the injection zone through nearby wells that are improperly cemented or plugged, or that have insufficient or leaky casing.

Direct contamination of fresh ground water could also occur by lateral travel of injected waste water from a region of saline water to a region of fresh water in the same aquifer.

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

In many existing injection wells, the potential for direct contamination of fresh ground water appears to be small because of the construction used in these wells and because of the large vertical distance between the injection zones and fresh water aquifers. The belief that the potential for direct aquifer contamination is small, based on the few instances of direct contamination that have been documented, is suspect however and ground water quality near such wells should be monitored carefully. The vertical or lateral movement of saline water into fresh water aquifers as a result of increased formation pressures can be expected to occur.

Contamination of Other Subsurface Resources

No instance of contamination of other subsurface resources by injected industrial waste water has yet been reported. The fact that little evidence of degradation of potable ground water and other resources by this type of injected waste water has been found may be due to the limited amount of monitoring being done and 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 waste water and formation minerals and water is a possible problem in well operations, 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 waste-water injection are not yet known. The general requirement is the presence of a fault system along which movement can be induced in an area where earth strains are present that can be relieved by such movement. It is believed that fluid injection can act as a trigger for release of such strain energy, thus causing earthquakes. A survey of presently existing industrial injection wells other than those injecting oil-field brine has shown that very few are present in such locations, and none, besides 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 waste water injection into aquifers. Control is based on proper siting, design, construction, operation, abandonment, and monitoring as briefly discussed in subsequent subsections.

- Evaluation of hydrogeologic framework and restriction on unsuitable locations and aquifers for waste water injection.

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

- Requirement of proper design and construction of injection wells including hardware and sealants.

- 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 fluid and aquifer fluids.

- Restriction on operating programs for injection wells.

- Surface equipment and programs for emergency procedures in the event of malfunction, including rapid shutoff and standby facilities and programs for long-term decontamination.

- Abandonment procedures for all wells.
- Monitoring programs for injection wells.
- Monitoring programs for aquifers.

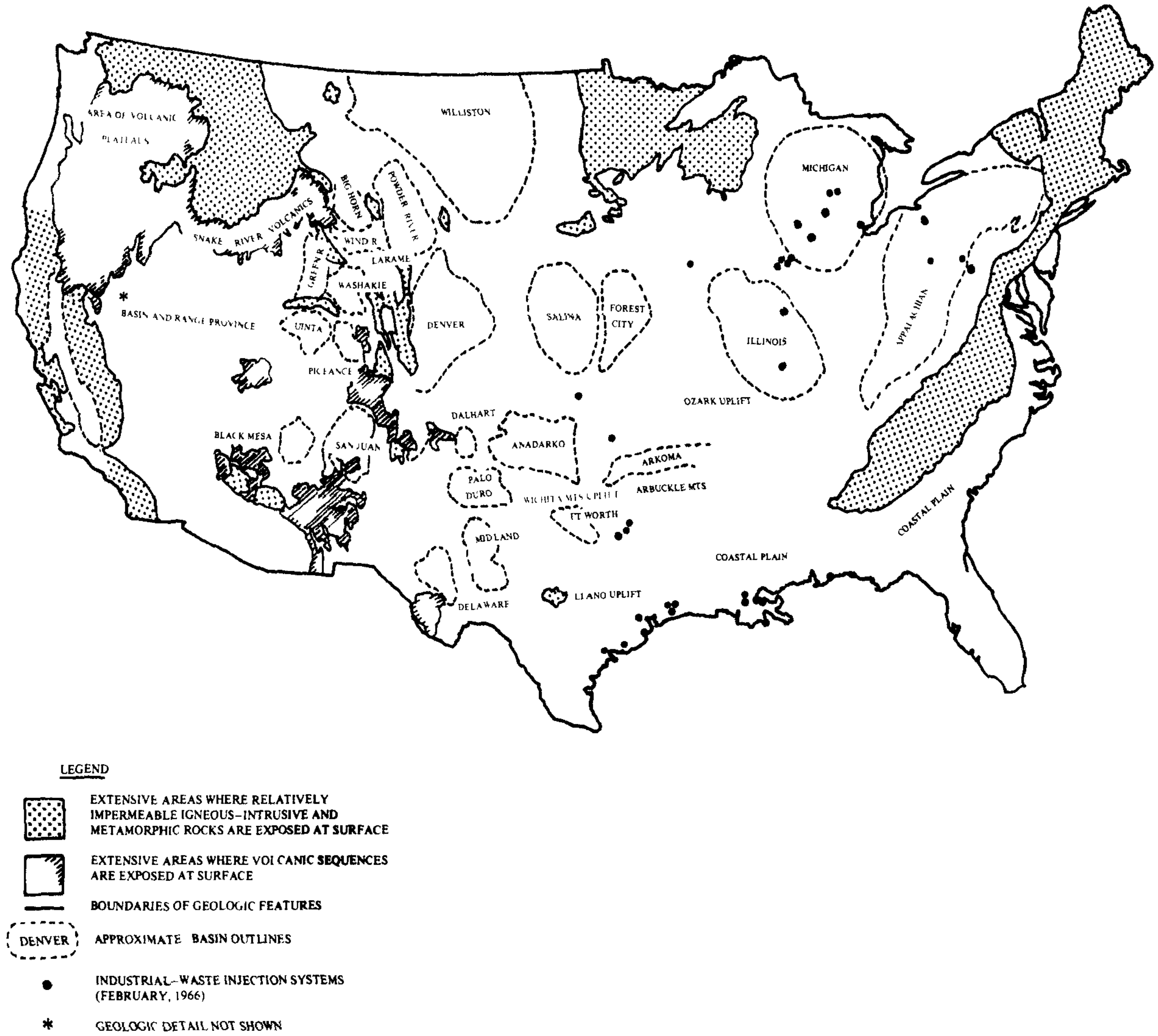


Figure A Geologic features significant in deep waste-injection well-site evaluation, and locations of industrial-waste injection systems (Warner, 1968).

Local Site Evaluation

An outline of the factors for consideration in the evaluation of injection-well sites is given in Table 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 pressures; and (2) an injection zone that is vertically below the level of fresh water circulation and is confined vertically by rocks that are, for practical purposes, impermeable to waste liquids.

Regional Geologic and Hydrologic Framework

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

Local Geology and Geohydrology

- 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)

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

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.

Unfractured beds of 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 salinity of natural 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 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 in arid regions may be set at a level higher than 30,000 mg/l of dissolved solids to provide a margin of safety and because water with this dissolved-solids content is used in certain areas to supply desalination plants which produce fresh water.

Illinois agencies have determined that ground water with a dissolved solids content less than 10,000 mg/l should be protected. All ground waters 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 a meter 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.

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 most natural aquifers only under restricted, 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 characterized an injection zone would still be a problem if few subsurface data were 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 discharge 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 in the area of other wells, or, improperly plugged wells that penetrate the injection zone and provide a means for escape of injected waste to ground water aquifers or to the surface; (4) the mineralogy of the injection zone and chemistry of the resident water, 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.

Waste Evaluation

A foremost consideration in evaluating the feasibility of waste injection is the character of the waste. Table 10 lists some 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.

- 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

Table 10 Factors to be considered in evaluating the suitability of untreated industrial wastes for well injection.

Waste disposal intc subsurface aquifers ordinarily constitutes the use of limited storage space, and only concentrated, very objectionable, relatively untreatable waste should be considered for injection. The fluids injected into deep aquifers do not occupy empty pores; each liter of waste will displace or compress a liter of the fluid which saturates the aquifer. Optimal use of underground storage space will be realized by use of 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.

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 waste water samples to confirm anticipated reactions.

Selm and Hulse (1959) lists 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.

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) give 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.

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 necessary geologic and hydrologic data. Logging and testing data should be filed with the appropriate state agency or agencies.

Table 11 summarizes the type of 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 ground water supplies are present, a casing string (surface casing) is usually installed to below the depth of the deepest ground water aquifer immediately after drilling through the aquifer (Figure B). One or more smaller-diameter casing strings are then set, with the bottom of the last string just above, into or through the injection horizon, depending on whether the well is to be completed as an open hole or is to be cased and perforated.

The annulus between the hole wall and the casing is filled with cement 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 to impart some particular quality to the cement. Additives can, for example, be selected to give increased resistance to acid, sulfates, pressure, temperature and shrinkage.

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

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

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. The injection tubing can be made from, or lined with, a material that is not affected by the particular waste involved. 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 annular space between the casing and the tubing with oil or water containing an added corrosion inhibitor.

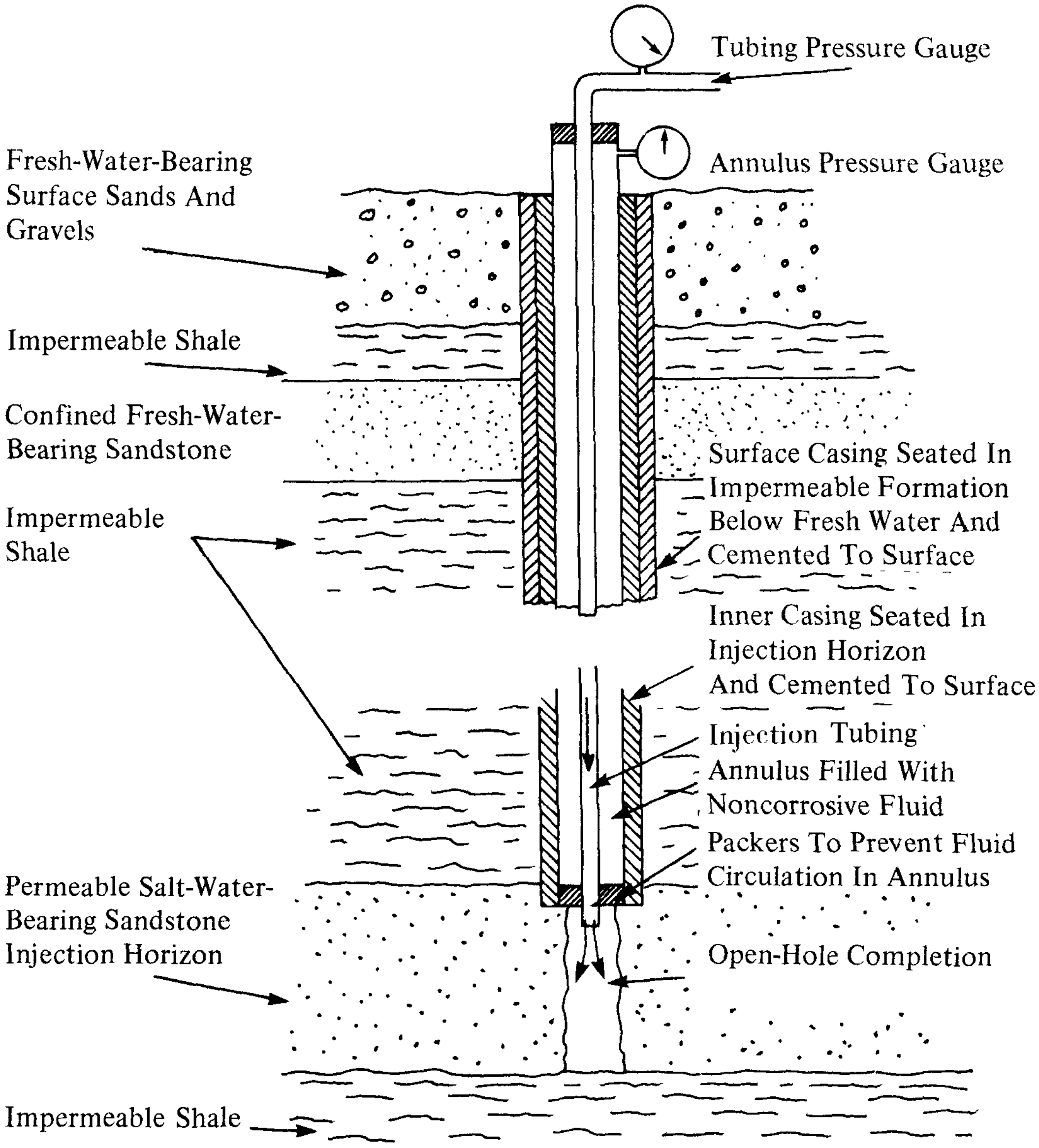


Figure B Schematic diagram of an industrial waste injection well completed in sandstone (modified after Warner, 1965).

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 build-up in the injection zone are important because the maximum pressure at which liquids can be injected may be the factor limiting the safe injection rate and operating life of an injection well. Excessive pressure may cause the rupturing of the injection formation and the movement of the waste to fresh water aquifers.

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 waste water injection. Van Everdingen (1968) outlines the methodology for estimating the pressure build-up resulting from injection wells.

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

Estimates of the extent and direction of waste water movement can be made after the hydrogeologic 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, differential permeability in the injection zone 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 0.11 to 0.23 kilograms per square centimeter per meter of well depth, depending on geologic conditions, but operating pressures are seldom allowed to exceed about 0.18 ksc per meter 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 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. 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.

Standby facilities are essential in order to cope with malfunctions 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 or holding tanks.

In situations where the character of the waste water being injected 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 waste water 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 declined to a level that would allow removel of the damaged tubing without backflow of the corrosive waste water. Such a procedure would help to minimize damage to the casing, packer, etc. Injection of a radioactive waste water would require establishment of procedures for use during well workovers or any other handling of equipment that might become contaminated.

Emergency procedures could also include notification of nearby users of ground water or other resources, should contamination be detected, or even a program for aquifer rehabilitation.

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 waste water and aquifer fluids.

As discussed by Warner (1965), monitoring with wells to determine the rate and extent of movement of waste water within the injection zone may be of limited value because of the difficulty of intercepting the waste water 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) discusses 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 waste water injection systems is that constructed in the fresh water 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, water supply wells, 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 oil field brine 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 waste water injection. A chronological list of these developments is given below:

1961	Texas - Injection well law adopted
1966	Kansas - Regulations adopted
1967	Ohio - Injection well law adopted
	New York - Ground water classified
1969	Indiana - "Test Hole" Legislation enacted
	Michigan - "Mineral Well Law" enacted
	New York - Injection well policy established
	Ohio Valley - Regulatory policy recommended

	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	EPA - Policy announced.

Texas was the first state to pass a law specifically concerning industrial, waste water 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 waste water 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 (ORSANCO) 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 hydrogeology at the proposed well site and the suitability of the waste water 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 waste water 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 waste water injection into the well, anticipated limitations on injection pressure and injected volumes, the probable monitoring requirements, and probable requirements for alternative waste water management programs in the event that operational problems cccur 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 waste water 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 waste water 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 the 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 is provided by Warner (1972) in a report to the Illinois Institute for Environmental Quality.

OTHER WELLS

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

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

Petroleum Industry Wells

Wells are used by the petroleum industry for exploration, for production of oil and gas, and for injection 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 the number exceeds 2,300,000. 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 1.4 billion metric tons of water were produced in 1963 in conjunction with petroleum. At that time, about 72 percent of the produced water was reinjected. The relative percent being reinjected today is undoubtedly higher as other means of disposal, such as in unlined pits, have since been outlawed in Texas and other states.

Hazard to usable ground water may result from any well, including petroleum production wells, that is inadequately cased, cemented, or plugged. Such wells provide avenues for interaquifer movement of saline ground water and other fluids. A particular danger to usable ground water 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 ground water 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) discuss cases from Arkansas, West Virginia, and Pennsylvania, respectively.

The mechanism of possible ground water contamination from oil field brine injection wells is essentially the same as was discussed for other industrial waste water injection wells. Since oil field brine is a natural water and does not usually 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 waste waters. 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 ground water if brine injection is not properly managed (Ostroff, 1965). It is commonly believed that most brine is returned to the same geologic formation from which it was removed. The relative amount returned to the same formation as compared with that injected into other 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 oil field 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 alternation of the position of the fresh-water saline-water interface.

The procedures and methods for control and regulation of brine injection are essentially the same as discussed for industrial waste water injection. Locating and plugging abandoned oil and gas wells may be difficult and expensive. Pasini and others (1972) discuss 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. The average cost for plugging 60 abandoned wells in The Hubbard Creek Reservoir Watershed during the period 1963-1965 was $1500 each.

A detailed investigation of the problems presented by one incident of pollution of a fresh water aquifer by an oil field brine was made by Fryberger (1972). The present extent of the brine pollution is 2.6 square kilometers (one square mile); however, it will spread to affect 11.7 sq. km (4-1/2 square miles) and may persist for more than 250 years before being flushed from the aquifer if indeed it were ever completely removed. 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 practice is the in situ mining of metals, particularly copper, by the injection (through wells) of acid into an ore body or a tailings pile, and the 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 ground water pollution from the 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. The mining itself may need to be carefully managed to avoid ground water contamination. Disposal of the spent acid solutions by injection would be similar to other industrial waste water injection.

McKinney (1973) and Pernichele (1973) discuss current trends in solution mining and mining geohydrology and list 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 0.73 million hectares (1.8 million acres) are designated as known geothermal resource areas and an additional 38.7 million hectares (95.7 million acres) have prospective value (USGS, 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 (U.S. Department of the Interior, 1971).

At present, the two most significant geothermal areas in the United States are 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 threefold 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 0.31 million hectare-meters (2.5 million acre-feet) of fresh water per year. The 0.37 to 0.49 million hectare-meters (3 to 4 million acre-feet) of brines withdrawn would be replaced by water from the Pacific Ocean, the Salton Sea, or other sources. 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 fresh water 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 salt water aquifers. It has also been proposed to inject brines from advanced waste treatment plants using desalination techniques, and from plants constructed to produce usable water by desalination methods.

The technology of injecting such waters is similar to that previously discussed. The particular problem with this category of waste waters is the very large volume that may be produced. In general the disposal of sewage effluent by injection into saline aquifers probably is questionable 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. Under certain conditions a double benefit can be realized by injecting a good quality sewage effluent so as to displace a poor quality ground water, thus creating a reserve of usable water in underground storage.

Injection of brines from desalination plants may be the most desirable method of disposing of these wastes in cases where the geology is suitable and the volumes of waste are not too large (Dow Chemical Company, 1972).

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 waste waters into deep aquifers, but the only one that has been used for this purpose 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 the heat generated by radioactive decay.

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 is 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 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 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 that 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 ground water by leakage of gas through the confining beds, through abandoned improperly plugged wells, or through inadequately constructed gas injection or withdrawal wells. Gas could also escape from an overpressured 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 confining bed, faulting of the confining bed, 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. Storage fields are subject to state or federal licensing and regulation so the engineering characteristics of a field must be carefully determined prior to licensing, and the fields must be monitored during operation.

Water Wells

The mere existence of any type of well so poorly constructed that surface materials can fall or run down the hole is a ground water pollution hazard. Due to the technology employed, most injection wells and oil wells are not so poorly constructed. The main offenders are water wells, some of which permit the introduction, directly into aquifers, of dead skunks and the like, and many of which provide a path for polluted surface water and septic tank effluent to drain directly into the aquifers from which drinking waters is drawn, at a point very near the intake.

This obvious hazard has an obvious solution in the excerise of reasonable care, by competent well drillers, in well construction. An impermeable material (preferably neat cement) should be emplaced around the surface casing, from top to bottom, to prevent downward movement of pollutants.

Specific water well pollution problems result from:

- Gravel packed wells where the gravel pack extends from land surface to the aquifer or extends into an aquifer containing mineralized or undesirable water.

- The pulling of the well casing in a gravel packed well that leaves a gravel conduit extending from the surface to the aquifer.

- Insufficient casing and improper grouting of casing in water wells in basalt formations.

- Improper location of perforations.

- Improper or inadequate welding of casing joints.

- Leaky pitless adapters.

- Leaky well seals.

These obvious hazards have an obvious solution in the application of adequate standards for the construction and abandonment of water wells by competent well drillers.

Dry Holes and Abandoned Wells

Most dry holes are not dry. The term "dry hole" is really an indicator of the failure of a hole in the ground to produce a desired fluid in a satisfactory amount, be it crude oil, natural gas, water or whatever.

As with most other human failures, the tendency is to avoid throwing good money after bad, to walk away and to forget it. Such a philosophy often leaves an improperly plugged hole that provides a direct and speedy route for the movement of surface pollutants into good aquifers. It also leads to the direct and speedy movement of fluids from contaminated aquifers to good aquifers, and to the surface. It should be noted that many states have regulations governing the plugging of abandoned wells, especially oil and gas wells.

Control measures are similar to those for successful wells, that is, the effective sealing by an impermeable substance of routes of unwanted vertical communication.

References

1. American Gas Association, Inc., *Survey of Gas Storage Facilities in United States and Canada,* New York (1967).

2. American Gas Association, Inc., *The Underground Storage of Gas in the United States,* New York (1971).

3. Arlin, Z.E., "Deep-Well Disposal of Urainum Tailing Water," *Proceedings 2nd Conference on Ground Disposal of Radioactive Wastes,* Chalk River, Canada, U.S. Atomic Energy Commission TID-7628, Bk. 2, pp 356-360 (1962).

4. Ballentine, R.K., Reznek, S.R., and Hall, C.W., *Subsurface Pollution Problems in the United States,* U.S. Environmental Protection Agency Technical Studies Report TS-00-72-02, Washington, D.C. (1972).

5. Belter, W.G., "Deep Disposal Systems for Radioactive Wastes," *Underground Waste Management and Environmental Implications,* American Association of Petroleum Geologists Memoir 18, Tulsa, Oklahama (1972).

6. Bureau of Reclamation, *Geothermal Resource Investigations, Imperial Valley, California; Developmental Concepts,* U.S. Department of the Interior, Boulder City, Nevada, 58 pp (1972).

7. Chasteen, A.J., "Geothermal Energy - Growth Spurred on by 'Powerful Motives'", *"Mining Engineering,* Society of Mining Engineers of AIME, Vol. 24, No. 10, pp 100-102 (1972).

8. Cook. T.D. (editor), *Underground Waste Management and Environmental Implications,* American Association of Petroleum Geologists Memior, Tulsa, Oklahoma, 412 pp (1972).

9. de Laguna, W., "Importance of Deep Permeable Disposal Formations in Location of a Large Nuclear-Fuel Reprocessing Plant," *Disposal in Geologic Basins - Study of Reservoir Strata,* American Association of Petroleum Geologists Memoir 10, pp 21-31 (1968).

10. de Laguna, W., et al, *Safety Analysis of Waste Disposal by Hydraulic Fracturing at Oak Ridge,* Oak Ridge National Laboratory Report 4665, Oak Ridge, Tennessee, pp 1-6 (1971).

11. Donaldson, E.C., *Subsurface Disposal of Industrial Wastes in the United States,* U.S. Bureau of Mines Information Circular 8212, 34 pp (1964).

12. Dow Chemical Company (Freeport, Texas), "Final Disposal of Effluent Brines from Inland Desalting Plants," *Environment Pollution and Control,* Report OSW-RDPR-72-817 (1972).

13. Ferris, J.G., "Response of Hydrologic Systems to Waste Storage," *Underground Waste Management and Environmental Implications,* American Association of Petroleum Geologists Memoir 18, Tulsa, Oklahoma, pp 126-130 (1972).

14. Dryberger, J.S., *Rehabilitation of a Brine-Polluted Aquifer,* U.S. Environmental Protection Agency, Environmental Protection Technology Series EPA-R2-014, Washington, C.C., 61 pp (1972).

15. Galley, J.E. (editor), *Subsurface Disposal in Geologic Basins,* American Association of Petroleum Geologist Memoir 10, Tulsa, Oklahama (1968).

16. Galley, J.E., "Geologic Basin Studies as Related to Deep-Well Disposal," *Proceedings 2nd Conference on Ground Disposal of Radioactive Wastes,* Chalk River, Canada, U.S. Atomic Energy Commission TID-7628, Bk. 2, pp 347-335 (1962).

17. Goolsby, D.A., "Hydrogeochemical Effects of Injecting Wastes Into a Limestone Aquifer Near Pensacola, Florida," *Ground Water,* Vol. 9, No. 1, pp 13-19 (1971).

18. Hallden, O.S., "Underground Natural Gas Storage (Herscher Dome)," *Ground Water Contamination,* U.S. Department of Health, Education, and Welfare, R.A. Taft Sanitary Engineering Center, Technical Report W61-5, Cincinnati, Ohio, 218 pp (1961).

19. Hubbert, M.K., and Willis, D.G., "Mechanics of Hydraulic Fracturing," Journal of Petroleum Technology, American Institute of Mining, Metallurgical Engineers Petroleum Division, Trans., T.P. 4597, pp 153-168 (1957).

20. Iglehart, C.F., "North American Drilling Activity in 1971," Bulletin, American Association of Petroleum Geologists, Vol. 56 No.7, pp 1145-1174 (1974).

21. Interstate Oil Compact Commission, Water Problems Associated with Oil Production in the United States, Oklahoma, City, Oklahoma, 88 pp (1964).

22. Irwin, J.H., and Morton, R.B., Hydrogeologic Information on The Glorieta Sandstone and the Ogallala Formation in the Oklahoma Panhandle and Adjoining Areas as Related to Underground Waste Disposal, U.S. Geological Survey Circular 630, 26 pp (1969).

23. Ives, R.E., and Eddy, G.E., Subsurface Disposal of Industrial Wastes, Interstate Oil Compact Commission, Oklahoma City, Oklahoma, 109 pp (1968).

24. Love, J.D., and Hoover, L., A Summary of the Geology of Sedimentary Basins of the United States, with Reference to the Disposal of Radioactive Wastes, U.S. Geological Survey Trace Elements Inv. Report 768 (open file), 92 pp (1960).

25. McKinney, W.A., "Solution Mining," Mining Engineering, pp 5657, February (1973).

26 Ostroff, A.G., Introduction to Oilfield Water Technology, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 412 pp (1965).

27. Pasini, J., III, et al, "Plugging Abandoned Gas and Oil Wells," Mining Congress Journal, pp 37-42, December (1972).

28. Pernichele, A.C., "Geohydrology," *Mining Engineering*, pp 67-68, February (1973).

29. Rima, R., et al, *Subsurface Waste Disposal by Means of Wells - A Selective Annotated Bibliography*, U.S. Geological Survey Water - Supply Paper 2020 (1971).

30. Roedder, E., *Problems in the Disposal of Acid Aluminum Nitrate High-Level Radioactive Waste Solutions by Injection Into Deeplying Permeable Formations*, U.S. Geological Survey Bulletin 1088, 65 pp (1959).

31 Selm, R.P., and Hulse, B.T., "Deep-Well Disposal of Industrial Wastes," *14th Industrial Waste Conference Proceedings*, Purdue University Engineering Extension Series No. 104 pp 566-586 (1959).

32. US Department of the Interior, *Geothermal Leasing Program*, NTIS Accession No. PB 203 102-D, Washington, D.C. (1971).

33. U.S. Environmental Protection Agency, *Subsurface Water Pollution, A Selective Annotated Bibliography, Part 1, Subsurface Waste Injection*, Office of Water Programs, Washington, D.C., 156 pp (1972).

34. Van Everdingen, A.F., "Fluid Mechanics of Deep-Well Disposals," *Subsurface Disposal in Geologic Basins - A Study of Reservoir Strata*, American Association of Petroleum Geologists Memoir 10, Tulsa, Oklahoma, pp 32-42 (1968).

35. Warner, D.L., *Deep-Well Injection of Liquid Waste*, U.S. Public Health Service Environmental Publication No. 999-WP-21, 55 pp (1965).

36. Warner, D.L., "Deep-Well Waste Injection -- Reaction with Aquifer Water," *Proceedings, American Society of Civil Engineers*, Vol. 92, No SA4, pp 45-69 (1966).

37. Warner, D.L., *Deep-Wells for Industrial Waste Injection in the United States - Summary of Data*, Federal Water Pollution Control Administration, Water Pollution Control Research Service Publication No. WP-20-10, 45 pp (1967).

38. Warner, D.L., "Subsurface Disposal of Liquid Industrial Wastes by Deep-Well Injection," *Subsurface Disposal in Geologic Basins - A Study of Reservoir Strata,* American Association of Petroleum Geologists Memoir 10, Tulsa, Oklahoma, pp 11-20 (1968).

39. Warner, D.L., *Subsurface Industrial Wastewater Injection in Illinois,* Illinois Institute for Environmental Quality Document N. 72-2, 125 pp (1972).

40. Warner, D.L., *Survey of Industrial Waste Injection Wells,* 3 Vols., Final Report, U.S. Geological Survey Contract No. 14-080001-12280, University of Missouri, Rolla, Missouri (1972).

41. Wilmoth, B.M., "Occurrence of Salty Groundwater and Meteoric Flushing of Contaminated Aquifers," *Proceedings of National Groundwater Quality Synposium,* EPA Water Pollution Control Research Series 16060 GRB 08/71 (1971).

42. Young, A., and Galley, J.E. (editors), *Fluids in Subsurface Environments,* American Association of Petroleum Geologists Memior 4, Tulsa, Oklahoma, 414 pp (1965).

INJECTION INTO FRESH WATER 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 the disposal of pollutants into fresh water 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 ground water pollution in the southwestern United States, state that "occasionally, industries or others have used shallow injection wells to dispose of liquid wastes," and cite as an example electronic industries that disposed of metalplating 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 C). 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 fresh water 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 water, 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).

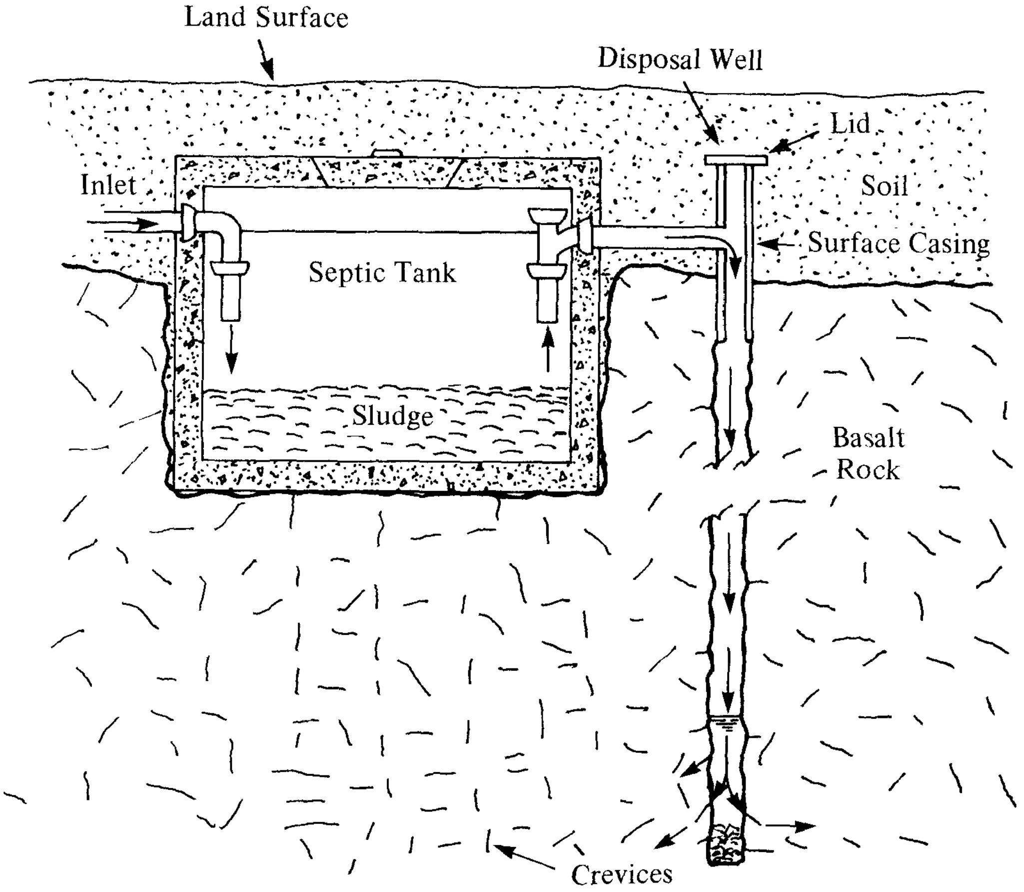


Figure C Diagram of domestic sewage disposal system employing a disposal well in the middle-Deschutes Basin, Oregon (after Sceva, 1968).

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 fresh water aquifers. Several of the proposed schemes not only would solve a sewage-disposal problem but also would help to recharge fresh-water aquifers or to establish hydraulic barriers against salt-water encroachment in fresh-water 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 the injection wells and to reduce or prevent significant contamination of the aquifer.

Modification of the existing quality of the native ground water 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 fresh-water aquifers tap the shallowest available aquifer, commonly a water-table aquifer. Some disposal wells, however, are terminated at greater depths in confined fresh water aquifers.

Environmental Consequences

Initially, injection of contaminated liquids through wells into fresh-water aquifers causes degradation of the chemical and bacteriological quality of the ground water 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 fresh-water aquifers.

Nature of Pollutants

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

In the case of cooling water returned to the same aquifer from which it has been pumped, the quality of the water may be 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. 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 to an aquifer.

Domestic sewage being disposed of into individual household wells is a waste highly polluted with organic and inorganic substances, bacteria, and viruses. It may receive little natural treatment during passage through septic tanks and cesspools except for the 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, phosphates, sulfates, chlorides, 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 qualities of tertiary treated sewage, native ground water and water recovered from observation wells, from an experimental injection study in Long Island, New York, are shown in Table 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 ground water. No analyses of the treated waste were made for heavy metals, viruses, or other objectionable constituents. The bacterial count in the treated sewage was low due to heavy chlorination before injection.

Storm-water runoff generally has a low dissolved-solids content. However, the initial slug of storm water may be contaminated with animal excrement, pesticides, fertilizer nitrate from lawns, organics from combustion of petroleum products, rubber from tires, bacteria, viruses, and other contaminants. Where deicing salts are applied to roads in the winter, the chloride content of the storm water 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 fresh water aquifers.

			Contaminated Water Recoverd from Observation Wells	
Constituent	Tertiary Treated Injection water (mg/ℓ)	Native Groundwater Depth 171m (mg/ℓ)	Depth 146m; Distance 6.1m (mg/ℓ)	Depth 140m; Distance 30m (mg/ℓ)
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

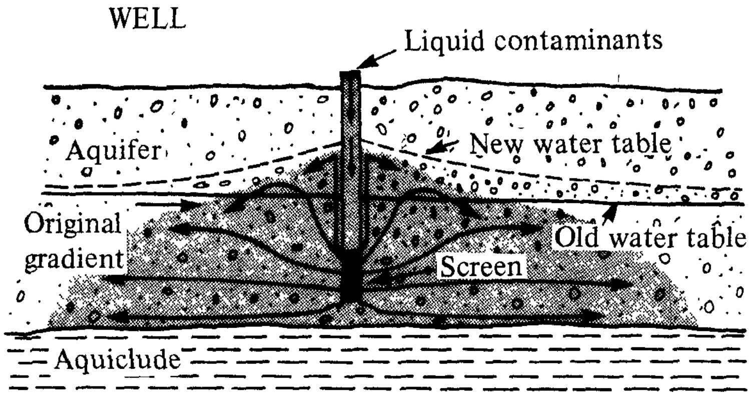
Table 12 Selected chemical-quality characteristics of native water and tertiary treated injection water (after Vecchiolo and Ku, 1972).

Pollution Movement

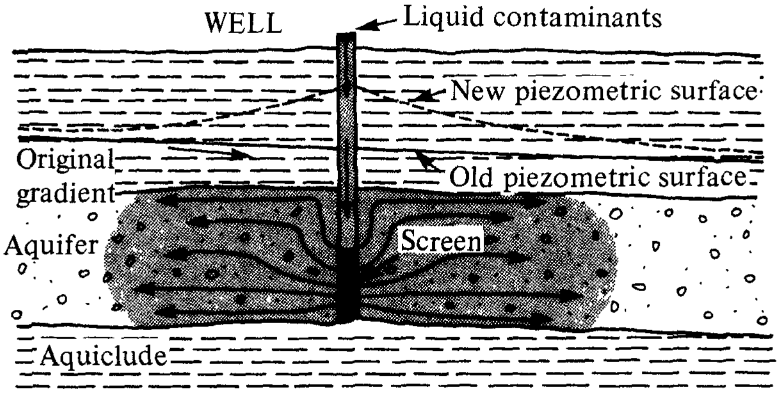
In principle, any well that produces water will also accept water. The rate of acceptance is dependent on the nature of the injected fluid, the hydraulic properties of the aquifer, and other factors. In some wells penetrating very permeable aquifers, water can be introduced under gravity conditions at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

The rate of injection is governed by the porosity, 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 compatibility of the injected fluid with the native ground water. If the fluid being injected contains suspended materials 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 an induced rise of the ground water level may cause breakthrough and overflow at the land surface.

Injection of fluid through a well creates a local ground water 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 D. Departures from these shapes may develop where aquifer lithologies are not uniform and where the natural ground water flow is rapid.



A. Water table aquifer



B. Artesian aquifer

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

After it has entered the saturated zone the injected fluid begins to move radially away from the well, displacing the native ground water 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 fresh-water 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 salt-water 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). A specially constructed injection well (Cohen and Durfor, 1966), 146 meters (480 feet) deep, with a fiberglass casing, stainless steel screen, and auxiliary monitoring wells at depths ranging from about 30 to 200 meters (100 to 700 feet), were installed to investigate the hydraulic and geochemical problems associated with the injection of treated sewage into a confined, sand aquifer used for public-water supply. The injected water moved radially from the well as a thin body in the injection zone and has been detected by monitoring wells as much as 60 meters (200 feet) away. As shown in Table 12, significantly higher concentrations of iron, ammonia, sulfate, chloride, sodium, and other dissolved constituents were present in the water at distances of 6.1 meters and 30.5 meters (20 feet and 100 feet), than in the native ground water. Bacteria were apparently filtered out after about 6.1 meters (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 build up in the injection well. Similar experiments in California on recharging fresh-water aquifers with Colorado River water and with reclaimed sewage (McGauhey and Krone, 1954), mainly as a barrier against sea-water encroachment, have been successfully conducted. Some barrier systems using highly treated river water are operational. Baier and Wesner (1971) have described experiments by Orange County Water District in which tertiary-treated effluent from a trickling filter sewage plant was injected into unconsolidated aquifers at depths of about 30 to 100 meters (100 to 350 feet). The experiments indicated that after about 150 meters (500 feet) of travel, the injected water was free of 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 water pumped from wells on Long Island at rates of 2.8 lps (45gpm) or more 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 ground water levels in western Long Island, with coastal encroachment of sea water. The heated effluent returned to the ground, which may range from 5 to 17°C warmer than the natural ground water, has increased the local temperature of shallow aquifers (Leggette and Brashears, 1938). Warming of the ground water, although of concern to users of ground water for cooling, has been regarded as less detrimental than the saltwater encroachment that could result from declining ground water 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, precast, 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 bypass for potential vertical movement of inorganic and organic contaminants and bacteria into an underlying aquifer.

Control Methods

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

1. Definition of the hydrogeologic environment and the factors affecting the ground water 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 pretreatment needed; and the compatibility of the treated fluids with the native ground water.

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 future land use at the injection-well sites.

Where the threat from contaminated ground water 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,possibly causing salt-water 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 cooling water. Here the loss of efficiency of the cooling system must be considered; more electrical energy may be required, with attendent air and thermal pollution problems. Also the undesirable "heat island" effect noted in large cities would be further increased by widespread use of atmospheric heat exchangers in place of the ground water for cooling.

Halting the disposal of wastes into wells may, in some instances, 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 conditons 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 ground water, and changes of ground water levels, can provide valuable data on the behavior of the underground contamination,and on the environmental threats to water wells or to other fresh-water resources in the vicinity.

References

1. Baier, D.C., and Wesner, G.M., "Reclaimed Waste Water for Ground-Water Recharge," *Jour. American Water Resources Assoc.,* v.7, no.5, pp. 991-1001 (1971).

2. Cohen, Philip, and Durfor, C.N., "Design and Construction of a Unique Injection Well on Long Island, New York," *Geological Survey Research, 1966, U. S. Geol. Survey Prof. Paper 550-D,* pp. D253-D257 (1966).

3. Deutsch, Morris, *Ground-Water Contamination and Legal Controls in Michigan,* U. S. Geol. Survey Water-Supply Paper 1691, 79 pp. (1963).

4. Fuhriman, D.K., and Barton, J.R., *Ground Water Pollution in Arizona, California, Nevada, and Utah,* U. S. Environmental Protection Agency, Water Pollution Control Research Series 16060, 249 pp. (1971).

5. Jones. P.H., *Hydrology of Waste Disposal National Reactor Testing Station, Idaho,* U. S. Geol. Survey Interim Report for U. S. Atomic Energy Comm., Idaho Falls, Idaho (1961).

6. Leggette, R.M. and Brashears, M.L., Jr., "Ground Water for Air Conditioning on Long Island, New York," *Trans. Amer. Geophys. Union,* pp. 412-418 (1938).

7. McGauhey, P.H., and Krone, P.B., *Report on the Investigation of Travel of Pollution,* California State Water Pollution Control Board, Publ. no. 5, 218 pp. (1954).

8. Oregon State Sanitary Authority, *Water Quality Control in Oregon*, Oregon State Sanitary Authority, vol. 1, 113 pp. (1967).

9. Sceva, J.E., *Liquid Waste Disposal in the Lava Terranes of Central Oregon,* U.S. Federal Water Pollution Control Admin., Northwest Region, Pacific Northwest Water Laboratory, Corvallis, Oregon (1968).

10. Schiff, Leonard, (Editor), Ground Water Recharge and Ground Water Basin Management, Proc. 1963 Biennial Conference Ground Water Recharge Center, Fresno, Calif. (1963).

11. Vecchioli, Hchn, and Ku, F.H., Preliminary Results of Injecting Highly Treated Sewage Plant Effluent into a Deep and Sand Aquifer at Bay Park, New York, U. S. Geol. Survey Prof. Paper 751A, 14 pp. (1972).

SECTION III - POLLUTION FROM OTHER SUBSURFACE EXCAVATIONS

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 from lagoons and basins by a smaller 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 a roof. Some are intended to discharge liquid to the soil system and hence to the ground water, others are designed to be watertight. The former are, therefore, unlined structures sited on good infiltrative surfaces; the later 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 ground water 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 waste water treatment plants by ground water recharge. In industry the unlined system may serve as a cooling pond or to hold hot waste water until its temperature is suitable for discharge to surface waters, or to store waste water 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, lined pits are used as holding sumps for brines or wastes as a stage in disposal by 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, undetected leakage of highly concentrated pollutants can have a significant effect on ground water.

Scope of Problem

Data by which to evaluate the existing scope of the problem of municipal and industrial waste lagoons and similar open excavations in relation to ground water 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 ground water 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 Public Law 92-500, 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; and
- 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 ground water and to monitor the effectiveness of control measures.

Potential Hazard to Ground Water

The potential of sewage lagoons to degrade ground water 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 ground water 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 ground water must, therefore, be loaded and rested intermittently to maintain an acceptable recharge rate. If, however, isolating the contents of the lagoon from the ground water 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 ground water 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 ground water.

Liquids percolating from lagoons or basins used by industry have a greater potential to degrade ground water than does domestic sewage. Chromates, gasoline, phenols, picric acid, and miscellaneous chemicals have been observed to travel long distances with percolating ground water. 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 ground water 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.

Where 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 ground water can be significant and the plume of polluted liquid may have traveled long distances with the percolating ground water. In some instances, the first realization that extensive ground water 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 1200 meters (4,000 feet) long, about 300 meters (1,000 feet) wide, and as much as 20 meters (70 feet) thick. Some of the contaminated ground water is being discharged naturally into a small creek that drains the aquifer. The maximum observed concentration of hexavalent chromium in the ground water 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 75 million liters (20 million gallons) of effluent into the upper 6 meters (20 feet) of aquifer over a period of only a few years. The contaminated ground water contains high concentrations of phenols, chromium, zinc, and nickel.

Control Methods

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

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

- Pretreatment of wastes for removal of at least the toxic chemicals.
- 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 ground water 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.
- Banning the use of pits. An example is found in Kansas, where thousands of brine pits were used by the oil industry. Kansas was the first State to ban their use because of the contamination of ground water.
- Locating and identifying unauthorized pits on industrial sites, on a case-by-case basis, and apply appropriate regulatory action.

Monitoring Procedures

Lagoons, basins, and pits represent pollution sources which may be of significance to ground water quality degradation. Therefore, a program involving special monitoring wells on a priority basis is a possible approach.

A program of periodic sampling and evaluation of data from existing wells, selected for their potential to reveal both normal ground water quality and point contamination, is another monitoring approach. Accompanying this should be an evaluation of the control measures themselves to assure that ground water protection is indeed being accomplished.

References

1. Anon., "Well Pollution by Chromates in Douglas, Michigan," *Michigan Water Works News* (1947).

2. California State Water Pollution Board, *Wastewater Reclamation in Relation to Groundwater Pollution*, Publication No. 6, Sanitary Engineering Research Laboratory, University of California, Berkeley (1953).

3. Davids, H.W., and Lieber, M., "Underground Water Contamination by Chromium Wastes," *Water and Sewage Works*, Vol. 98, pp 528-534 (1951).

4. Geraghty & Miller, Inc., *Consultant's Report*, Port Washington, New York (1972).

5. Harmond, B., "Contamination of Groundwater Resources," *Civil Engineering*, Vol. 11, p 343 (1941).

6. Lang, A., "Pollution of Water Supplies, Especially of Underground Streams, by Chemical Wastes and by Garbage," *Z. Gesundheitstech. & Stadtehyg.* (Ger.), Vol.24, No. 5, p 174 (1932).

7. Lang, A., and Gruns, H., "On Pollution of Groundwater by Chemicals," *Gas u. Wasser*, Vol. 83, No. 6; Abstract, *Journal American Water Works Association*, Vol. 33, p 2075 (1940).

8. McGauhey, P.H., and Krone, R.B., *Soil Mantle as a Wastewater Treatment System*, Final Report SERL Report No. 67-11, Sanitary Engineering Research Laboratory, University of California, Berkely (1967).

9. McGauhey, P.H. and Winneberger, J.H., *Causes and Prevention of Failure of Septic-Tank Percolation Systems*, Technical Studies Report, FHA No. 533, Federal Housing Administration, Washington, D.C. (1964).

10. Muller, J., "Contamination of Groundwater Supplies by Gasoline," *Gas u. Wasser, Vol. 93*, pp 205-209 (1952).

11. Perlmutter, N.M., and Lieber, M., *Dispersal of Plating Wastes and Sewage Contaminants in Ground Water and Surface Water, South Farmingdale-Massapequa Area, Nassau County, New York,* U.S.G.S., Water Supply Paper 1879-G, 67 pp (1970).

12. Sayre, A.N., and Stringfield, V.T., "Artificial Recharge of Groundwater Reservoirs," *Journal of American Water Works Association,* Vol. 40, pp 1152-1158 (1948).

SEPTIC SYSTEMS

Scope of the Problem

Septic systems are used in every state in the Union, the heaviest concentration being in suburban subdivisions developed following World War II and in recreational lake development. 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 waste water, 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.

The relationship between a septic sytem and the quality of nearby ground water 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 75 centimeters (30 inches) in diameter extending down to a depth of 6 meters (25 feet) or more, and filled with gravel surrcunding 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 ground water table makes it necessary to place the percolation system above the normal ground level. Here a one meter (three 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 ground water.

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 ground water. 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. Thus, the purpose of the percolation system is to dispose of sewage effluents by utilizing the same natural phenomena which lead to the accumulation of ground water.

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.

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 ground water quality is direct discharge of untreated septic tank or cesspool effluent into the ground water 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 ground water itself often carries for long distances putrescible sewage solids, bacteria, viruses, 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, 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 ground water and move with it. Tastes and odors are introduced, and the organic fraction, being biochemically unstable, remains capable of supporting bacterial growth when the ground water outcrops or is withdrawn through a well.

It may be said that at best septic systems increase the total dissolved mineral solids in ground water. 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 ground water. 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 ground water has been readily detected.

Control Methods

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

1) Septic tank installations are already in existence.
2) New septic tank systems are to be installed.
3) 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 ground water 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 aquifers 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 ground water 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 ground water 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, viz.,

- Require any existing subdivision subject to septic system failure or observed by mandatory monitoring to be damaging to ground water 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 hydrogeologists, 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 each 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 alternatives are to:

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 ground water quality.
3. Permit use of septic systems but restrict the materials which may be discharged to them, specifically, by prohibiting 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.

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 meteoric 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.

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 waste water and of the receiving ground water, and to requirement of permits and inspection for any 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 sytem. In general, the monitoring of septic system percolate is probably an unnecessary and unrewarding procedure.

If ground water receiving percolate from overlying septic systems is to be monitored, it is desirable to sample both at the water table and at greater 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 ground water.

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 ground water 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 when sewers collect effluent and discharge it to a stream or coastal waters.)

References

1. Bendixen, T.W., et al., *Study to Develop Practical Design Criterial for Seepage Pits as a Method of Disposal of Septic-Tank Effluent*, Report to FHA, Robert A. Taft Sanit.Eng. Center, USPHS, Cincinnati (1962).

2. Coulter, J.B., et al., *Study of Seepage Beds*, Report to FHA, Robert A. Taft Sanit. Eng. Center, USPHS, Cincinnati (1960).

3. McGauhey, P.H., and Winneberger, J.H., *Soil Mantle as a Wastewater Treatment System, Final Report, SERL Rept. No. 67-11*, Sanitary Engineering Research Lab., Univ. of California, Berkeley (1967).

4. McGauhey, P.H., and Winneberger, J.H., *Causes and Prevention of Failure of Septic-Tank Percolation Systems*, Tech. Studies Rept., FHA No. 533, Federal Housing Administration, Washington, D.C. (1964).

5. Perlmutter, N.M., and Guerrera, A.A., "Detergents and Associated Contaminants in Ground Water at Three Public-Supply Well Fields in Southwestern Suffolk County, Long Island, New York," U. S. Geol. Survey, *Water-Supply Paper 2001-B*, 22 pp (1970).

6. Schmidt, D. E., "Nitrate in Groundwater of the Fresno-Clovis Metropolitan Area, California," *Ground Water*, v.10, no., 1 pp. 50-64 (1972).

7. U. S. Public Health Service, *Quad-City Solid Wastes Project - An Interim Report*, July 1, 1966 to May 13, 1967, USPHS, Cincinnati (1968).

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. 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. A "sanitary landfill" is:

> "A method of disposal of refuse on land without creating nuisances or hazards to public health or safety, by utilizing the principles of engineering to confine the refuse to the smallest practical area, to reduce it to the smallest practical volume, and to cover it with a layer of earth at the conclusion of each day's operation or at such more frequent intervals as it may be necessary."

Less than 10 percent of the refuse disposal sites in the United States are operated within this accepted definition of a sanitary landfill. Very few of those considered true sanitary landfills were established in sites studied and selected for the special purposes of hazardous waste disposal.

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.

Environmental Consequences

The potential hazard of landfills to ground water 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 U.S. Environmental Protection Agency estimated that in 1969 urban solid waste totaled 225 million tons per year, while industrial solid waste was about 100 million tons. Various estimates of this total for 1972 are about one ton per capita per year--almost 2.72 kilograms per person per day. In 1970 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 13. From this Table 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 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 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 14. It shows that 75 percent of waste solids were noncombustible process solids and that 71 percent of the 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.

	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.
Paper Products	50	41	60	45	42	46	52	50
Food Wastes	12	6	18	i	12	17	10	15
Garden Waste[h]	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	
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

Table 13 Components of domestic solid waste (expressed as percentages of total).

	Total Per Year (Thousands of Metric Tons)	Percent Total
Type of Waste		
Process solids, non-combustible	7,624	75
Process solids, combustible	520	5
Containers, non-combustible	58	1
Containers, combustible	152	1
Fly ash from fuel combustion	1,440	14
Other, or unspecified	423	4
	10,217	
Disposal Method		
Landfill on company property	7,318	71
Landfill away from company property	472	5
Incineration, with heat recovery	83	1
Incineration, without heat recovery	210	2
Open dump burning	99	1
Contracted disposal	1,476	15
Other, or unspecified	559	6
	10,217	

Table 14 Landfill disposal of chemical process wastes.

Leaching of Landfills

Leaching of landfills with consequent degradation of underlying ground water 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) precipation, (2) moisture content of refuse, (3) surface water infiltrating into the fill, (4) percolating water entering the fill from adjacent land area, or (5) ground water 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 4.11 cm of water per meter of depth of fill is reported to be necessary. 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. Because of the high paper content and the relatively inert material shown in the typical analyses, Table 13, only a small amount of moisture is released by the decomposition of the organic solids in refuse. A composite sample of an average municipal refuse is shown in Table 15.

	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

Table 15 Composition of municipal refuse

To induce composting, a moisture content of 50 to 60 percent is required, hence a fill in a very arid region 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.

Percolating water entering a landfill from surrounding land is not likely in a proper landfill. If other sources of water are excluded from a landfill by employing procedures described in a later section, the production of leachate in a well designed and managed landfill can be effectively eliminated. A proper landfill not intersecting the water table will not cause water quality impairment for either domestic or irrigation use. Subsequent reports of test borings around landfills dating back as far as 50 years in England showed no evidence of ground water pollution as a result of leaching. Similarly, no evidence was found in Holland that past landfilling has been a source of pollution of ground water. Evidence reported from Illinois and Minnesota is that leaching did not contaminate ground water in two major fills built within the aquifer itself. Compaction of fill material, clogging of fill area walls and balance of hydrostatic pressure cause ground water 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 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 that of 124 cm annual rainfall in New York, 45 percent will infiltrate into an unsealed and unprotected dump. At some seasons of the year up to 75 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 ground water at a rate governed by the degree of clogging of the underlying and surrounding soil. Clogging, however, may reduce permeability at the infiltrative surface; 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 ground water, a large fill area, even at a low rate of movement into the underlying strata, could with time, discharge a significant volume of leachate.

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 ground water. A refuse of the composition shown in Table 15 is theoretically capable of producing 0.169 cubic meters of CO_2 per kilogram 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.

Nature and Amount cf 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 effects 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 16.

Table 16 indicates what many observers have reported: the initial values of BOD and COD are always high. Studies of operating landfills show constituents of leachate to include:

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

Table 16 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	1.36 tons
Calcium plus magnesium	0.9 tons
Chloride	0.83 tons
Sulfate	0.21 tons
Bicarbonates	3.54 tons

Determination (mg/ℓ)	Source[a]					
	1[b]	2[b]	3[b]	4[c]	5[c]	6[c]
pH	5.6	5.9	8.3			
Total hardness ($CaCO_2$)	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 $CaCO_2$	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).

Table 16 Leachate composition

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. 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 11 cm of rain fell in 24 hours. On that occasion 806.1 liters of leachate were collected. Flow then continued at a rate of about 5678 liters 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 17 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.

Pilot studies were made in 1964 to 1966 to study the effects of rainfall and irrigation on landfill leaching. Two cells, 15 meters square at the bottom and sloped to the top, were filled with a single 5.3 meter lift of refuse, plus a 61 cm 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 330 cm 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 429 cm of applied water.

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

Table 17 Change in leachate analysis with time (Meichtry, 1971).

Limited experiments, such 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, a 2.44 meter lift of refuse with 61 cm of earth cover will take from 1 to 2 1/2 years to reach field capacity and produce leachate if 117.8 cm of rainfall is allowed to infiltrate and percolate into the fill.

In one field observation (Hassan, 1971) a landfill partly inundated by ground water 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 ground water was not seriously affected. However, similar studies in Germany revealed the presence of leachate effects in ground water 3,000 meters away.

In the case of industrial wastes disposed of by landfill on company property, little is known of the nature and extent of leachate. Table 14 shows that noncombustible solids represent 75 percent and ashes another 14 percent of the total. These data suggest that soluble minerals provide the most common materials which might be leached from industrial waste fills. In terms of ground water 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 ground water, 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 ground water 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 restrictions on materials for disposal,
- 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 ground water. 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 ground water in the vicinity.
    - Importance of underlying ground water as a resource, both present and future.
    - Nature of geology of the site.
    - Feasibility of excluding both surface water and ground water 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 water table, as is most commonly required, this will minimize the rate of escape of leachate from the fill. If the fill is in an aquifer, the movement of the ground water 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 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 ground water 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 ground water 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

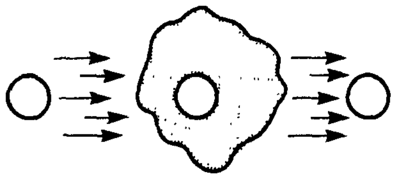
landfills on an economic scale, phasing out with time the leachate contribution to ground water.

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 ground water pollution by leachate. Siting, constructing, operating, and maintaining fills are in this category of control measures. Existing well-engineered landfills, although not generally equipped with underdrains, are minimal in their effects upon ground water quality and hence 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 waste treatment 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 is illustrated in Table 18 along with the results of ground water quality observations.



Groundwater Characteristics	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

Table 18 Ground water quality

It would be feasible to drill and gravel pack a sampling well in a landfill, then seal its bottom and drill through to the ground water 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 ground water quality. In any event the best procedure is the use of control measures which minimize the possibility of leaching of landfills.

References

1. Anderson, D.R., and Callinan, J.P., Gas Generation and Movement in Landfills, paper (1969).

2. Anon., "Sanitary Landfills: The Latest Thinking," Civil Engineering, Vol. 43, No. 3, pp 69-71 (1973).

3. Bergman, R.D., "Urgent Need to Recycle Solid Wastes?," Civil Engineering, Vol. 42, No. 9 (1972).

4. Bell, J.M., "Characteristics of Municipal Refuse," Proceedings of National Conference on Solid Wastes Research, American Public Works Association Research Foundation, Chicago (1963).

5. Burch, L.A., "Solid Waste Disposal and Its Effect on Water Quality", Vector Views, Vol. 16, No. 11 (1969).

6. California State Water Pollution Board, Report on Investigation of Leaching of a Sanitary Landfill, Publication No. 10, Sacramento, California (1954).

7. Dall, Frank R., "The Effect of Solid Waste Landfills on Groundwater Quality," Sixth Biennial Conference on Ground Water Recharge, Development Management, University of California, Berkeley (1967).

8. Emrich, G.H., and Landon, R.A., "Generation of Leachate from Landfills and Its Subsurface Movement," Annual Northeastern Regional Anti-Pollution Conference, University of Rhode Island, Kingston (1969).

9. Environmental Protection Agency, "A Citizen's Solid Waste Management Project", Mission 5000, EPA (1972).

10. Environmental Protection Agency, *Comprehensive Studies of Solid Waste Management, First and Second Annual Reports*, U.S. Public Public Health Service, Publication No. 2039, Research Grant EC-00260, University of California (1970).

11. Environmental Protection Agency, *Solid Wastes Disposal Study, Vol. 1, Jefferson County, Kentucky*; Institute of Industrial Research, University of Louisville, U.S. Department of Health, Education, and Welfare, Bureau of Solid Waste Management (1970).

12. Golueke, C.G., and McGauhey, P.H., *Comprehensive Studies of Solid Waste Management*, First Annual Report, SERL Report No. 67-7, Sanitary Engineering Research Laboratory, University of California, (Berkeley 1967).

13. Ham, R.K., personal communication, University of Wisconsin (1971).

14. Hassan, A.A., "Effects of Sanitary Landfills on Quality of Groundwater -- General Background and Current Study," Paper presented at Los Angeles *Forum on Solid Waste Management* (1971).

15. Hughes, G.M., et al, *Hydrogeology of Solid Waste Disposal Sites in Northeastern Illinois, Progress Report D01-00006*, US. Department of Health, Education, and Welfare (1968).

16. Kaiser, E.R., "Chemical Analysis of Refuse Components," *Proceedings 1966 Incinerator Conference*, American Society of Mechanical Engineers, New York, New York (1966).

17. Los Angeles County, Development of Construction on Use Criteria for Sanitary Landfills, USPHS Grant No. D01-U1-00046, County of Los Angeles, California (1968).

18. Manufacturing Chemists Association, "Most Solid Wastes from Chemical Processes Used as Landfill on Company Property," Currents (1967).

19. Meichtry, T.M., "Leachate Control Systems," Paper presented at Los Angeles Forum on Solid Waste Management (1971).

20. Merz, R.C., and Stone, R., Progress Report on Study of Percolation Through a Landfill, USPHS Research Grant SW 00028-07 (1967).

21. McGauhey, P.H., and Krone, R.B., Soil Mantle as a Wastewater Treatment System, Final Report, SERL Report No. 67-11, Sanitary Engineering Research Laboratory, University of California, Berkely (1967).

22. McGauhey, P.H., and Winneberger, J.H., Causes and Prevention of Failure of Septic-Tank Percolation Systems, Tech. Studies Report, FHA No. 533, Federal Housing Administration, Washington, D.C. (1964).

23. LeGrand, H.E., "Systems for Evaluation of Contamination Potential of Solid Waste Disposal Sites", American Water Works Association Journal, Vol.56, pp 959-974 (1964).

SEWER LEAKAGE

Scope of the Problem

Gravity sewers above the ground water table, and pressure outfalls either above or below it, 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 original 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 has grown to tens of thousands of kilometers. Joints in many of the gravity sewer systems carrying domestic sewage number from 621 to 1243 per kilometer. 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 ground water is both varied and variable. Conceptually, a sewer is intended to be water-tight and thus to present no hazard to ground water 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 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 pocr foundation,
- Rupture of pipe joints or pipe sections by slippage of soil in hilly topography,
- Fracture and displacement of pipe by seismic activity; e.g., 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 ground water 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 closing 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.

Material 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 ground water, pollutants may be released below the biologically active zone of the soil and so introduce into the receiving ground water 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 ground water quality is probably far less than the theoretical potential.

If a fractured sewer is below the water 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 ground water 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 ground water 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 ground water.

Looking to the future, it seems certain that sewer leakage will be less of a hazard to ground water 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.
- Muncipal public works departments, using their own personal 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 ground waters 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 ground water 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 ground water.

Monitoring Procedures

As in the case of lagoons, basins, and pits, monitoring of ground water quality in relation to sewer leakage is best accomplished by a program of collection and evaluation of ground water 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 failures from a wide variety of causes and the subsequent leakage then becomes a source of contamination to local ground waters. 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 ground water pollution. Emphasis in this section is on petroleum products because they constitute 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 ground water pollution were reported in a single year from gasoline stations. In northern Europe, where most homes are heated by oil stored in subsurface tanks, oil pollution has become a major threat to ground water quality (Todd, 1973).

Radioactive Wastes

Tanks of solid 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 for storing low-level wastes 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 Morehead, Kentucky. 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 ground water in the vicinity of the sites as well as from sumps in the backfilled pits. The high-level wastes are under Federal control and there has been some leakage from such facilities. The EPA is reviewing both types of storage at this time.

History

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. 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

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 follow-up or periodic checks are required to determine whether or not leaks have developed. Because such tanks are small and comparativley inexpensive, cathodic protection is not required even when the tanks are buried in clay soils, which are known to promote galvanic action.

Pipelines are used for transportation, for collection, and for distribution. Transportation pipelines are used for a wide number of chemicals including 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 19.

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, and for 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 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 ground water pollution has not heretofore been the primary consideration. Because interstate piplines are a major means of transportation, they are regulated by Federal government agencies in the Department of Transportation.

Because leaks of petroleum products can produce a fire or explosion hazard, these regulated pipelines have been required, for the past five years, to report leaks and spills. An analysis of these reports has been made and is summarized in Table 20. It should be noted that the quantities reported represent only leakage associated with interstate carrier systems. This means that local collection and distribution systems, gas stations, residential users, and even relatively large intrastate carriers are not included. Therefore, it must be assumed that the leakage reported covers considerably less than 100 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.

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.

Commodity	No. of Accidents	% of Total	Loss (kiloliters)	% of Total
Crude Oil	172	55.9	18,404	47.2
Gasoline	51	16.6	6,677	17.1
L. P. G.	39	12.7	6,341	16.3
Fuel Oil	21	6.8	2,102	5.6
Diesel Fuel	5	1.6	1,105	2.8
Condensate	5	1.6	582	1.5
Jet Fuel	4	1.3	355	.9
Natural Gasoline	4	1.3	1,390	3.6
Anhydrous Ammonia	3	1.0	1,560	4.0
Kerosene	2	.6	111	.3
Alkylate	2	.6	252	.7
Total	308	100.0	245,057	100.0

Table 19 Summary of interstate liquid pipeline accidents for 1971 (Office of Pipeline Safety, 1972).

Number of accidents – 300 to 500

Number of tons lost – 33,333 to 66,666

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

Table 20 Range of annual pipeline leak losses reported on DOT Form 7000-1 for the period 1968 through 1971.

Chemicals such as ammonia and other agricultural or industrial chemicals can have toxic properties. For example, ammonia will add to the nitrification of ground water, while acids can change the pH of ground water 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 report of leakage of interstate pipelines appears to be representative of the cause of leaks for all pipelines and tanks. Table 21 is extracted from Office of Pipeline Satety (1972) to show the relative frequency of causes. Other causes that have been reported in other years but did not occur in 1971 were floods and surges 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 accidents caused by earth moving equipment. The remaining few causes include vandalism (usually bullet holes in exposed sections of pipe, tanks or valves), severe weather, lightning, floods, earthquakes and forest fires.

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

Table 21 Frequency of causes of pipeline leaks in 1971 (Office of Pipeline Safety, 1972).

Pollution Movement

Liquid leaked 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 relatively impermeable soil, the leak liquid will tend to remain in the trench. In a sloping trench in impermeable soil, the fluid will tend to move through the backfill in the trench along the outside of the pipe in the direction of the slope. As liquid moves downward through the soil under the influence of gravity, it will coat the soil particles as it advances. This process removes some liquid from the downward moving material. If the quantity of liquid is small enough, it may be immobilized by this process; however, the leaked liquid may not remain immobilized. Subsequent rainfall may wash the pollutant from the soil particles and carry it further downward until it reaches 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 dilute slowly with distance and time. Subsequent rainfall will tend to displace oil or other low density fluids floating on the water table, producing a contaminated mixture in the upper part of the aquifer. Once in the saturated zone, a pollutant will move downgradient.

Figure E shows a plan view of an actual situation involving a large gasoline spill and indicates how the leakage is 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 and the same can happen along a pipeline, as described earlier, until it reaches a permeable region where it can move downward.

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

Control Methods

Most of the research and development on methods for controlling and abating the contamination of ground water 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 ground water, it may be applicable if judiciously applied. Many described methods for handling hazardous materials can also be applied to handling leakage materials such as sewage, brines, and agricultural and industrial chemicals not consid

hazardous.

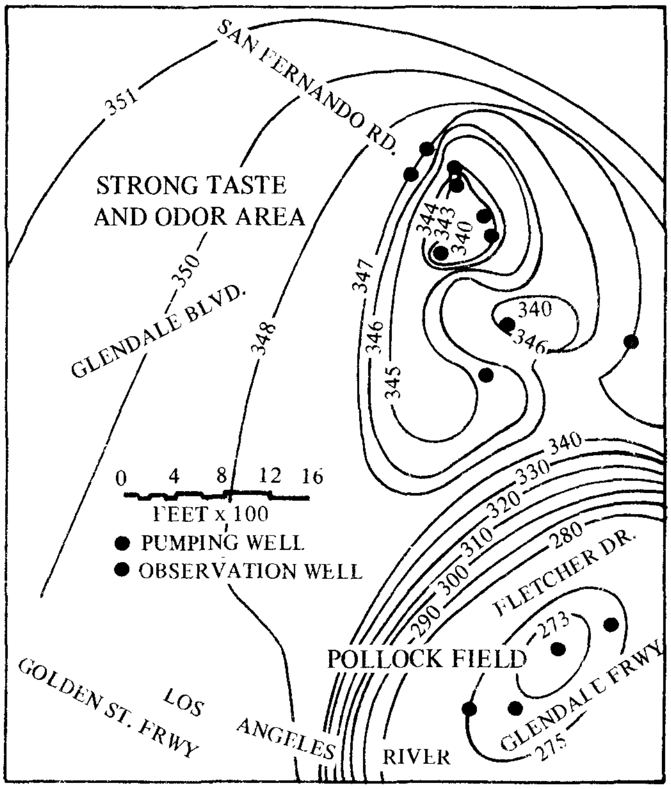


Figure E Area contaminated by subsurface gasoline leakage and ground water contours in the vicinity of Forest Lawn Cemetery, Los Angeles County, as of 1971 (Williams and Wilder, 1971).

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

1) Corrosion-preventing coatings such as tar or plastic used on the outside of tanks and pipelines,

2) Cathodic protection used to minimize corrosion resulting from galvanic action (Dept. of Transportation, 1969, 1970a),

3) Internal fiberglass linings, which do not deteriorate, used 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 shutoff 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 ground water contamination is removal of the contaminated soil. 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.

Figure F indicates that from several hours 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, 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 rapidly.

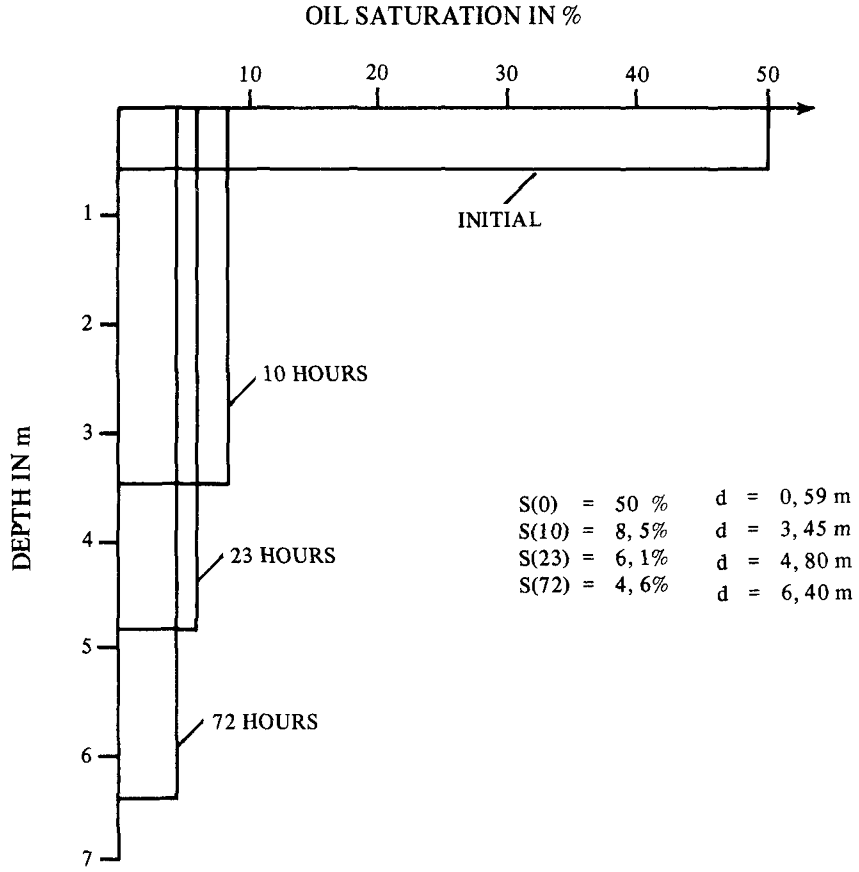


Figure F Experimental results from Switzerland on the distribution of oil in soil as a function of time (Todd, 1973).

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, 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 materials 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 direction of movement 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 oil (Figure G).

If the pollutant has moved so far downgradient that recapture by use of a drawdown cone is infeasible, a ditch placed across a shallow contaminated plume can be used to capture the pollutant. Figures H and I 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 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.

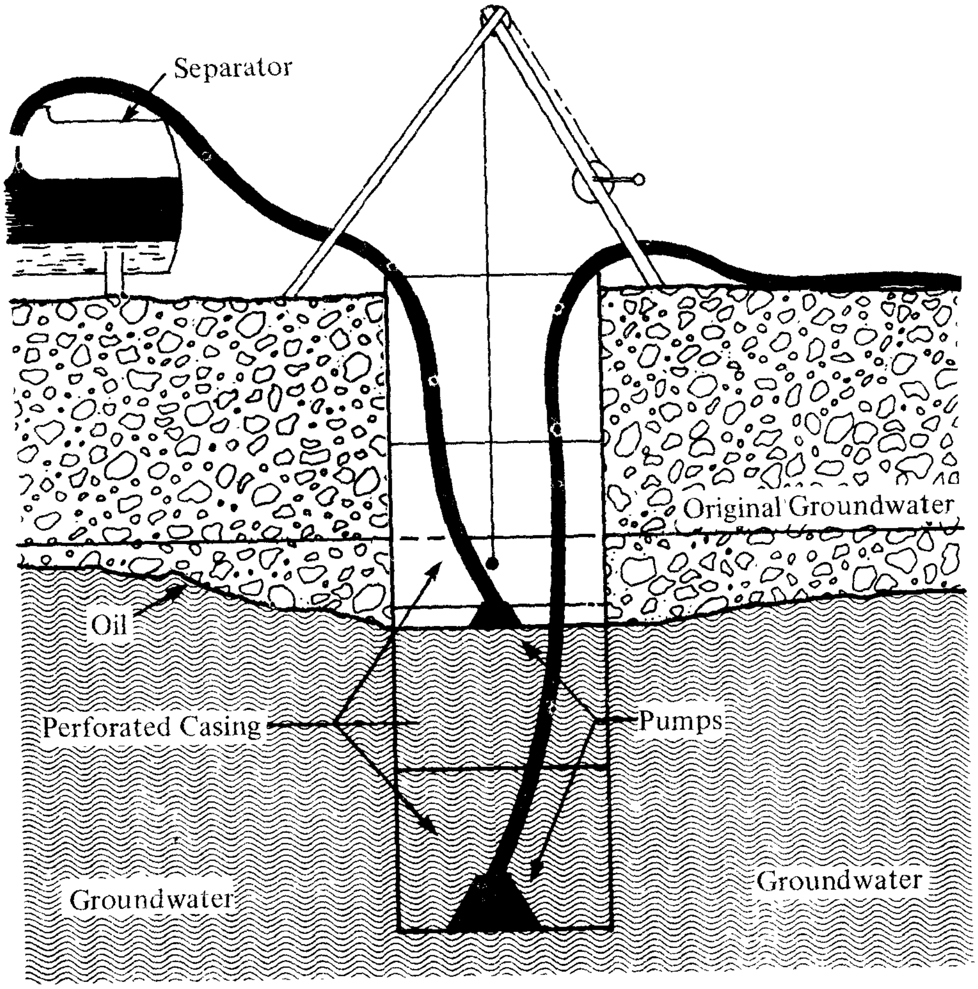
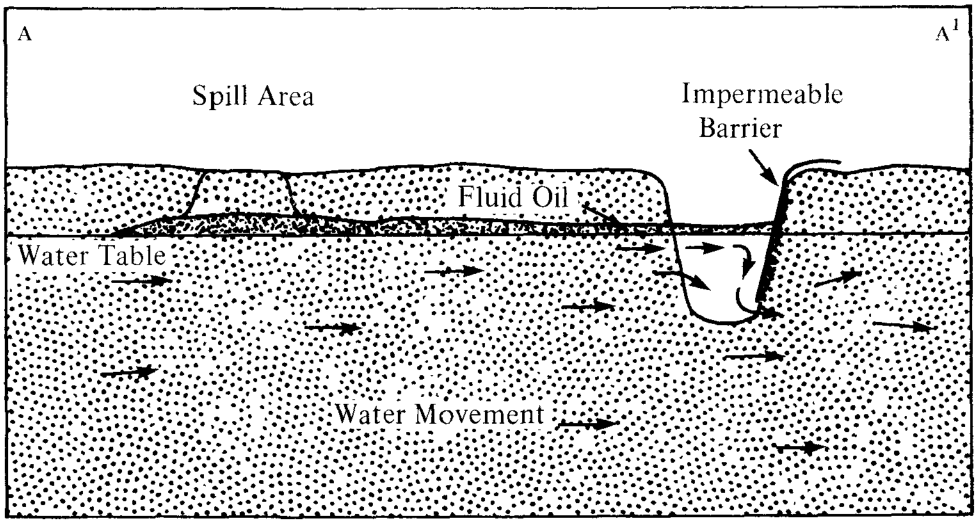
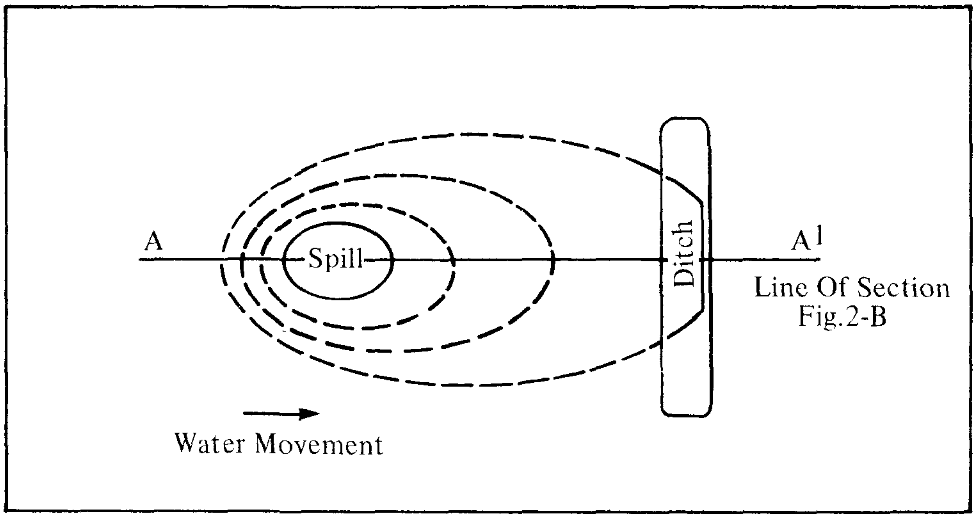


Figure G Swedish two-pump method for removal of oil pollution from a well (Todd, 1973).

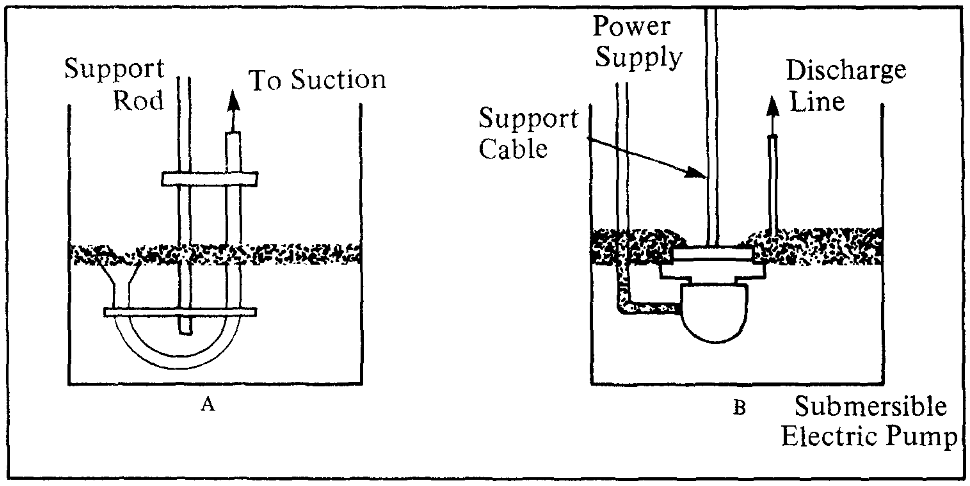


Cross Section

Figure H Oil moving with shallow ground water is intercepted by a ditch constructed across migration path (Comm. on Environmental Affairs, 1972).



Plan View



A Flotation Device May Be Substituted
For The Handling Cable Or Rod.

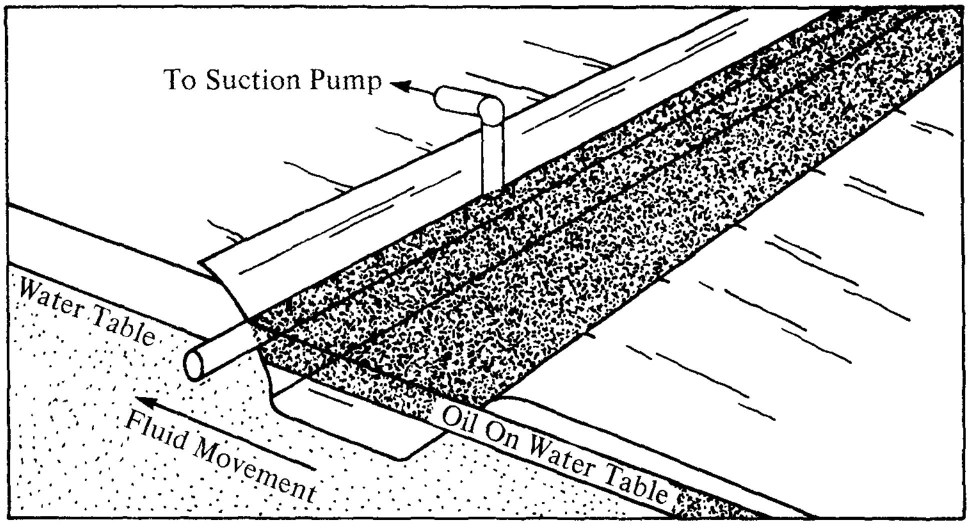


Figure I Three systems for skimming oil from a water surface in ditches or wells (Comm. on Environmental Affairs, 1972).

Abatement by biodegradation. A 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.

Abatement by chemical action. The use of chemicals to cause precipitation of pollutants within the soil is being investigated. 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 proportional to the quantity of chemicals handled.

In small installations such as 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 discovers that his water 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 when, during the rainy season the water table rises above the level of a leak in a tank, 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 leakage in excess of 8000 liters of commodities from initiation of the leak to the time of cessation.

Monitoring procedures 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. Regular checking of pipelines and tanks is accomplished by throughput monitoring, periodic inspection, and periodic pressure testing.

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 tube 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 by aircraft. In all cases the dominant method of detection is visual. In addition to seeking direct evidence of pipeline leaks, inspectors are adept at identifying leaks by their effects 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 leakage, if any, 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. A pipeline near the cemetery was suspected as the source of gasoline leakage, shown in Figure E. 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, 189,000 liters of gasoline had been recovered at this site, and it is estimated that the total spill amounted to 946,000 liters.

Monitoring solid radioactive wastes. The monitoring methods used for tanks containing radioactive 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.

References

1. Atomic Energy Commission, "Category VIII - Services," *The Nuclear Industry*, pp. 251-268 (1969).

2. Bureau of Surface Transportation Safety, *A Systematic Approach to Pipeline Safety*, National Transportation Safety Board, Washington, D. C. (1972).

3. Committee on Environmental Affairs, *The Migration of Petroleum Products in Soil and Ground Water--Principles and Countermeasures*, Publ.no. 4149, Amer. Petroleum Inst., Washington, D. C., 36 pp. (1972).

4. Department of Transportation, "Title 49 - Transportation," *Federal Register*, v. 34, no. 191, Washington, D. C., 4 October (1969).

5. Department of Transportation, "Part 195-- Transportation," *Federal Register*, v. 35, no. 62, Washington, D.C., 31 March (1970).

6. Department of Transportation, "Title 49 -- Transportation," *Federal Register*, v. 35, no. 218, Washington, D.C., 7 November (1970a).

7. Geraghty, J.J., "Movements of Contaminants" *Water Well Jour.*, v. 16, October (1961).

8. Gilmore, D., Personal Communication, March (1973).

9. Hepple, P. (Ed.), *The Joint Problems of the Oil and Water Industries*, Proc. of a Symposium Held at the Motel Metropole, Brighton, 18-20 January 1967, The Institute of Petroleum, London, England (1967).

10. Jones, W.M.C., "Prevention of Water Pollution from Oil Pipelines," *Water Pollution by Oil*, The Institute of Petroleum, London, England (1971).

11. Laska, L., "Water Pollution Control in Alaska," *Water, Air, and Soil Pollution*, D. Reidel Publishing Co., Dordrecht-Holland, pp. 415-432 (1972).

12. Matis, J.R., "Petroleum Contamination of Groundwater in Maryland," *Ground Water*, v. 9, no. 6, pp. 57-61 (1971).

13. McKee, J.E., et al., "Gasoline in Groundwater," *Jour. Water Pollution Control Federation*, v. 44, pp. 293-302 (1972).

14. Office of Hazardous Materials, *Summary of Liquid Pipeline Accidents Reported on DOT Form 7000-1 from January 1, 1968 through December 31, 1968*, Dept. of Transportation, Washington, D. C. (1969).

15. Office of Pipeline Safety, *Summary of Liquid Pipeline Accidents Reported on DOT Form 7000-1 from January 1, 1970 through December 31, 1970*, Dept. of Transportation, Washington, D. C. (1971).

16. Office of Pipeline Safety, *Summary of Liquid Pipeline Accidents Reported on DOT Form 7000-1 from January 1, 1971 through December 31, 1971*, Dept. of Transportation, Washington, D. C. (1972).

17. Office of the Secretary of Transportation, "Title 49 - Transportation", *Federal Register*, v. 35, no. 5, Washington, D. C., 8 January (1970).

18. Office of the Secretary of Transportation, "Title 49 - Transportation," *Federal Register*, v. 36, no. 86, Washington, D. C., 4 April (1971).

19. Office of the Secretary of Transportation, "Title 49 - Transportation," *Federal Register*, v. 37, no. 180, Washington, D. C., 15 September (1972).

20. Todd, D.K., *Groundwater Pollution in Europe -- A Conference Summary*, GE73TMP-1, General Electric Co., Santa Barbara, Calif., 79 pp. (1973).

21. Toms, R.G., "Prevention of Oil Pollution from Minor Users," *Water Pollution by Oil*, The Institute of Petroleum, London, England (1971).

22. Williams, D.E., and Wilder, D.G., "Gasoline Pollution of a Groundwater Reservoir--a Case History," *Ground Water*, v. 9, no. 6, pp. 50-56 (1971).

23. Wood, L.A., "Groundwater Degradation--Causes and Cures," *Groundwater Quality and Treatment*, Proc. of the 14th Water Quality Conference, Univ. of Illinois, College of Engineering, Urbana-Champaign, pp. 19-25 (1972).

APPENDIX

ADMINISTRATOR'S DECISION STATEMENT NO. 5

SUBJECT: EPA POLICY ON SUBSURFACE EMPLACEMENT OF FLUIDS BY WELL INJECTION

This ADS records the EPA's position on injection wells and subsurface emplacement of fluids by well injection, and supersedes the Federal Water Quality Administration's order COM 5040.10 of October 15, 1970.

GOALS

The EPA Policy on Subsurface Emplacement of Fluids by Well Injection is designed to:

1. Protect the subsurface from pollution or other environmental hazards attributable to improper injection or ill-sited injection wells.
2. Ensure that engineering and geological safeguards adequate to protect the integrity of the subsurface environment are adhered to in the preliminary investigation, design, construction, operation, monitoring and abandonment phases of injection well projects.
3. Encourage development of alternative means of disposal which afford greater environmental protection.

PRINCIPAL FINDINGS AND POLICY RATIONALE

The available evidence concerning injection wells and subsurface emplacement of fluids indicates that:

1. The emplacement of fluids by subsurface injection often is considered by government and private agencies as an attractive mechanism for final

disposal or storage owing to: (1) the diminishing capabilities of surface waters to receive effluents without violation of quality standards, and (2) the apparent lower costs of this method of disposal or storage over conventional and advanced waste management techniques. Subsurface storage capacity is a natural resource of considerable value and like any other natural resource its use must be conserved for maximal benefits to all people.

2. Improper injection of municipal or industrial wastes or injection of other fluids for storage or disposal to the subsurface environment could result in serious pollution of water supplies or other environmental hazards.

3. The effects of subsurface injection and the fate of injected materials are uncertain with today's knowledge and could result in serious pollution or environmental damage requiring complex and costly solutions on a long-term basis.

POLICY AND PROGRAM GUIDANCE

To ensure accomplishment of the subsurface protection goals established above it is the policy of the Environmental Protection Agency that:

1. The EPA will oppose emplacement of materials by subsurface injection without strict controls and a clear demonstration that such emplacement will not interfere with present or potential use of the subsurface environment, contaminate ground water resources or otherwise damage the environment.

2. All proposals for subsurface injection should be critically evaluated to determine that:

   (a) All reasonable alternative measures have been explored and found less satisfactory in terms of environmental protection;

   (b) Adequate preinjection tests have been made for predicting the fate of materials injected;

(c) There is conclusive technical evidence to demonstrate that such injection will not interfere with present or potential use of water resources nor result in other environmental hazards;

(d) The subsurface injection system has been designed and constructed to provide maximal environmental protection;

(e) Provisions have been made for monitoring both the injection operation and the resulting effects on the environment;

(f) Contingency plans that will obviate any environmental degradation have been prepared to cope with all well shut-ins or any well failures;

(g) Provision will be made for plugging injection wells when abandoned and for monitoring plugs to ensure their adequacy in providing continuous environmental protection.

3. Where subsurface injection is practiced for waste disposal, it will be recognized as a temporary means of disposal until new technology becomes available enabling more assured environmental protection.

4. Where subsurface injection is practiced for underground storage or for recycling of natural fluids, it will be recognized that such practice will cease or be modified when a hazard to natural resources or the environment appears imminent.

5. The EPA will apply this policy to the extent of its authorities in conducting all program activities, including regulatory activities, research and development, technical assistance to the States, and the administration of the construction grants, State program grants, and basin planning grants programs and control of pollution at Federal facilities in accordance with Executive Order 11507.

Signed 6 Feb. 1973
William D. Ruckelshaus
Administrator

RECOMMENDED DATA REQUIREMENTS FOR ENVIRONMENTAL EVALUATION OF SUBSURFACE EMPLACEMENT OF FLUIDS BY WELL INJECTION

The Administrator's Decision Statement No. 5 on subsurface emplacement of fluids by well injection has been prepared to establish the Agency's position on the use of this disposal and storage technique. To aid in implementation of the policy a recommended data base for environmental evaluation has been developed.

The following parameters describe the information which should be provided by the injector and are designed to provide regulatory agencies sufficient information to evaluate the environmental acceptability of any proposed well injection.

(a) An accurate plat showing location and surface elevation of proposed injection well site, surface features, property boundaries, and surface and mineral ownership at an approved scale.

(b) Maps indicating location of water wells and all other wells, mines or artificial penetrations, including but not limited to oil and gas wells and exploratory or test wells, showing depths, elevations and the deepest formation penetrated within twice the calculated zone of influence of the proposed project. Plugging and abandonment records for all oil and gas tests, and water wells, should accompany the map.

(c) Maps indicating vertical and lateral limits of potable water supplies which would include both short- and long-term variations in surface water supplies and subsurface aquifers containing water with less than 10,000 mg/l total dissolved solids. Available amounts and present and potential uses of these waters, as well as projections of public water supply requirements must be considered.

(d) Descriptions of mineral resources present or believed to be present in area of project and the effect of this project on present or potential mineral resources in the area.

(e) Maps and cross sections at approved scales illustrating detailed geologic structure and a stratigraphic section (including formations, lithology, and physical characteristics) for the local area, and generalized maps and cross sections illustrating the regional geologic setting of the project.

(f) Description of chemical, physical, and biological properties and characteristics of the fluids to be injected.

(g) Potentiometric maps at approved scales and isopleth intervals of the proposed injection horizon and of those aquifers immediately above and below the injection horizon, with copies of all drill-stem test charts, extrapolations, and data used in compiling such maps.

(h) Description of the location and nature of present or potentially useable minerals from the zone of influence.

(i) Volume, rate, and injection pressure of the fluid.

(j) The following geological and physical characteristics cf the injection interval and the overlying and underlying impermeable barriers should be determined and submitted:

(1) Thickness;

(2) areal extent;

(3) lithology;

(4) grain mineralogy;

(5) type and mineralogy of matrix;

(6) clay content;

(7) clay mineralogy;

(8) effective porosity (including an explanation of how determined);

(9) permeability (including an explanation of how determined);

(10) coefficient of aquifer storage;

(11) amount and extent of natural fracturing;

(12) location, extent, and effects of known or suspected faulting indicating whether faults are sealed, or fractured avenues for fluid movement;

(13) extent and effects of natural solution channels;

(14) degree of fluid saturation;

(15) formation fluid chemistry (including local and regional variations);

(16) temperature of formation (including an explanation of how determined);

(17) formation and fluid pressure (including original and modifications resulting from fluid withdrawal or injection);

(18) fracturing gradients;

(19) diffusion and dispersion characteristics of the waste and the formation fluid including effect of gravity segregation;

(20) compatibility of injected waste with the physical, chemical and biological characteristics of the reservoir; and

(21) injectivity profiles.

(k) The following engineering data should be supplied:

(1) Diameter of hole and total depth of well;

(2) type, size, weight, and strength, of all surface, intermediate, and injection casing strings;

(3) specifications and proposed installation of tubing and packers;

(4) proposed cementing procedures and type of cement;

(5) proposed coring program;

(6) proposed formation testing program;

(7) proposed logging program;

(8) proposed artificial fracturing or stimulation program;

(9) proposed injection procedure;

(10) plans of the surface and subsurface construction details of the system including engineering drawings and specifications of the system (including but not limited to pumps, well head construction, and casing depth);

(11) plans for monitoring including a multi-point fluid pressure monitoring system constructed to monitor pressures above as well as within the injection zones; and description of annular fluid;

(12) expected changes in pressure, rate of native fluid displacement by injected fluid, directions of dispersion and zone affected by the project;

(13) contingency plans to cope with all shut-ins or well failures in a manner that will obviate any environmental degradation.

(1) Preparation of a report thoroughly investigating the effects of the proposed subsurface injection well should be a prerequisite for evaluation of a project. Such a statement should include a thorough assessment of: 1) the alternative disposal schemes in terms of maximum environmental protection; 2) projection of fluid pressure response with time both in the injection zones and overlying formations, with particular attention to aquifers which may be used for fresh water supplies in the future; and 3) problems associated with possible chemical interactions between injected wastes, formation fluids, and mineralogical constituents.

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