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MONITORING GROUNDWATER QUALITY: ILLUSTRATIVE EXAMPLES

Edited by

Richard M. Tinlin

General Electric Company—TEMPO
Center for Advanced Studies
Santa Barbara, California 93101

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Project Officer

George B. Morgan
Monitoring Systems Research and Development Division
Environmental Monitoring and Support Laboratory
Las Vegas, Nevada 89114

U.S. ENVIRONMENTAL PROTECTION AGENCY
OFFICE OF RESEARCH AND DEVELOPMENT
ENVIRONMENTAL MONITORING AND SUPPORT LABORATORY
LAS VEGAS, NEVADA 89114

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ABSTRACT

This report is designed to show by example site-specific procedures for monitoring various classes of groundwater pollution sources. The first five case histories of actual or potential groundwater pollution are presented with the monitoring techniques which were employed as well as a retrospective view of these techniques and their efficacy. The case histories cover brine disposal in Arkansas, plating waste contamination in Long Island, New York, landfill leachate pollution in Milford, Connecticut, an oxidation pond near Tucson, Arizona, and multiple-source nitrate pollution in the Fresno-Clovis, California, metropolitan area. The report concludes with hypothetical illustrative examples for developing and selecting monitoring alternatives based on a cost comparison between other alternatives and hydrologic judgment. The examples illustrated cover agricultural return flow, septic tanks, percolation ponds, and landfills.

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Office of Research and Development (Program Area Management)

Mr. Albert C. Trakowski, Jr.
Mr. John D. Koutsandreas

Environmental Monitoring and Support Laboratory, Las Vegas (Program Element Direction)

Mr. George B. Morgan
Mr. Edward A. Schuck
Mr. Leslie G. McMillion
Mr. Donald B. Gilmore

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SECTION I
INTRODUCTION

This report is designed to serve as a companion report to two other documents — Monitoring Groundwater Quality: Monitoring Methodology (Todd et al., 1976) and Monitoring Groundwater Quality: Methods and Costs (Everett et al., 1976). The first report presents the following 15-step methodology for monitoring groundwater quality degradation resulting from man's activities:

Step 1 — Select Area or Basin for Monitoring

Step 2 — Identify Pollution Sources, Causes, and Methods of Waste Disposal

Step 3 — Identify Potential Pollutants

Step 4 — Define Groundwater Usage

Step 5 — Define Hydrogeologic Situation

Step 6 — Study Existing Groundwater Quality

Step 7 — Evaluate Infiltration Potential of Wastes at the Land Surface

Step 8 — Evaluate Mobility of Pollutants from the Land Surface to Water Table

Step 9 — Evaluate Attenuation of Pollutants in the Saturated Zone

Step 10 — Prioritize Sources and Causes

Step 11 — Evaluate Existing Monitoring Programs

Step 12 — Establish Alternative Monitoring Approaches

Step 13 — Select and Implement the Monitoring Program

Step 14 — Review and Interpret Monitoring Results

Step 15 — Summarize and Transmit Monitoring Information

Application of these 15 steps by a Designated Monitoring Agency (DMA), be it at the Statewide or local level, will result in the selection of the area to be monitored and the identification and prioritization of pollution sources and causes for monitoring. The second report summarizes specific techniques for monitoring groundwater quality together with detailed estimates of their costs.

In many instances government and industrial organizations divide monitoring responsibilities among their various departments according to activities such as agriculture, mining, public health, etc. As a consequence, classes of pollution sources, e.g., irrigation return flow, waste-water treatment and disposal, and solid waste disposal, have become institutionalized along similar lines. Individuals with a responsibility for monitoring such class-specific problems are not likely to be interested in the complete 15-step areawide monitoring methodology, but instead will want to know how to deal with a particular pollution source. Sections II and III of this report have been specially prepared to illustrate the application of site-specific monitoring methodology.

Section II presents a critique of five actual groundwater pollution case histories given with the monitoring techniques which were employed as well as a retrospective view of these techniques and their efficacy. The five case histories are as follows: Brine Disposal in Arkansas; Plating Waste Contamination in Long Island, New York; Landfill Leachate Contamination in Milford, Connecticut; Pollution Potential of an Oxidation Pond Near Tucson, Arizona; and Multiple-Source Nitrate Pollution in the Fresno-Clovis, California, Metropolitan Area.

Section III presents illustrative examples of how to apply those steps of the methodology applicable in site-specific situations to the following pollution sources: (Agricultural Return Flow, Septic Tanks, Percolation Ponds, and Solid Waste Landfills.) Steps 1, 10, 14, and 15 are omitted from the discussion because the area will already have been specified and the priority of the sources for monitoring established. In addition, the review, interpretation, and transmission of the monitoring results will be a function of the goals of the DMA which are not specified in this instance. The costs for the monitoring methods selected in each example were obtained from Everett et al. (1976).

SECTION II

GROUNDWATER POLLUTION CASE HISTORIES AND EVALUATION OF MONITORING TECHNIQUES

BRINE DISPOSAL IN ARKANSAS

Background

Disposal of the salt water produced along with the oil from oil wells has long been a pollution problem. Prior to the 1960s the salt water was commonly placed in "evaporation" pits as a disposal method. Pits dug into an impermeable formation or lined would generally function as intended; however, in most cases, considerable saltwater infiltrated downward to pollute the groundwater. In the older oil fields the use of such pits was widespread and, even though many pits have been filled and are no longer visible, plumes of polluted groundwater are still present.

Today oil-field brines are more commonly disposed of through wells. Saltwater disposal wells can be classified in increasing order of safety from pollution as follows: (1) disposal through the annulus between the surface casing and production casing, (2) disposal using a converted abandoned oil well, and (3) disposal in a well specifically designed and drilled for saltwater disposal. The most common causes of pollution associated with saltwater disposal wells are (1) corroded or broken casing allowing the saltwater to escape into a fresh-water aquifer and (2) excessive injection pressure resulting in upward movement of brines outside an improperly cemented casing or through fractures in containing formations.

The groundwater pollution discussed in this subsection was caused by disposal of oil-field brine first through an "evaporation" pit and later through a faulty disposal well (Fryberger, 1972). The scope of the original report includes the following:

- A history of the cause of the pollution
- Determination of the extent of pollution
- Evaluation of chemical changes in the polluting brine
- Cost-benefit evaluation of potential remedial measures.

Description of Area

LOCATION. The polluted area is in Miller County in the southwest corner of Arkansas (Figure 1). The site selected for detailed investigation is 2-1/2 miles* southwest of Garland City on the floodplain of the Red River and about 2-1/2 miles west of the present river channel.

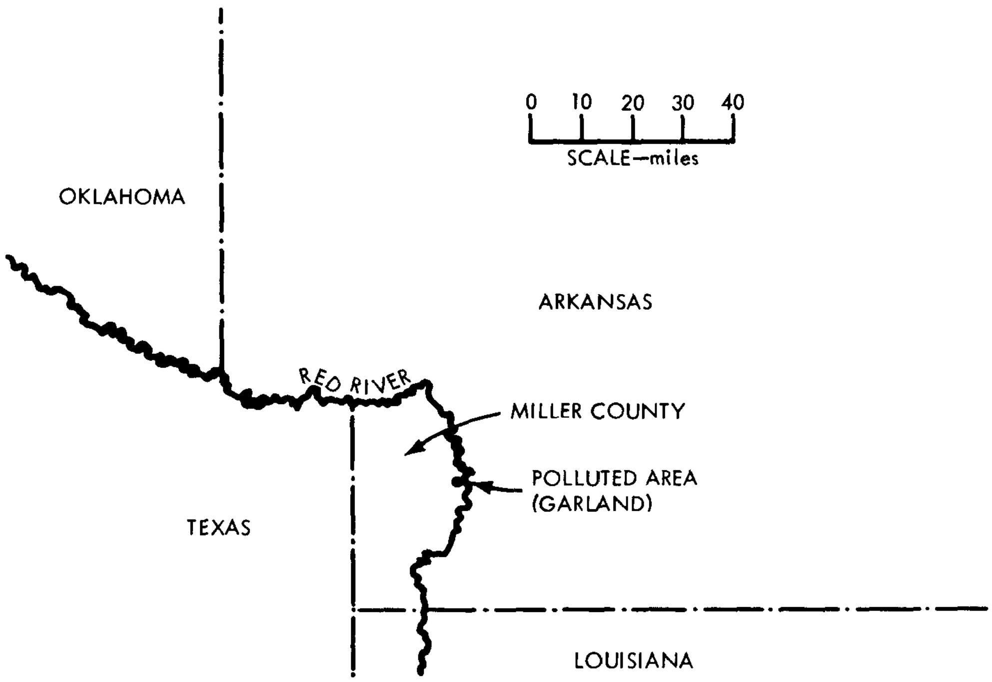


Figure 1. Location of polluted areas.

GEOLOGIC SETTING. The floodplain of the Red River is 9 miles wide in the project area and is characterized by oxbow lakes and poorly drained bayous, typical of a mature, meandering, aggrading river. Clean, highly permeable sand was deposited by the river during much of its early depositional history. In the polluted area the alluvial sand extends to a depth of 40 feet, but elsewhere the alluvium extends up to 90 feet (Ludwig, 1973). Alluvial clays and silts extending from ground surface to a depth of about 12 feet overlie the alluvial sands in the polluted area. The bedrock underlying the alluvium consists of sedimentary formations of Eocene and Cretaceous ages.

The static water level in the alluvium is about 8 feet below ground level in the polluted area. This alluvial aquifer is the most commonly tapped water source in the County for municipal, domestic, and agricultural water uses.

*See Appendix for conversion to metric units.

HISTORY. In 1967 a farmer owning land adjacent to the polluted area complained to State agencies that his 1,000 gallons per minute (gpm) irrigation well had turned salty.

During the summer of 1967 interested State agencies with overlapping jurisdiction (Arkansas Soil and Water Conservation Commission, Arkansas Geological Commission, Pollution Control Commission, and the Oil and Gas Commission) conducted a preliminary investigation to determine the source of the pollution. This investigation consisted of sampling the sand-water mix brought to the surface by a continuous auger-type drill in the area around the nearby "evaporation" pit. These preliminary test hole samples strongly suggested that the "evaporation" pit was the source of the polluting brine.

In addition, under a reconnaissance study being conducted simultaneously by the U. S. Geological Survey, groundwater samples were obtained over a 20-square mile area along the Red River in Miller County. This more general study delineated two other polluted areas where chlorides exceeded 500 milligrams per liter (mg/l). Pollution of all three of the areas is believed caused by improper disposal of oil-field brines through "evaporation" pits, two of which had been abandoned and filled in. The operator of the remaining "evaporation" pit was ordered to fill the pit and dispose of the brine using some other means. An abandoned oil well next to the pit was then used by the operator as a disposal well.

Funded by an EPA grant, the Arkansas Soil and Water Conservation Commission conducted a detailed investigation of the polluted area using numerous test/observation wells. During this investigation it was noted that periods of water-level rises in an observation well 500 feet from the disposal well correlated with periods of saltwater injection into the disposal well. Further investigation revealed that when the disposal well was first put into operation, injection pressures of 300 to 400 pounds per square inch (psi) were required to pump the brine into the disposal formation at a depth of about 2500 feet. However, at the time of observation no injection pressure was required to inject the brine at the same flow rate. Based on these facts and other observations it was determined that most of the brine then being pumped was escaping from the disposal well through a corroded or faulty surface casing and was being injected into the fresh-water alluvial aquifer. A new injection well was then constructed nearby for disposal of the brine. The continued pollution through the original faulty disposal well could have been avoided had the appropriate State agency required monitoring of a fluid-filled annulus outside of the tubing to detect leaks.

The investigation of the Arkansas Soil and Water Conservation Commission was completed with preparation of the report, "Rehabilitation of a Brine-Polluted Aquifer," Fryberger (1972).

Monitoring Methods

OBJECTIVES. Objectives of most investigative projects can be divided into two categories. The first includes general objectives that are common to most investigations of a similar nature; the second includes special objectives not common to all projects of a similar nature.

The general objectives of this investigation were to (1) delineate the lateral and vertical areal extent of pollution and the gradation in concentration away from the source, (2) positively identify the source, and (3) determine the rate and direction of movement of the pollution plume by determining the transmissivity of the aquifer and the slope of the water table.

The special objectives of the investigation were to (1) determine the chemical changes taking place in the aquifer as a result of the polluting brine mixing with the native groundwater and the formation of solids in the aquifer, (2) determine the present and future monetary loss caused by the pollution, and (3) determine the technical and economic feasibility of rehabilitation of the aquifer by removing the saltwater.

Further discussion of the monitoring program is limited to the three general objectives and to the first special objective.

EXPLORATION ALTERNATIVES. The selection of specific monitoring methods from the wide choices available is primarily dependent on the objectives and the geologic conditions in the project area, and is secondarily dependent on relative reliability and costs of the alternate choices.

Three alternate general exploration methods of collecting the data required to meet the objectives of the investigation were considered. These were: (1) drill test holes, install permanent casing, and obtain water samples, (2) conduct a surface resistivity survey (supplemented by drilling and sampling), and (3) rotary drill holes (uncased) and run electric logs on the holes (supplemented by casing and sampling).

The first alternate, drilling test holes, installing permanent casing, and obtaining water samples, was chosen as the general exploration method because it is the only monitoring method of the three that provided the means to achieve all of the objectives. It offered the advantages of:

- Ability to determine both lateral and vertical distribution of brine
- Ability to obtain water samples for chemical analysis to determine chemical changes in the injected brine
- Ability to obtain water levels and formation samples to determine rate of movement of the plume

- Provision for a permanent monitoring system for determining actual plume movement with time.

Although the cost of drilled and cased monitoring holes is higher than the alternate choices, the cost was not considered prohibitive because of the shallow depths and easy drilling provided by the soft geologic formations.

Under different geologic conditions it may have been advantageous to use the alternate methods to augment or replace some of the cased drill holes. For instance, if the polluted aquifer were deeper and presented more costly drilling conditions, then to reduce costs down-the-hole electric logging methods to determine relative water salinity could be used in place of water sampling at some of the sampling points. In addition, under vertically and laterally uniform geologic conditions, surface resistivity could be used to replace some test holes to help delineate the lateral extent of the pollution at less cost than the test holes (Oklahoma Water Resources Board, 1974).

DRILLING ALTERNATIVES. Having selected cased holes and water sampling as the exploration method, alternative methods of setting the casing were considered to best fit the objectives and the requirements of geologic conditions, cost, and reliability of data. The methods considered were use of drive points, continuous-flight auger drilling, mud/water rotary drilling, cable tool drilling, and air rotary drilling. The drilling method selected for this project was a combination of two alternatives, continuous-flight auger drilling and drive points.

Two advantages of continuous-flight auger drilling: (1) there is no drilling fluid to contaminate the native groundwater, and (2) the drilling rigs are relatively mobile. Disadvantages: (1) formation samples are mixed and obtaining an accurate detailed geologic log is not possible, (2) because the unconsolidated, loose formations, such as saturated sands, cave in, the casing cannot be set, and (3) drilling is possible only in relatively soft formations.

Drive points, which are pipes with a short, pointed well screen on the bottom, are driven through the formation to the desired depth. Although practical for only shallow, soft formations, drive points have the advantages of low cost and no need for using foreign matter such as drilling fluid; therefore, water samples can be obtained quickly without fear of contamination. However, because no samples of the formation material are obtained in the process, detailed geologic logs cannot be constructed. Also, determination of aquifer transmissivity and rate of movement of the plume is much less reliable without formation samples.

In sinking the well shafts, a continuous-flight auger was used to drill a hole down through the 10 to 15 feet of clayey soil overlying the sand aquifer. This method was fast and economical for that specific part of the work, but not suited for drilling the entire hole because the loose sand aquifer would not stand open. Drive points with 2-inch pipe were then set into the open hole, drilled through the remaining clay, and mechanically driven to the desired depth in the sand aquifer. The drive points could not be driven through the clay because excessive force would have been required and the clay would have sealed off the drive point well screen.

This approach made it feasible to obtain water samples at intermediate depths as the drive point was being driven to its final depth. The bottom of the soft alluvial sand was detected when the drive point reached the hard underlying bedrock.

Water samples were obtained by pumping with a centrifugal pump attached directly to the top of the drive point pipe. If the water table had been lower than about 20 feet, then other pumping methods such as a submersible or turbine pump would have been required and a larger-diameter casing would have been necessary.

The primary disadvantage of the method selected is the lack of aquifer formation samples obtained. This made it more difficult to determine aquifer transmissivity necessary to calculate the rate of movement of the plume. Pumping tests and sample descriptions from other sources not in the immediate area had to be used for transmissivity estimates.

Critique of Monitoring Project

RESULTS OBTAINED. Twenty-eight sampling sites were located around the pollution source. At many of the sampling sites water samples were obtained at intermediate depths in order to provide data on the vertical distribution of the brine.

Figure 2 shows the distribution of the sampling sites relative to the pollution source, the lateral distribution of chloride concentration at the bottom of the aquifer, and the location of the vertical section through the area that is depicted in Figure 3.

Generally, the monitoring methods selected for this project were successful in achieving the objectives. The vertical and horizontal distribution of the chlorides within the polluting plume were determined with sufficient accuracy. A survey of water level elevations in all the test wells plus adjacent domestic wells provided accurate data to calculate the slope of the water table. Good water samples were obtained from the test wells to meet both the general and special objectives, and additional water samples were obtained from adjacent domestic wells to determine background quality.

RECOMMENDED CHANGES. In retrospect, two changes would be desirable if the project were to be repeated. One change involves a general objective, and the other a special objective.

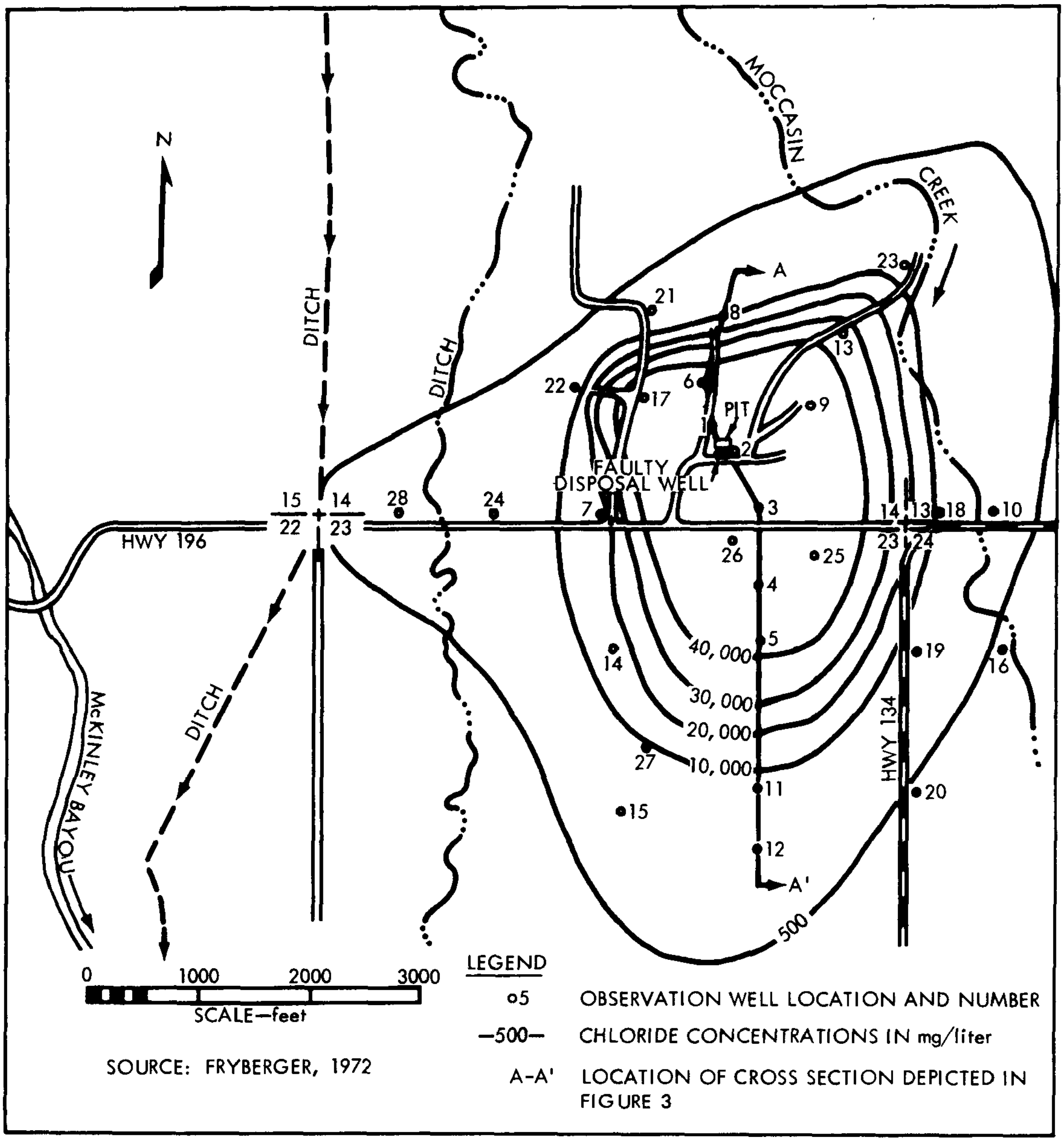


Figure 2. Contours of chloride concentration at bottom of alluvium.

First, a rotary drill using clear water for a drilling lubricant would be used in place of an auger and drive points. Rotary drilling would permit sampling of the aquifer formation in order to better evaluate the aquifer transmissivity for calculating the rate of movement of the polluting plume. This procedural change would entail (1) drilling and sampling the hole, (2) setting casing with a short screen on the bottom to the desired depth, and (3) pumping for a sufficient time to clear all of the drilling fluid out of the formation. The length of pumping time required would be determined by monitoring the pumped water in the field using a portable specific conductivity meter.

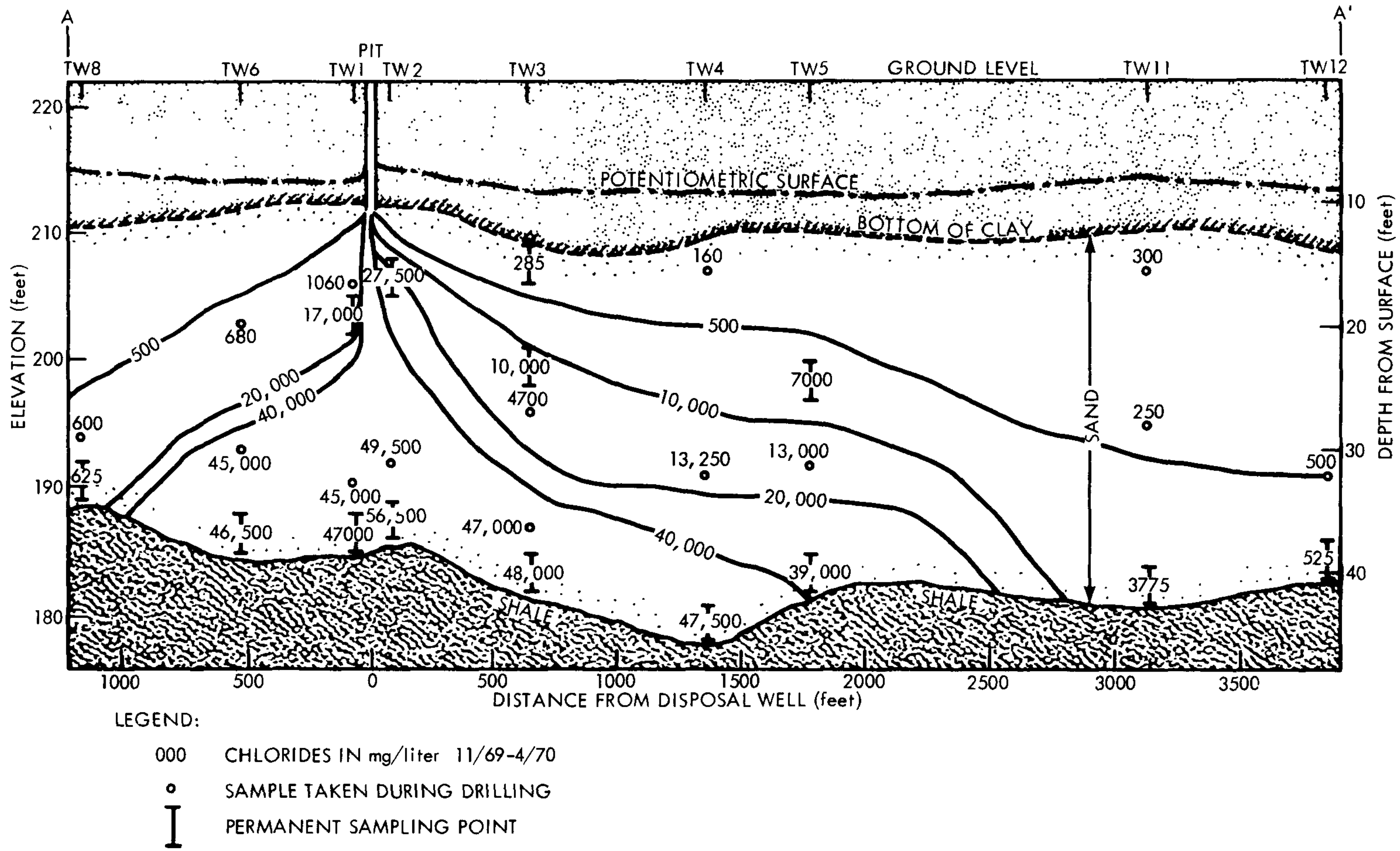


Figure 3. Section A-A' showing brine distribution.

The second change would be to conduct certain key chemical analyses such as for pH, CO_2 (carbon dioxide), and HCO_3 (bicarbonate) either in the field or, if in a laboratory, shortly after samples were obtained to provide better quality data for the objective of determining chemical changes in brine as it mixed with the native water and aquifer solids.

PLATING WASTE CONTAMINATION IN LONG ISLAND, NEW YORK

Background

In 1942, the Nassau County Department of Health, Long Island, N.Y., undertook a routine survey of the water-supply system in a former aircraft plant at South Farmingdale. The survey revealed that water from a well near a basin used to dispose of wastes from metal-plating operations at the plant contained about 0.1 mg/l of chromium.

The plating-waste contaminants were derived from chemical solutions used chiefly in anodizing and other metal plating processes, starting in about 1941. Until several years after World War II, large quantities of virtually untreated plating-waste effluents were recharged into the groundwater through disposal basins. Only scanty records were kept of the quantities, but it is estimated that during the early 1940s, as much as 200,000 to 300,000 gallons of effluent, containing about 52 pounds of chromium and smaller amounts of other metals, was recharged daily into the upper glacial aquifer. After the war, the quantities of effluent were reduced substantially and the character of the waste changed to some extent.

It was not determined initially whether the chromium was in the nontoxic trivalent ion or the toxic hexavalent ion, but the plant management was advised by the Health Department to prohibit the use of water from the contaminated well for drinking purposes and to initiate treatment for removal of chromium from the plating wastes.

Nothing further was done until 1945, when the Department of Water Supply, Gas, and Electricity of the City of New York installed a series of shallow test wells in an area several hundred feet south of the aircraft plant. This work was undertaken because the City was concerned over potential contamination of its auxiliary groundwater system at Massapequa, several miles to the south. The chromium content of the water from the test wells, which penetrated the water table for only a short distance, ranged from zero to a trace, and consequently City officials decided that no real threat to the water system existed.

In 1946, after the U.S. Public Health Service established a limit of 0.05 mg/l for hexavalent chromium in drinking water, the New York State Department of Health requested that the new owners of the metal-plating facilities present plans for the removal of chromium from the plating wastes before disposal into the groundwater reservoir. In 1948, the New York State Department of Health analyzed another set of samples from the test wells drilled in 1945 and also took samples from a shallow domestic well about 1500 feet south of the disposal basins. The results showed about 1 to 3.5 mg/l of hexavalent chromium, 0 to 0.24 mg/l of cadmium, and 0.06 to 0.16 mg/l of copper and aluminum. In conformance with recommendations of the County and State Health Departments, a waste-treatment unit for chromium was placed in operation in 1949, but discharge of the effluent containing cadmium and other metals continued at the disposal basins.

HYDROGEOLOGIC SETTING. The groundwater reservoir in the South Farmingdale area consists of about 1300 feet of saturated consolidated deposits resting on crystalline bedrock. In general, this sedimentary sequence is divided into three principal aquifers or water-bearing units. The upper glacial aquifer extends from the water table, at depths of less than 15 feet below land surface, to the top of the second aquifer, referred to as the Magothy aquifer. The upper glacial aquifer consists mainly of beds and lenses of fine-to-coarse sand and gravel. The Magothy aquifer, whose upper surface ranges from about 80 to 140 feet below land surface, consists chiefly of beds and lenses of fine sand, sandy and silty clay, and clay. The third aquifer, the Lloyd sand member of the Raritan formation, lies more than 1,000 feet below land surface. Only the upper glacial aquifer was affected by the contamination.

The general direction of groundwater movement in the upper glacial aquifer is toward the south, and the shallow groundwater in the area of the study eventually discharges into Massapequa Creek. Water enters the upper glacial aquifer by direct infiltration of precipitation and by lateral subsurface inflow.

DIMENSIONS OF PLUME. Figures 4 and 5 show a plan view and vertical sections of the plume of hexavalent chromium and cadmium contamination, as defined by the test drilling and sampling. The plume was as much as 4,300 feet long and 1,000 feet wide in 1962. In the vertical dimension, it extended from the water table to depths of as much as 50 to 70 feet below land surface. Maximum concentrations of hexavalent chromium, which were as much as 40 mg/l in 1949, had decreased to about 10 mg/l in 1962. Concentrations of cadmium were as high as 3 mg/l in 1962, and as high as 10 mg/l in 1964 at a spot not previously tested.

Mapping of Plume

Aware of the potential danger to public water supplies, the Nassau County Departments of Health and Public Works began a systematic investigation of the plume in 1949 with the drilling of about 40 test wells along several streets

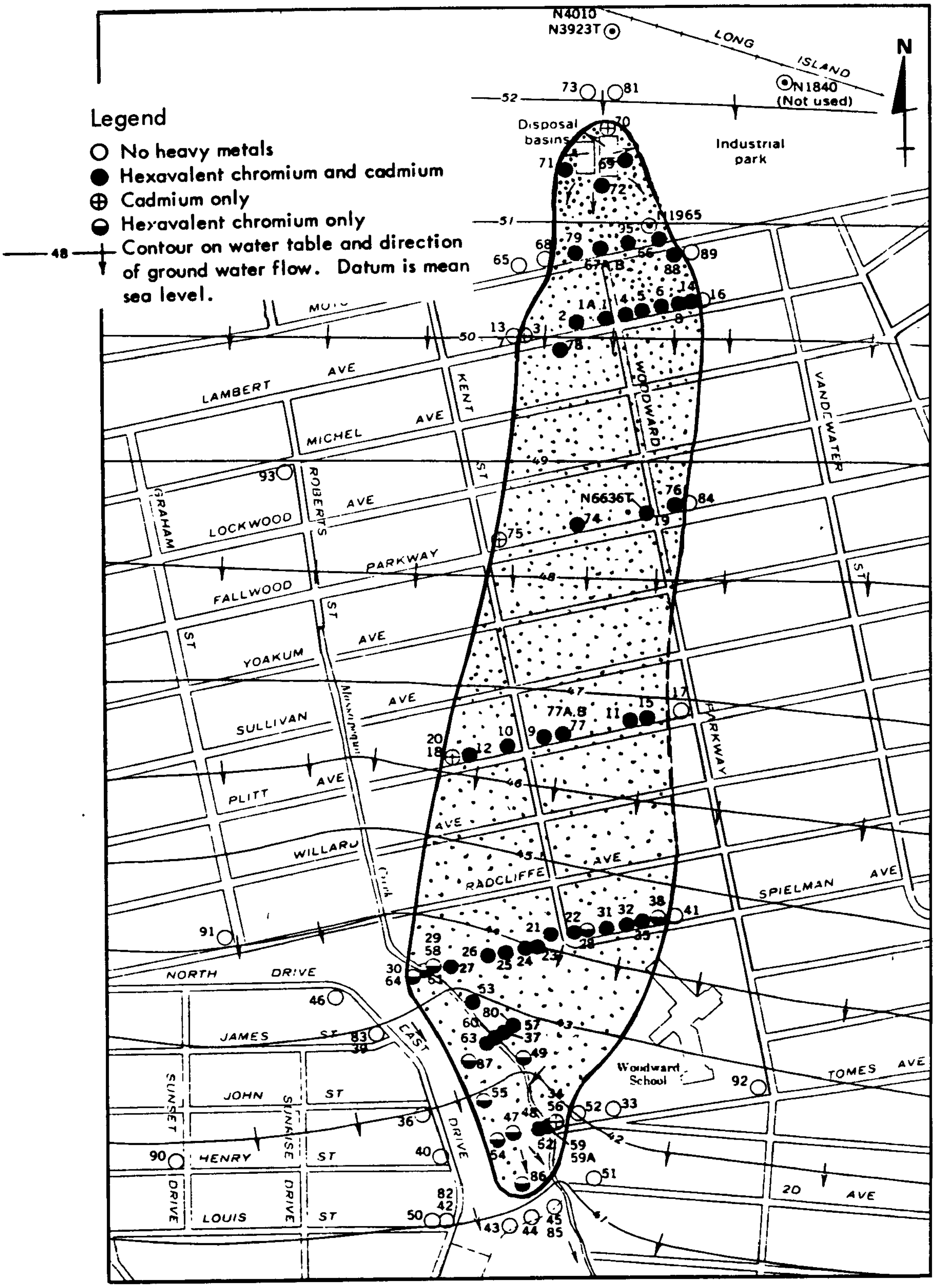


Figure 4. Map showing plating-waste plume, water-table contours, and selected test wells (modified after Perlmutter and Lieber, 1970).

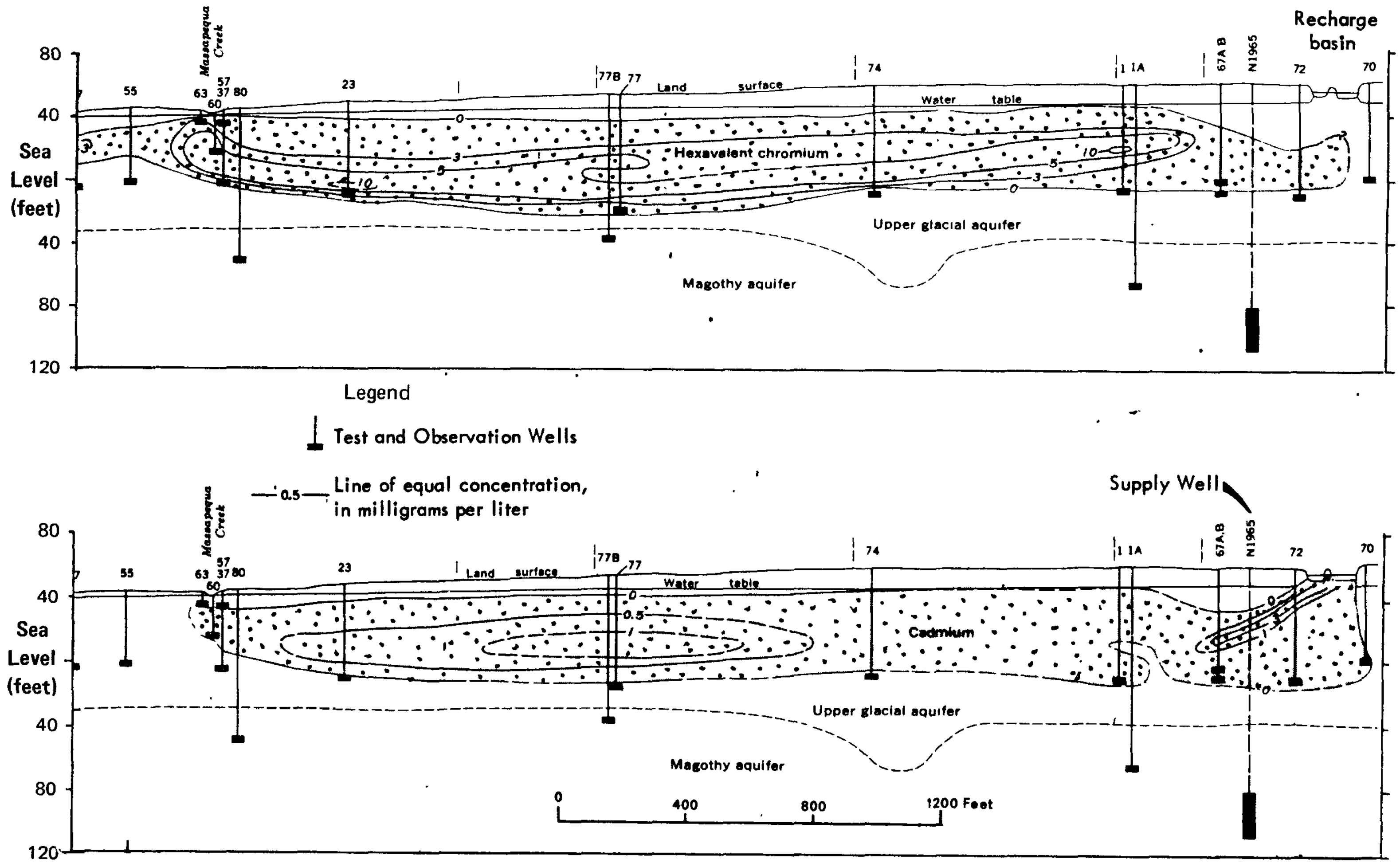


Figure 5. Vertical profiles of hexavalent chromium and cadmium along the center line of the plating-waste plume (modified after Perlmutter and Lieber, 1970).

south of the disposal basins (Figure 4). These wells were 1-1/4-inch driven points which were sampled by hand pumping at 5-foot intervals. Drilling was continued to depths (generally 50 to 60 feet) at which field testing showed no evidence of chromium contamination. Maps and profiles of the plume were prepared for the first time from the results of this drilling (Suter et al., 1949).

In 1953, 1958, and 1962, additional test wells were installed to map changes in the boundaries of the plume and changes in concentrations of the cadmium and chromium. In the 1962 investigation, which was the most detailed of the series, about 100 sampling wells were installed and several test holes were drilled in which cores were taken to define the lithology and hydraulic coefficients of the geologic units in more detail. Extensive sampling of Massapequa Creek and underlying beds also was undertaken to determine the concentration and load of heavy metals at various points in and beneath the stream. Spectrographic analyses of several water samples were made to determine the presence of metals other than cadmium and chromium. Detailed maps and cross sections of the plume again were prepared, a water budget calculation was made, and the pattern of movement of contaminated water from the shallow aquifer into the stream was delineated (Perlmutter and Geraghty, 1963; Perlmutter et al., 1963).

Steps That Could Have Been Taken

The basic objectives of the investigation were somewhat limited, and were focused mainly on defining threats to drinking-water supplies, especially to the groundwater facility operated by the City of New York and to private wells in the area. Although a relatively large expenditure was made on the study, several approaches were not tried that might have yielded better information and might have led to a better understanding of the occurrence and behavior of the plume. These other approaches are surface resistivity surveys, more comprehensive chemical analyses, pumping tests, and contaminant transport modeling.

SURFACE RESISTIVITY SURVEY. Surface resistivity surveys might have proven of value by detecting changes in subsurface conductivity caused by differences in the conductivities of the native and contaminating fluids. Such surveys are simple to conduct, do not require extensive test drilling, and offer a quick way of mapping the broad dimensions of a plume. Although they do not provide quantitative information on the mineral composition of the plume, they may be useful in selecting areas within which drilling should be undertaken. The success of such surveys depends on the degree of contrast in conductivities and on the depths of the fluids to be detected.

COMPREHENSIVE CHEMICAL ANALYSES. Some of the samples taken during the investigation should have been analyzed for more chemical constituents, especially other heavy metals and trace elements. Spectrographic analyses could have been made at the start of the investigation to at least define the presence of rare or exotic constituents.

HYDRAULIC PROPERTIES OF THE AQUIFER. No pumping tests were conducted to define the water-bearing properties of the upper glacial aquifer, and most of the information developed in the study was obtained empirically through test drilling and sampling. It is likely that a better knowledge of the hydraulic behavior of the groundwater system at the site could have expedited the evaluation of the problem and saved some of the costs of drilling. Predictions of flow velocities, for example, might have been made at an early stage in order to estimate the probable length of the plume.

CONTAMINANT TRANSPORT MODEL. Another useful step would have been to develop a mathematical model to predict rates of movement of contaminated water and changes in concentration, distribution, and dispersion of the contaminants. This would require information on such factors as porosity, hydrodynamic dispersion coefficient, hydraulic conductivity of the aquifer materials, and the thickness and hydraulic conductivity of the stream bed material in Massapequa Creek, which was the discharge point at the southern end of the plume. Such a model recently has been made by Pinder (1973), who predicted that contamination of Massapequa Creek would effectively cease in about 7 years after cessation of disposal or institution of complete treatment.

What Should Have Been Done

IMPROVED TREATMENT. As with many such projects, after the extent and composition of the plume had been reasonably well defined between 1949 and 1962, the public agencies decreased the detailed monitoring effort. In order to abate the contamination, a recommendation was made to the plant owners to improve the effectiveness of the methods of treating the hexavalent chromium, but little was done to eliminate other metals in the waste. A more complete treatment method should have been used to remove all of the toxic constituents.

SAMPLING OF WELLS AND STREAMS. Although a reasonably good picture of the extent and movement of the plume was developed during the detailed field investigation, little has been done since to determine if the hydrologic situation has altered significantly. No new information has been obtained, for example, on the attenuation of the plume or whether the contamination has started to move downward into the underlying Magothy aquifer, which is the principal source of potable water in Nassau County. It is conceivable, with the growing stress being placed on the Magothy aquifer by public water supply systems, that a downward hydraulic gradient could develop eventually, with possible long-term implications to the quality of drinking water. It probably would be desirable to conduct follow-up studies involving periodic sampling of strategically located shallow wells and of parts of Massapequa Creek, and determinations of changes of heads and directions of flow in both the shallow and deep aquifers.

RECOVERY OF CONTAMINANTS. Another step that should have been given greater consideration is the feasibility of pumping out the contaminated groundwater for transport to a water-treatment plant or other disposal facility. The transmissivity of the upper glacial aquifer is reasonably high, so that even a single shallow pumping well could withdraw a fairly large quantity of the contaminated groundwater. This could have been tried at least experimentally to show how effective such a procedure would be.

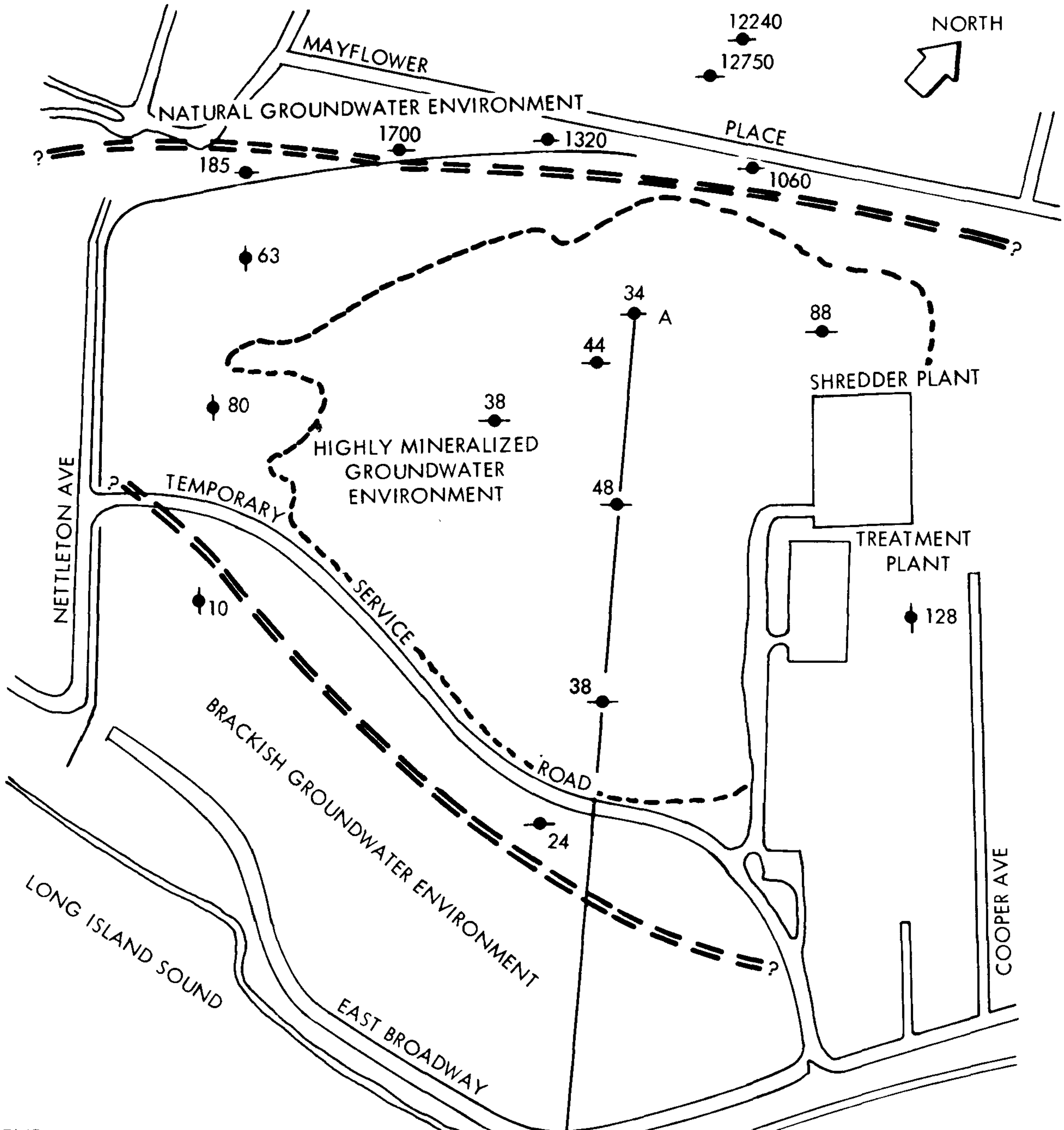
LANDFILL LEACHATE CONTAMINATION IN MILFORD, CONNECTICUT

Background

In 1973, the State of Connecticut authorized an investigation of a sanitary landfill site in Milford, Connecticut, that was under consideration as the location for a new State park. The main objectives of the study were to determine if contamination of the ground and surface waters would prevent the use of the area for this purpose and whether or not the contamination problem was severe enough to warrant shutting down the landfill. Drilling and sampling were carried out to define the chemical quality and pattern of movement of the ground and surface water beneath and adjacent to the landfill, and an evaluation was made of gases being generated by the landfill materials (Geraghty and Miller, 1973).

The landfill area, part of which is an old fly-ash disposal site formerly operated by the Devon Power Plant, covers approximately 90 acres. The refuse is derived from nearby communities and consists largely of ordinary household wastes, construction rubble, brush and vegetative materials, and various types of solid and liquid wastes from local industries. A volume-reduction plant was constructed at the site to shred a portion of the refuse prior to its deposition in the landfill.

HYDROGEOLOGIC SETTING. The landfill is located on an old tidal marsh about one-half square mile in area bordering on Long Island (Figure 6). Part of the original marsh is still visible around the landfill materials. The entire project site was at one time underlain by swamp deposits ranging from several feet to a few tens of feet in thickness. Directly beneath the landfill, the marsh deposits have been somewhat compressed and mixed with fill materials so that they do not show up as a distinct unit in drilling logs. The marsh is now mostly isolated from tidal effects except for a small channel in the eastern section. The channel discharges freshwater during low tide and contains some salty water part way upstream during high



LEGEND:

80 RESISTIVITY STATION WITH APPARENT RESISTIVITY VALUE IN μmho/cm AT A SINGLE SELECTED DEPTH

APPROXIMATE LIMIT OF ENVIRONMENT

LIMIT OF EXISTING LANDFILL

SOURCE: Geraghty and Miller, 1973

Figure 6. Three major groundwater environments as delineated by interpretation of resistivity data 15 to 20 feet below land surface, Milford, Connecticut.

tide. About half of the original marsh area is covered by the artificial fill.

The marsh deposits are underlain by unconsolidated materials about 40 to 60 feet thick (Figure 7). These materials are essentially glacial till and some outwash sediments, consisting chiefly of layers of fine to medium sand, silt, and clay. The individual beds do not appear to be very extensive laterally.

The glacial materials are underlain by consolidated bedrock consisting primarily of schist and some gneiss. A bedrock valley extends from west to east across the northern portion of the landfill site. The bedrock slopes generally to the southeast and an outcrop is present northwest of the landfill. The water table ranges in altitude from sea level to about 8 feet above sea level (Figure 7). The altitude has been raised above its normal level due to the construction of the landfill mounds.

DIMENSIONS OF PLUME. Because the landfill is in a hydrologic system of limited areal extent, the contaminated fluid has not moved a great distance away from the site. In general, a mound of highly contaminated water is within the landfill materials. The contaminated water moves out radially from the center of the mound and most of it eventually discharges into Long Island Sound, only a few hundred feet to the south. Leachate moving to the west and southwest from the landfill discharges almost immediately into the

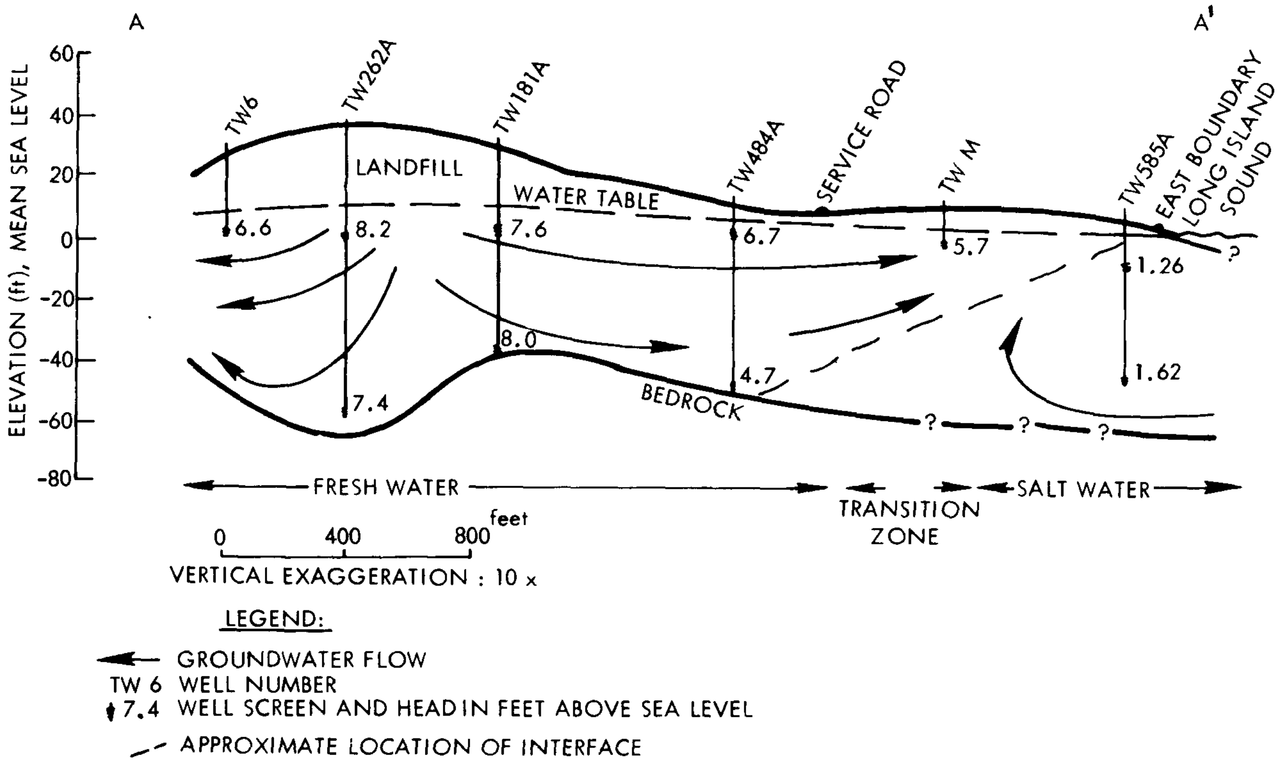


Figure 7. Schematic hydraulic profile along section A-A' of Figure 6, Milford, Connecticut.

surface waters in the marsh and the small streams that drain the area. In some parts of the marsh, the water table is above land surface and has formed ponds containing leachate.

The investigation showed that some of the groundwater has moved vertically downward to invade deeper zones of the unconsolidated material directly below the landfill. The quality of the water at these depths is much better than that of the water in the landfill materials, suggesting that the underlying fine-grained sediments have been at least partly effective in attenuating the contamination. Several hundred million gallons of groundwater has been slightly to heavily contaminated by leachate at the site. A water-budget calculation indicates that about 80,000 gallons per day of water derived from precipitation is recharged into the landfill materials, and that an equivalent amount of contaminated fluid discharges through the bottom and sides of the landfill.

MAPPING OF PLUME. Initially, background information was reviewed on topography, vegetation, records of wells and borings, rainfall, tides, and surface drainage. Following this, seismic and electrical-resistivity geophysical methods were utilized to give a preliminary idea of the character and thickness of the materials at the site. In the next step, 36 test observation wells were drilled in and around the landfill. At some of the well sites, two wells (one deep and one shallow) were installed to define vertical head relationships. The wells ranged in depth from 12 to 96 feet.

Periodic measurements of water levels, referenced to sea level, were made in all wells. Water samples were collected from the wells for chemical analysis, and where the water levels were below suction lift, the samples were collected by first blowing water out of the well casings with compressed air and then bailing out the water sample. A field laboratory was set up to make determinations of some chemical constituents, and samples were sent to a certified laboratory for more detailed analyses.

Water temperature profiles were made in the deeper wells by means of an electronic thermometer. Specific-conductance and dissolved oxygen determinations were made on water samples from principal surface water bodies. Complete chemical and bacteriological analyses were run for some of these samples.

A series of shallow gas sampling tubes was installed in the landfill at depths ranging from 3 to 5 feet. Analyses were made to determine the percentage of methane in the gas mixture and its explosive levels.

The vegetation was studied by biologists from a local research institute to define stresses on the vegetation and the relationships with the groundwater system. Color, stereo, and multispectral photographs were taken of the landfill and the surrounding area and were used to construct base maps, establish topographic contours, and define vegetative patterns. The abnormally high water table, contaminated groundwater, and insect infestation accounted for most of the stress on the vegetation.

What Could Have Been Done

The information collected during the investigation provided adequate answers to the questions asked by the State, and led to the shutting down of the landfill. Funds were not allocated in the first stage for a more intensive monitoring effort, simply because it was not needed. However, a number of other monitoring steps could have been taken for general research purposes, or to provide data that might have proved useful if an early decision could have been made on covering the landfill.

GAS GENERATION. The investigation provided some information on the generation of gases within the landfill. However, no detailed observations were made to define which types and concentrations of gases were being generated, where they were concentrated, and the pressure distribution. More studies could have been conducted along these lines, since ultimately there would have to be some requirement for venting gases in order to permit multipurpose use of the landfill area.

ADDITIONAL CHEMICAL DETERMINATIONS. Although numerous common chemical constituents and a few heavy metals such as iron, lead, copper, and manganese were determined in the water samples, little attention was given to the possible presence of other toxic heavy metals and trace elements. At some additional expense, these could have been determined through spectrographic analysis which might have helped detect other toxic constituents possibly responsible for some of the ecological damage.

BACTERIOLOGICAL STUDIES. Coliform bacteria found in nearby surface-water bodies were believed to be largely, if not entirely, from contaminated materials in the landfill. However, because of the great difficulty in sterilizing pumps and wells and in disinfecting the environment around the wells, it was not considered feasible to collect samples of groundwater for bacteriological analysis. With sufficient funds, time, and suitably constructed wells, it would have been possible to study this aspect of the problem.

ADDITIONAL TEST WELLS. Samples taken from the limited number of wells drilled directly within the landfill materials showed a wide divergence in chemical composition, owing partly to differences in the types of materials placed at different locations within the landfill and partly to dilution of the contaminated water. It would have been useful, therefore, to have installed a denser grid of sampling wells in order to define particular "hot" spots of highly contaminated water. The results of such sampling might have helped locate the sources of particularly objectionable contaminants.

However, problems in constructing wells in the landfill materials and the fact that the landfill was still in operation during the test program made it impractical to fully explore the entire landfill area.

INFILTRATION RATES. Another useful procedure would have been to prepare a more accurate and detailed water budget for the landfill area to determine the rate of leachate production. Field measurements of infiltration, runoff, and evaporation would have been useful in this regard. However, the estimates made were considered to be reasonably useful for the purpose of the investigation, since the landfill was still active at the time and the rates of leachate production were probably variable.

What Should Have Been Done

Because of the intention to convert the landfill area into a State park, more intensive monitoring of stresses on the vegetation during the field study and following the investigation should have been planned. However, this additional work was not authorized. Consequently, although the landfill is covered over and converted into a recreational area, monitoring has ceased, although the original test wells still are in place. Additional monitoring of vegetative stress and of leachate discharge would prove of considerable value in showing the effectiveness of the landfill cover and of the slow changes anticipated as the production of leachate slowly diminishes.

POLLUTION POTENTIAL OF AN OXIDATION POND NEAR TUCSON, ARIZONA*

Site Description

The Ina Road oxidation pond site is located about 10 miles northwest of Tucson, Arizona, in SE1/4, Section 1, T13S, R12E (see Figure 8). The site abuts the Santa Cruz River, the principal drainage channel of the Tucson Basin, and is immediately downstream of the confluences of Canada del Oro and Rillito Rivers. Discharge in these channels is primarily ephemeral. However, the Santa Cruz River drains the entire effluent discharge from the City of Tucson Treatment Plant about 6 miles upstream, as well as overflow from the Ina Road ponds.

The Ina Road ponds, serving as principal treatment facilities for sewage in northwest Tucson, are managed by The Metropolitan Utilities Management Authority. These ponds will be replaced in the near future by a regional treatment plant of standard design. A sanitary landfill is located along the Santa Cruz River immediately to the southwest of the ponds.

*The work reported in this subsection was supported in part by a grant from The Office of Water Research and Technology, U. S. Department of the Interior, Washington, D. C.

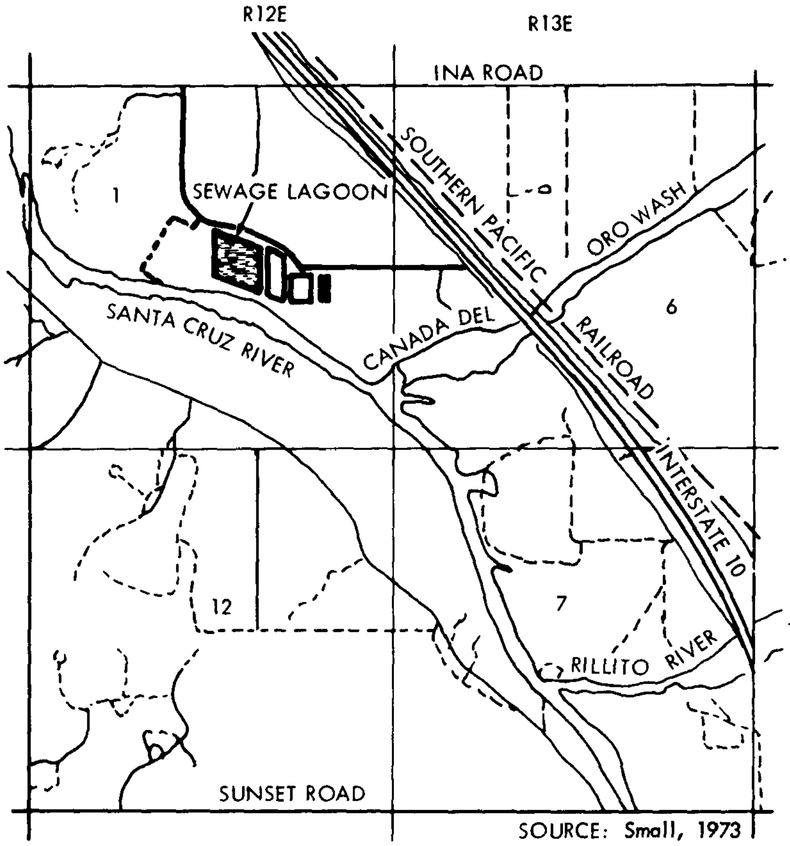


Figure 8. Location of pond near Tucson, Arizona.

Sediments underlying the pond site are typical of the Basin and Range physiographic province. Specific geologic units and their water-bearing properties are discussed by Davidson (1973). The source materials for these sediments are volcanic rocks from the Tucson Mountains, immediately to the west, and the granitic rocks of the Santa Catalina and Tanque Verde Mountains to the east. Principal aquifers in the region comprise surficial material, Fort Lowell formation and the Tinaja Beds. For the Ina Road site, Randall (1974) estimated the transmissivities of the aquifers comprising the surficial deposits to be between 150,000 - 300,000 gallons per day per foot (gpd/ft). The corresponding transmissivity of the combined Fort Lowell and Tinaja Beds aquifer was estimated to be 35,000 gpd/ft. Depth to the water table at the time of the tests was about 70 feet.

Groundwater flow in the vicinity of the pond is predominantly in a northwesterly direction, corresponding to underflow in the Santa Cruz River, but is moderated by southwesterly flow in the Canada del Oro system. Similarly, groundwater quality reflects two distinct sources: underflow and recharge in the Canada del Oro and Rillito systems; and underflow and recharge in the Santa Cruz River, including the contribution of sewage effluent (Schmidt, 1972a).

An additional complicating factor is that shallow perching layers within the vadose zone may conduct water laterally at substantial rates (Wilson and DeCook, 1968). If such layers are hydraulically connected to the Santa Cruz River, sewage effluent may move laterally from the river into the pond area, eventually leaking into the water table. Leaching of the landfill deposits by river seepage is also a distinct possibility and is the subject of a recent study (Wilson, 1974).

Map of Nitrate Levels

Nitrate was the principal ion considered in the pond study. In general, groundwater quality in the region downstream of the City of Tucson Treatment Plant is noted for localized high concentrations of nitrate (Matlock et al, 1972; Schmidt, 1972a). Such nitrate may have originated from sewage effluent recharging in the Santa Cruz River, recharging of effluent applied during irrigation of cropland, leaching of nitrogenous fertilizers, leaching of indigenous nitrogen, or leaching of landfill deposits.

One of the major purposes of the study by Wilson et al. (1973) at the pond site was to monitor the movement of nitrate during deep seepage, particularly during the period immediately after the pond was placed into operation. Wilson et al. found no positive evidence that lagoon seepage had resulted in nitrate contamination of groundwater in the area.

The areal distribution of nitrate in wells within the area encompassing the pond in October 1971, three months after the pond was initiated, is shown in Figure 9. Data were obtained by the Department of Soils, Water and Engineering, University of Arizona. The two wells sampled in the southeast quarter, upstream of the pond, contained nitrate levels of 72 mg/l and 48 mg/l. Wells in the northwest quarter, downstream of the pond, generally contained nitrate concentrations of about 30 mg/l except for the furthermost northwest well, with a level of 45 mg/l.

An irrigation well 300 feet downstream of the pond (see Figure 10) contained 28 mg/l nitrate in October 1971. The vertical distribution of nitrate in the profile beneath the pond after several months of pond operation is reported by Wilson et al. (1973). Subsequent nitrate values on 19 April 1973, within the same profile reported by Wilson and Small (1973) were: 60-foot PVC well 27.28 mg/l, No. 1 access well 7.48 mg/l, and irrigation well 18.04 mg/l. In 1974 the PVC wells were dry and could not be sampled. Nitrate levels in the No. 1 and No. 2 access wells were reported by Wilson (1974) to be 1.2 mg/l and 1.5 mg/l respectively. Pump water from the irrigation well contained 11.7 mg/l nitrate.

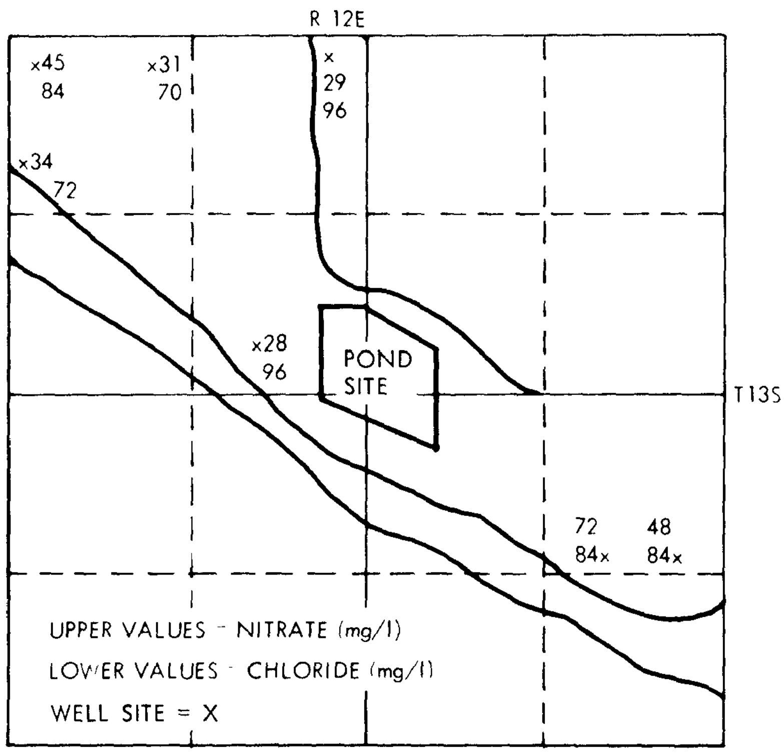


Figure 9. Nitrate and chloride distribution in wells near the pond site, October 1971.

Rationale of Project

The monitoring program at the pond site was based on experience from prior studies. One of these studies was conducted at the site before construction of the pond. Other studies were conducted at the University of Arizona Water Resources Research Center (WRRC) field laboratory about 6 miles south of the pond. The latter studies involved investigations of artificial and natural recharge, with particular references to mechanisms of water movement in the vadose zone and water quality changes during such movement. Results of some of these studies were reported by Wilson and DeCook (1968) and Wilson (1971). Monitoring facilities included observation wells, pumping wells, shallow piezometer-water sampling wells, and access wells. By means of neutron logs in the latter wells, the growth and dissipation of two perched water tables in the sediments overlying the principal aquifer were clearly observed. The existence of such perched tables in surficial deposits of the Tucson Basin has been known for many years. The advantage of neutron logging is that the location and behavior of the tables can be followed. Furthermore, knowing the location of regions in which tables develop, it is possible to terminate sampling wells in sediments which saturate during recharge. Based in part on such reasoning, two batteries of sampling wells were installed at the WRRC recharge site. Four wells in each battery terminated within the vadose zone, and a fifth terminated below the water table.

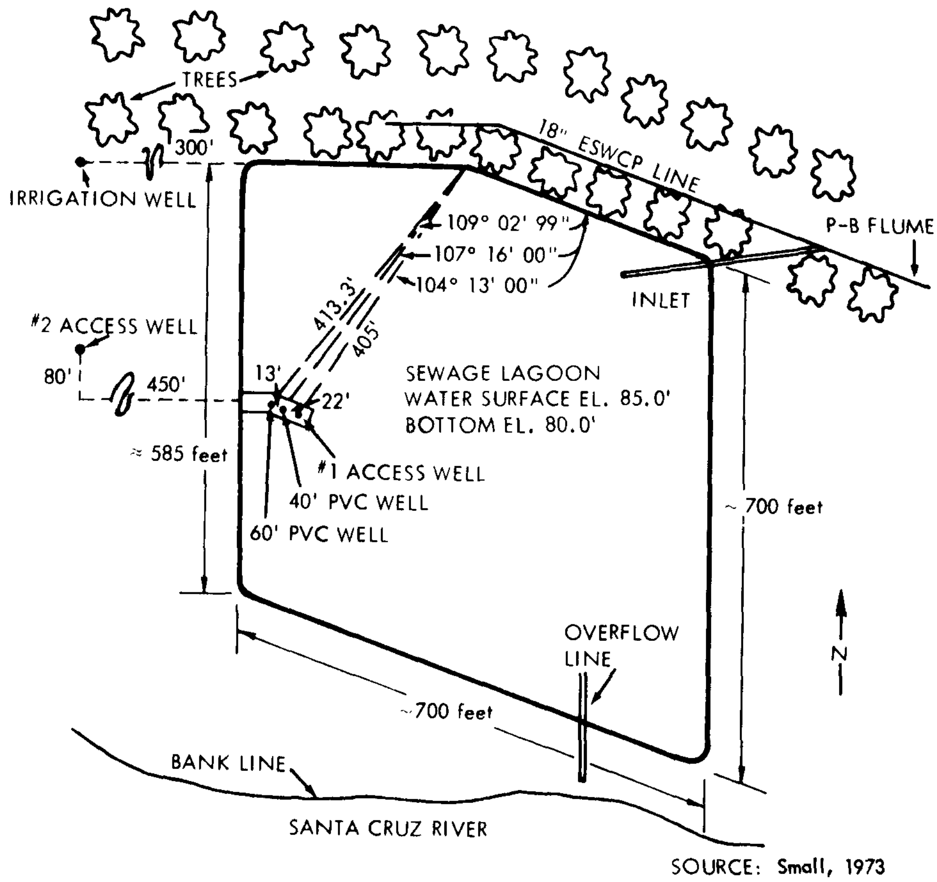


Figure 10. Location of monitoring facilities at the pond site.

One observation of interest from the recharge study was that water moved very rapidly (up to 200 feet per day) in the perched layers. In fact it appeared that the upper layer served essentially to spread water for a considerable lateral distance away from the recharge source, with leakage into the lower layers. Furthermore, samples from the wells in the vicinity of the water table showed a gradual displacement of native groundwater by recharge effluent, suggesting that recharge effluent flows along the top of the main, but slower moving, water body. Mixing then takes place by dispersion, etc.

The experience gained during the installation and operation of the facilities at the WRRC site prompted the installation and operation of similar facilities at the oxidation pond site during investigations of grass and soil filtration in 1967-1968. Results of these investigations were reported by Wilson and Lehman (1967) and Lehman (1968). Basically, the studies involved metering oxidation pond effluent onto three Bermuda grass plots, each 25 feet by 1,000 feet. Two 100-foot access wells were installed on the central plot. Neutron logging in these wells during preliminary experiments seemed to indicate the presence of two perched layers within the vadose zone, one at about 30 feet below land surface and a deeper layer at about 50 feet. Two 4-inch-diameter PVC wells terminating at depths of

40 and 60 feet were then installed by the cable-tool method. Each well contains a 4-foot-long plastic well screen. PVC was selected as material for these wells to minimize interference during studies involving the monitoring of heavy metals during effluent irrigation. Drill cuttings were obtained during construction of the wells but unfortunately, except for the upper 8 feet, these cuttings were not examined for physical or chemical makeup.

In addition to the PVC wells and access wells, the central plot was instrumented with three sets of four suction cup batteries, extending 2 feet below ground surface. These units were installed to permit soil solution sampling in the unsaturated state.

Results of flooding trials showed that grass filtration was not particularly effective as an overall, tertiary-treatment technique, compared with soil filtration. As expected, effluent arriving in the two PVC wells contained excessive levels of nitrate (in excess of 90 mg/l), but phosphate concentrations were lowered.

In 1970 the Pima County Department of Sanitation began plans for a new 10-acre stabilization lagoon, which would encompass several hundred feet of the grass plots. The County and City had received unfavorable publicity a short time before this period due to a threatened lawsuit by a homeowner near the ponds. The homeowner claimed that he could not drill a well for fear of nitrate contamination. Although the matter was settled before the new pond was due to be constructed, the University approached the County Department of Sanitation with the suggestion that a joint study be undertaken to monitor seepage from the new pond, with particular emphasis on nitrate movement. Fortunately, the two PVC wells and one access well were close enough to the western dyke of the lagoon that it was possible to construct a platform to reach them. The resultant arrangement is shown in Figure 10. Not shown in Figure 10 are two batteries of ceramic suction cups, one located on the western side of the pond and the second near the eastern side.

With the physical arrangement of wells shown on Figure 10, it was conjectured that a fair representation of the vertical changes in effluent quality could be obtained during deep seepage. Thus, the shallow suction cups would provide samples of soil solution, the two PVC wells would sample from mounds within the vadose zone, the access wells would sample just below the water table, and the irrigation well would provide an integrated sample from its perforated region of 80 feet to 278 feet. Also, the two access wells, one within the pond and one outside, offered the opportunity to detect the lateral movement of water in the vicinity of the main water table.

What Could Have Been Done

Additional steps could have been taken to upgrade the monitoring program but were not because of limited funds.

An interdisciplinary team could have been assembled to ensure that all parameters of significance would be monitored during the study. The following disciplines would have been desirable: soil chemistry, soil microbiology, soil physics, sanitary engineering, aquatic biology, and hydrology. An interdisciplinary team would have allowed relating changes in physical, chemical, and biological properties of the aqueous environment of the pond to corresponding changes in effluent during flow across the benthic-soil interface and during deep seepage. Some of the specific parameters which could have been monitored by the team are presented below.

Since the pond site is located in a region of complex hydrogeology at the confluences of the Canada del Oro and Santa Cruz Rivers, bulk groundwater flow from the two systems creates a complex effect on flow patterns and water quality. Also the effect of flood recharge and inflow of sewage effluent and landfill leachate through perching layers should be taken into account. Therefore, a thorough hydrogeological study would have helped to delineate and separate the interrelated effects, and thereby assisted in interpreting results.

Standard techniques for hydrogeological studies (Walton, 1970) could have been employed to delineate sources and sinks, boundary conditions, etc. In addition, test wells could have been constructed to provide drill cuttings for particle-size analyses and chemical composition. Resistivity and seismic surveys and down-hole gamma and neutron logging would be included. Results would have been carefully examined for more precise delineation of possible perching layers in the vadose zone, as well as regions of varying permeability below the water table.

As part of the hydrogeologic study the team could have attempted to trace inflow of sewage effluent from the Santa Cruz River by introducing suitable dyes upstream of the pond and collecting samples of well water. (Unfortunately, chloride levels are about the same in all sources.)

Based on the hydrogeological studies, additional monitoring facilities could have been installed around the pond. For example, from moisture logging (i.e., neutron probe) data, additional shallow wells could have been constructed down to perching layers. These wells would have allowed more accurate examination of the lateral spread of pond effluent through the layers. Similarly, better estimates could have been made of the mixing in these layers of inflowing sewage effluent (and possibly landfill leachate), natural recharge, and downward flowing pond effluent.

Several deeper observation wells could have been constructed around the pond. Additional information on aquifer transmissivity and storability could have been obtained by pumping these wells. Water samples could have been extracted from various zones beneath the water table in these wells before and after initiating the pond operation. Data from such a program would have provided a picture of the vertical distribution of quality (e.g., nitrate content), below the water table and indicated the effects of dispersion, etc.

A ring of access wells would provide moisture content data via neutron moisture-logging to facilitate water balance studies.

The drill cuttings obtained as part of the hydrogeological study could have been examined for chemical composition. In particular, the concentration of indigenous nitrogen and phosphorous in saturated extracts from the cuttings would have indicated the vertical distribution of these constituents in the vadose zone.

The C:N ratio of sludge within the benthic layer of the pond could have been evaluated periodically to determine the effects of changes in this ratio on mineralization of nitrogen (see Miller, in Sopper and Kardos, 1973). Similarly, soil cores from the soil-benthic interface could have been taken to determine changes in organic matter, cation exchange capacity (CEC) and exchangeable cations (particularly ammonium-nitrogen (NH_4-N)). Wilson et al. (1973) hypothesize that increase of soil organic matter by penetration of sludge would increase the CEC. Changes in NH_4-N or nitrate-nitrogen (NO_3-N) levels in shallow tensiometer samples could have been examined for a relationship between organic matter content and CEC.

Vertical movement of heavy metals and organic toxins originating in pond effluent could have been monitored in shallow tensiometers, deeper PVC wells, and access wells.

An attempt could have been made to install a system of electrodes in the soil-benthos interface for monitoring redox potential. However, as pointed out by Ellis (in Sopper and Kardos, 1973) in-situ determination of redox has not proven to be successful.

Wells constructed for the sampling program could have been used to obtain data for the development and calibration of computer models. In particular, data could have been obtained to provide realistic estimates of dispersivity coefficients of aquifer materials.

At the time of the study (1971), a few finite difference models were available to simulate groundwater flow. Mass transport effects were handled by the method of characteristics. Today finite element models are being developed to simulate joint hydraulic-mass transport phenomena in aquifer systems. Such models could be adapted to the pond site.

What Should Have Been Done

Some monitoring programs or techniques that should have been used in the pond study were not included because of lack of insight or lack of time.

A hydrochemical balance (albeit gross) of the groundwater system of the area should have been conducted before the pond was placed in operation. A fair amount of data was readily available for developing such a balance. For example, the Department of Soils, Water, and Engineering at the University of Arizona had been involved in obtaining hydraulic data of the Tucson aquifer system for a number of years. These data could have been examined to estimate flow trends in the vicinity of the pond. In the early 1970s the same department was also actively involved in collecting chemical data from well-water samples. These data should have been examined and used to construct trilinear diagrams, etc.

Much data could have been collected from wells in the area; a basic program to monitor water levels and quality in nearby domestic and irrigation wells should have been established. Water levels and chemical data were obtained in access wells and the irrigation well at the pond site for several months before the pond was put into operation, but this program should have been expanded.

The major oversight in the pond study, vis-à-vis the hydrochemical balance, was in not monitoring seepage of effluent in the Santa Cruz River. Later studies by Wilson and Small (1973) showed that intake rates of sewage effluent in the reach of the Santa Cruz River along the pond site are substantial, ranging from 1.5 feet per day to 7.7 feet per day. A program to monitor trends in the quality of river effluent (including, for example, total nitrate and boron) should have been implemented before and after the pond was placed in operation. Resultant data could have been used with groundwater data to construct trilinear diagrams.

One other possible source of subsurface inflow into the area was not examined, namely, deep seepage from irrigation across the river from the ponds. In particular, the movement of leached fertilizers should have been considered.

Pond overflow should have been metered or sampled. The rationale at the time was that the various transformations within the aqueous system of the pond were of interest only as the pond filled. When the groundwater monitoring program was continued a metering device should have been installed on the pond overflow and a sampling program established. A nitrogen balance of the aqueous system could have been conducted subsequently to relate to changes in the groundwater system. For example, since the pond frequently shifted from an aerobic to an anaerobic state, valuable data could have been obtained on nitrification-denitrification processes. Samples from the shallow suction cups might have reflected these processes. Also, a meter on the overflow line would have allowed calculation of long-term intake rates.

In addition to monitoring seepage rates in the pond by the gross inflow-change in storage technique, seepage measurements should also have been attempted at several locations via seepage meters, infiltrometers, etc. The measurement results should have been related to soil core data on bulk density, particle size distribution, etc. (Consideration was given to mounting one or two seepage meters permanently near the platform in order to relate seepage rates to development of the benthic layer at precise locations.)

Although the primary purpose of the study was to monitor the movement of nitrogen species, the chemical data (see Table 2 of Wilson et al., 1973) showed that the total phosphate increased from 3.7 mg/l to 52 mg/l in the 40-foot PVC well, and from 6.7 mg/l to 24.5 mg/l in the 60-foot PVC well. Normally, migration of phosphate in soils and groundwater systems is not considered a problem and soil filtration studies at the site showed a diminution of phosphorus during soil filtration. Consequently, the observed trends should have prompted additional sampling for phosphate beyond the period of the study. Furthermore, the forms of phosphorus, i.e., organic versus ortho or condensed phosphate, should have been determined. A soil microbiologist could perhaps have related the mobility of indigenous or effluent phosphate to soil transformations in the soil-benthos region and underlying zones. (As pointed out by Ellis in Sopper and Kardos (1973), a soil under reducing conditions will not adsorb as much phosphorus as the same soil would in well-aerated conditions.)

Although it is known that soils are capable of the chemical filtration of boron (Ellis, in Sopper and Kardos, 1973), there are cases reported where boron levels increase in the soil solution during irrigation with sewage effluent (Bouwer, in Sopper and Kardos, 1973). Therefore, the movement of boron should have been monitored in the well system at the pond site.

Additional technical details relating to monitoring should have included:

- Checking the interaction, if any, of the ceramic materials used for suction cups with nitrogen, phosphorus, boron, etc.
- Installing a system of tensiometers to measure soil moisture tension near ceramic cups. This would have ensured applying the proper suction so as not to affect moisture flow

- Taking samples periodically to other laboratories as a quality control measure
- Monitoring groundwater temperatures in the network of wells.

MULTIPLE-SOURCE NITRATE POLLUTION IN THE FRESNO-CLOVIS, CALIFORNIA, METROPOLITAN AREA

Background

The objective of the Fresno-Clovis study was to determine the extent of nitrate pollution in the groundwater, the sources of pollution, and time trends in nitrate content of water pumped by wells.

The Fresno-Clovis Metropolitan Area (FCMA) is a predominantly urban area of 145 square miles in the central San Joaquin Valley of California (Figure 11). The surrounding lands are agricultural and rainfall averages

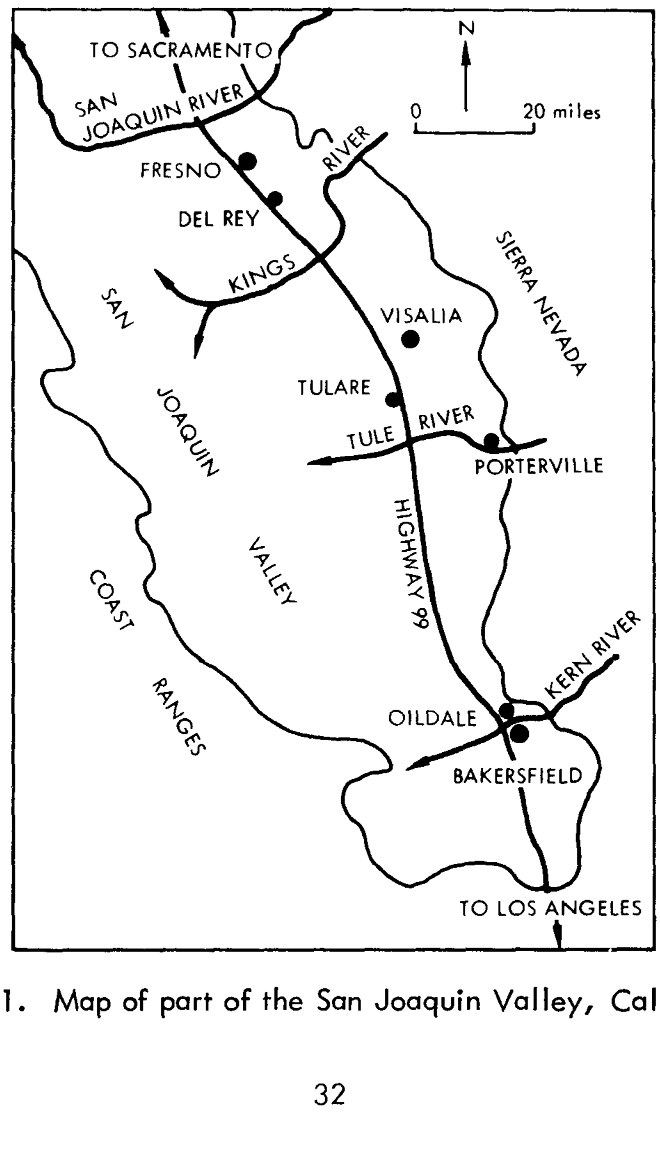


Figure 11. Map of part of the San Joaquin Valley, California.

about 11 inches per year. Groundwater occurs in permeable alluvial deposits and water levels average about 70 feet in depth. Wells average several hundred feet in depth and yields exceeding 1,000 gpm are common. Groundwater is the sole source of water supply in the urban area, whereas irrigation demand in the surrounding area is supplied by both canal water and groundwater. The primary means of liquid waste disposal other than evapotranspiration is by percolation, as there are no significant discharges to surface water.

Major sources of nitrogen include septic tank effluent in unsewered areas, sewage effluent, leakage from sewers, fertilizers, and meat-packing plant and winery wastes. Natural sources of nitrogen do not appear to be of major significance and background levels of nitrate in the aquifer are less than 10 parts per million (ppm).

Summary of the Monitoring Program

The two major constraints on the project were time and funding. The project was a doctoral dissertation, the time available was about 1 year, and no grant funds were available on such short notice. Thus maximum use had to be made of existing data and the cooperation of local individuals and agencies. Limited personal funds were used for research (mainly photocopying and kits for chemical quality determinations in the field).

The monitoring phase of the project encompassed the following steps:

1. Determination of the extent of data on groundwater and water quality in the proposed study area. Sufficient data were available to warrant proceeding with the program.
2. Completion of an exhaustive literature review on the pollutant of interest, in this case nitrogen or nitrate. Studies of sources of nitrogen and the occurrence of nitrate in soils and groundwater were reviewed (American Water Works Association, 1967; Schroepfer and Polta, 1969; and Stout et al., 1965).
3. Collection of all available reports and data on (a) groundwater, (b) soils, (c) well data, (d) pollution sources, and (e) chemical analyses of groundwater and pollution sources in the study area (Behnke and Haskell, 1968; California Department of Water Resources, 1965; Nightingale, 1970; and Page and LeBlanc, 1969).
4. Preliminary evaluation of the areal distribution of sources of nitrogen and nitrate in groundwater.
5. Collection of supplementary data to fill in gaps; such as water samples for more extensive areal coverage of groundwater quality, recent hydrogeologic records, historical development of nitrogen sources, and chemical analyses of waste waters.

The remainder of the project was interpretation and report preparation (Schmidt, 1972b and 1975).

COLLECTION OF ADDITIONAL WATER SAMPLES. High capacity wells (500 to 2500 gpm) were selected for water sampling at the discharge after prolonged pumping. Localized situations, such as the effect of a septic tank or lawn fertilizer on groundwater beneath one lot were not of concern in this study. Low capacity domestic wells (less than 50 gpm) pumping for short time periods generally reflect very localized conditions. Water samples taken from high capacity wells after long periods of pumping are much more indicative of regional conditions, which were of interest in this investigation. Figures 12 and 13 illustrate the areal distribution of chloride southwest of Fresno as determined from analysis of water samples from high capacity wells. Chloride was evaluated in this case because of its use as a tracer in this area, its being present in waste waters but almost absent in native groundwater. In the case of point or line sources, high capacity wells can be used for monitoring at a distance of several hundred or thousand feet from the source. This is due to the lateral extent of the cone of depression after prolonged pumping.

Because nitrate content varies vertically in groundwater, well construction is an important parameter in the selection of monitor wells. Figure 14 illustrates the vertical distribution of nitrate in a septic tank area of the FCMA as determined from pumping of open-bottom (unperforated) wells. Highest nitrates occur in the shallowest part of the aquifer. Because of this vertical stratification of water quality, nitrate contents of well water often change with pumping time over short time periods. Short-term trends in some cases can be plotted as straight-line relations on semilogarithmic graph paper (Figure 15). Seasonal fluctuations were also considered in evaluating chemical analyses of water samples from monitor wells (Figure 16). Short-term and seasonal trends must be established before long-term time trends can be evaluated.

As a number of individuals and agencies operate wells within the FCMA and no uniform monitoring program for groundwater quality exists, the existing chemical analyses are often for water samples taken at different times. It was desirable to sample many wells over a period of several days to several weeks to establish the areal and vertical distribution of nitrate at a specific time. The optimum sampling time was during the warmest time of the year, when the maximum pumpage occurred from high capacity wells. This served two purposes: (1) sampling was much easier with almost all wells already pumping, and (2) the most typical chemical quality of the regional groundwater could be monitored.

Several hundred municipal wells were sampled by one individual within 2 or 3 days. This was because only five or six agencies operated these wells. Sampling of irrigation wells southwest of the urban area took much

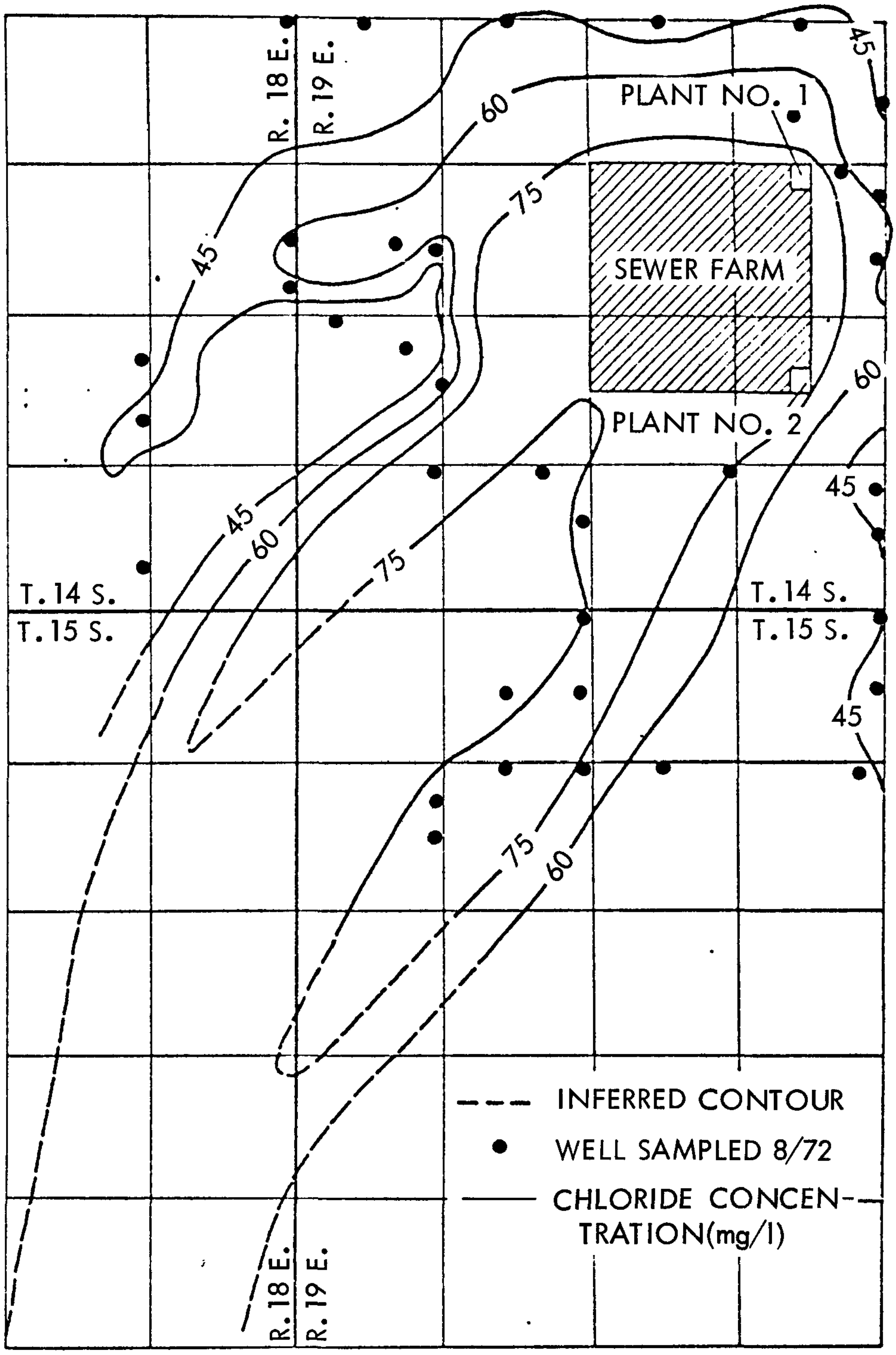


Figure 12. Chloride concentration contours (mg/l) in groundwater at and downgradient of Fresno sewage treatment plant.

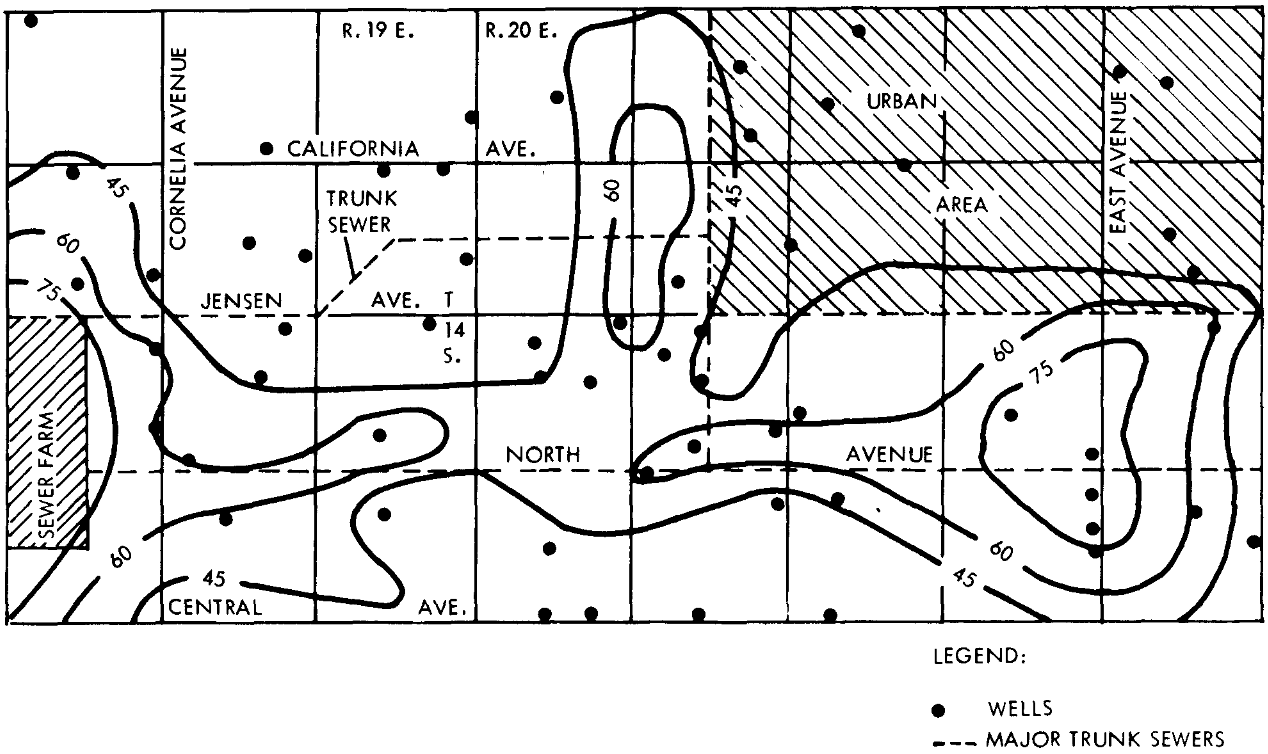


Figure 13. Chloride concentration contours (mg/l) in groundwater east of the Fresno sewage treatment plant.

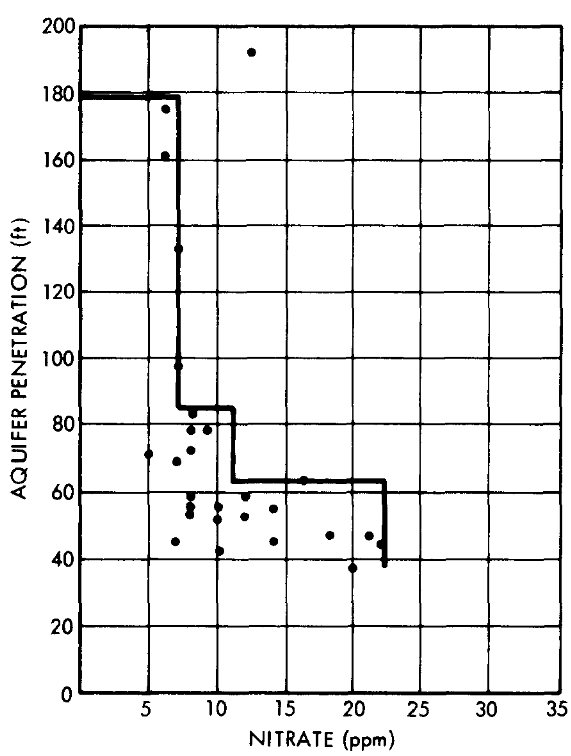


Figure 14. Relation between aquifer penetration and 1970 nitrate for wells in Figarden-Bullard area.

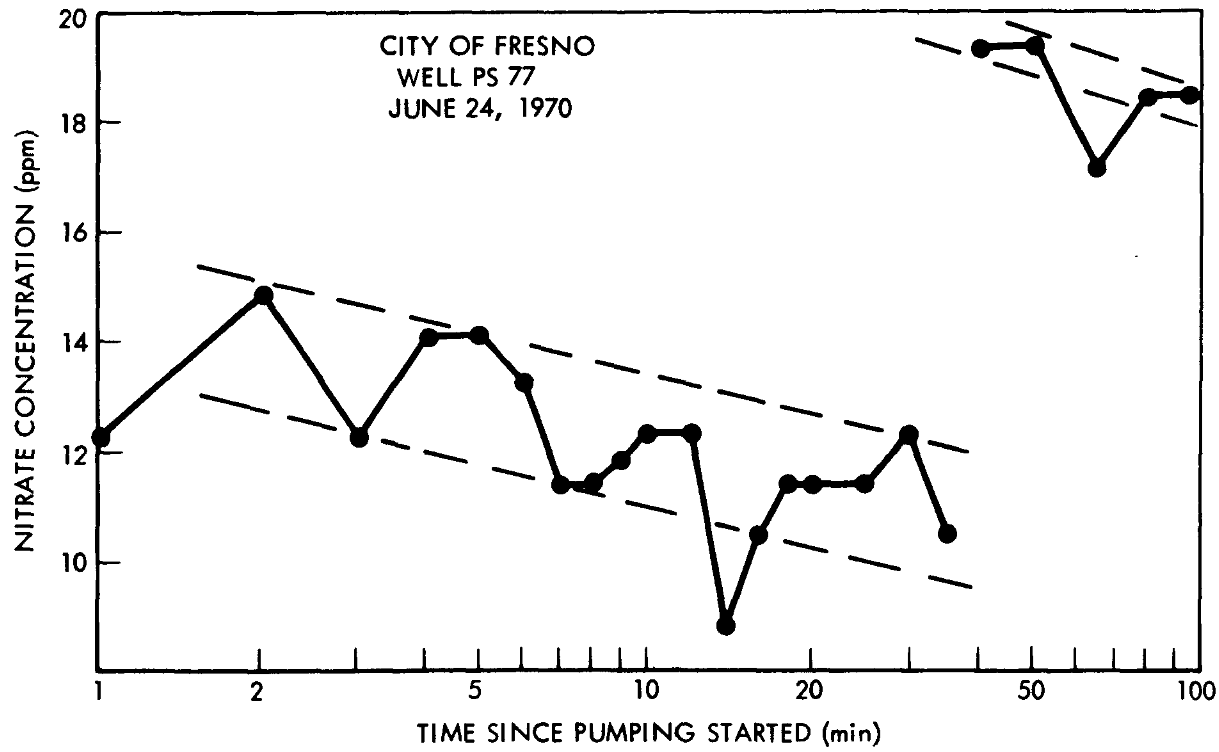


Figure 15. Short-term trends in nitrate during pump test on a large-capacity well in FCMA.

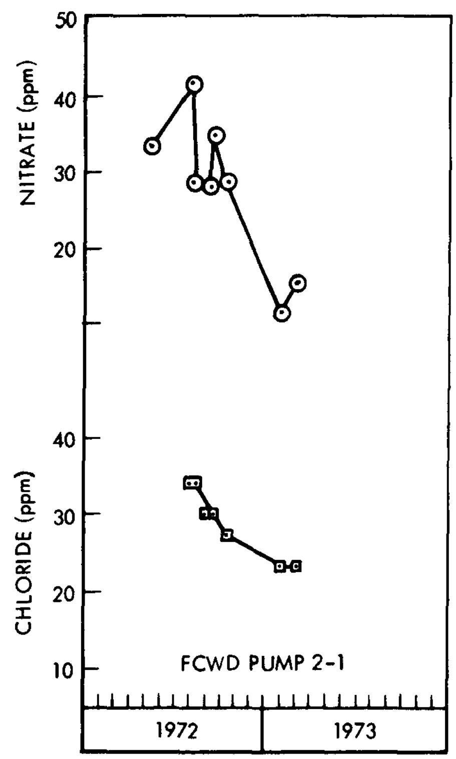


Figure 16. Seasonal trends in nitrate and chloride for a large-capacity well in a septic tank area.

longer because of access problems (poor roads), individual ownership in many cases, and lack of a faucet or open discharge. Because nitrate content can change with storage time, determinations were made immediately after collection. Electrical conductivity, water temperature, and chloride content were also measured.

SITE SPECIFIC DATA AND INTERPRETATION. The FCMA was subdivided on the basis of the predominant nitrogen source and on hydrogeology and the areal distribution of nitrate in the aquifer. This subdivision (Figure 17) was probably the key aspect of the entire study. The Figarden-Bullard area and Fresno sewage treatment plant were selected because of the predominance of one nitrogen source in each case (septic tanks and sewage effluent, respectively). Evidence gained from studies in these areas was then used in the Tarpey Village and Mayfair-Fresno Air Terminal areas, where both sources as well as others were present. The latter two areas had the highest nitrates in groundwater of the urban area. The Downtown Fresno area had no obvious source, but high nitrate contents were present in the aquifer. Each area had distinct hydrogeologic conditions with respect to the other areas.

In areas of diffuse sources, such as septic tanks or fertilizers, semiannual analyses are often sufficient to detect seasonal trends. However, near point sources of large volume, such as the Fresno sewage treatment plant disposal ponds, weekly or monthly sampling of wells is necessary

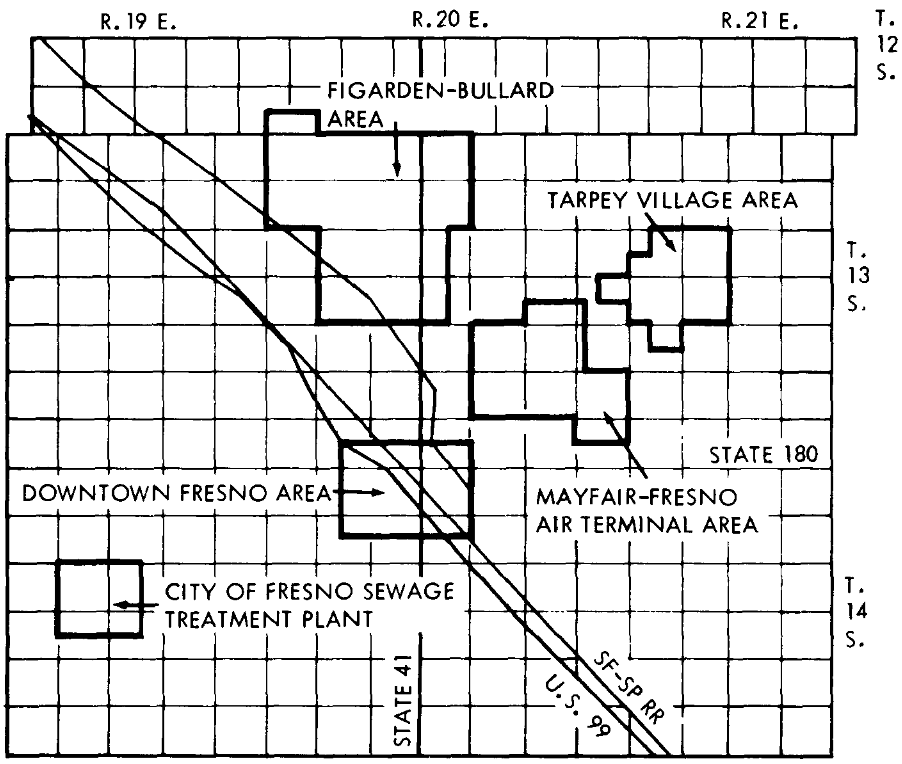


Figure 17. Study areas in the Fresno-Clovis Metropolitan Area.

(Figure 18). The density of existing wells is generally sufficient to delineate the areal water quality distribution. Open-bottom wells drilled by the cable-tool method are especially valuable as they tend to draw water from specific depth zones and thus give an indication of vertical stratification of groundwater quality. Other constituents, such as chloride, potassium, ammonium, and calcium are valuable in differentiating among various sources of nitrate. Trilinear diagrams can be prepared for waste waters and groundwater to illustrate similarities in chemical types of water. Historical chemical analyses in the FCMA have documented the buildup of nitrate in groundwater due to the development of nitrogen sources at certain times.

SPECIAL CASES AND ASSUMPTIONS. The travel time of recharged waste waters from the land surface through the vadose zone to the water table is in terms of weeks, months, or several years in the FCMA. Calculations on the water budget indicate that near point sources in particular, wastes must move rather rapidly to the water table. If not, there would be no storage space in the vadose zone for storage of these large volumes of water. Hydrographs of water levels and water quality data as related to land surface phenomena confirm that movement of water through the vadose zone is relatively rapid.

In the particular case of nitrate, which originates usually as organic or ammonium nitrogen at the land surface, there is no gross uptake in the vadose zone, as might be the case for certain trace metals. The fate of

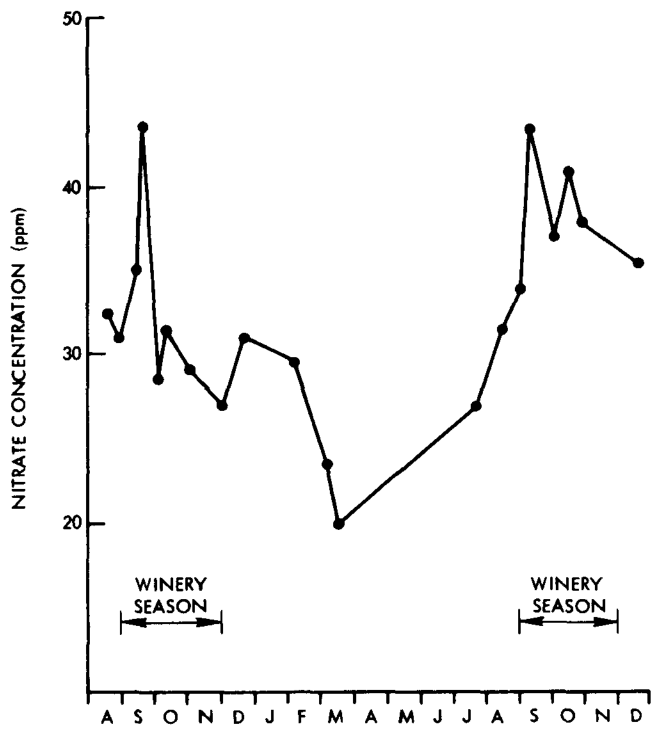


Figure 18. Nitrate concentrations in groundwater near Fresno sewage treatment plant.

most of the nitrogen applied at the land surface is (1) plant uptake, (2) denitrification and loss to the atmosphere, or (3) nitrification and leaching to the groundwater. In this particular case, natural nitrate contents are low, which makes it easier to detect nitrate groundwater pollution.

INSTITUTIONAL CONSTRAINTS. Little or no monitoring has been done by regulatory agencies, thus there was a lack of supplementary data, particularly on waste dischargers. Most polluters had an ingrained belief that they were not polluters. Thus they tended to hesitate to sample or permit sampling. In addition, in the literature reviewed, the researchers often represent some interest, such as agriculture, and bias is sometimes evident. Thus the literature is confusing with regard to effects of specific pollutants on groundwater.

Description of Alternative Monitoring Programs

Additional monitoring would have been possible without the two major constraints of time and funding. If more money had been available, the following could have been done:

- Sampling of nitrate in soil moisture and the vadose zone in septic tank areas, as well as near some point sources
- Measurement of water movement in the vadose zone beneath point sources
- More detailed sampling of waste at the land surface, including determinations of viruses, stable organics, nitrogen forms, chloride, boron, and trace metals
- Test well drilling near some point sources, such as wineries and meat packing plants, where no nearby wells existed
- Possibly, use of stable nitrogen isotopes to differentiate among sources of groundwater nitrate
- More complete chemical analyses of groundwater, as many existing analyses were incomplete.

If more time was available, the following could have been done:

- Establishment of seasonal trends in groundwater nitrate in more detail
- Evaluation of minor sources, such as lawn fertilizers
- Statistical correlation of septic tank density and groundwater nitrate content
- Calculation of water budgets and nitrogen budgets for various sources, including determination of evapotranspiration, percolation, denitrification, crop uptake, and other factors.

Strengths and Weaknesses of Monitoring Program

The major strengths of the investigation were the development of a detailed hydrogeologic framework in the area and the comprehensive use of water well sampling. The selection of high capacity wells for water sampling and chemical analyses permitted evaluation of regional groundwater conditions. Historical records compiled during the investigation permitted development of long-term time trends in groundwater nitrate related to nitrogen sources at the land surface. Other constituents, such as chloride, proved to be strong tools in determination of possible sources of nitrate. The thorough literature study preceding the field work was invaluable.

Many of the weaknesses of the investigation were due to the limited experience of the investigator, as well as time and funding constraints. Some sources were ruled out or considered negligible without acquisition of data to support such a decision. Leaking sewers and lawn fertilizers should have been analyzed in more detail. Insufficient consideration was given to soils and the vadose zone. Too large an area was selected for study, and the Fresno sewage treatment plant and the agricultural area southwest of Fresno should have been studied separately. Reliable chemical analyses were unavailable for some pollution sources, and data on plant operation were lacking.

Description of Optimal Monitoring Program

An optimal monitoring program would have included the following:

- More land surface or source monitoring, specifically waste water sampling
- Test well drilling at selected point sources of pollution
- The Fresno sewage treatment plant should have been studied separately from the rest of the FCMA
- Sampling in the topsoil and the vadose zone, specifically measurement of the movement of percolating water and nitrate and chloride contents.

Most of the additional types of monitoring would be costly. The least costly would be more monitoring at the land surface. Sampling in the vadose zone would probably have to be limited to a reconnaissance level, especially for diffuse sources. The existence of a monitoring program by regulatory agencies for waste waters and other potential sources of groundwater pollution would have greatly enhanced the study.

SECTION III

SITE-SPECIFIC GROUNDWATER QUALITY MONITORING EXAMPLES

Four potential categories of groundwater pollution have been selected to illustrate application of the major steps in development of the groundwater pollution monitoring methodology for site-specific conditions—agricultural return flow, septic tanks, percolation ponds, and landfills. Agricultural return flow represents one of the major potential sources of groundwater pollution in the western United States. Septic tanks are known to be a major source of groundwater pollution in some suburban areas. Both of these sources are generally diffuse, and thus monitoring programs for the two have certain similarities. Disposal and storage of various types of liquid wastes in ponds or pits subject to percolation represent another major potential source of groundwater pollution. Landfills for disposal of solid wastes can be major sources of groundwater pollution in humid areas. Percolation ponds and landfills are both point sources and thus monitoring programs for the two have certain similarities.

After discussion of the salient aspects of monitoring each type of pollution source, an example illustrating the procedure for selecting site-specific monitoring alternatives and estimating associated costs is presented. Steps 1, 10, 14, and 15 of the methodology which relate to areawide aspects in application of the methodology are not included in the discussions.

AGRICULTURAL RETURN FLOW

The area selected to monitor return flow depends primarily on soil conditions, the type of crops irrigated, irrigation methods, farming practice, and groundwater characteristics. In most cases, large farms (hundreds to thousands of acres) and irrigation districts (tens to hundreds of thousands of acres) would be areas of suitable sizes for monitoring.

Nonquality parameters to be monitored include volumes of applied water, precipitation, recharge from other pollution sources in the area, evapotranspiration, and infiltration of excess applied irrigation water. Quality-related parameters include the quality of applied water, amounts of additives such as fertilizers and pesticides, concentration due to evapotranspiration, dissolution and precipitation reactions in the soil-groundwater system, crop uptake of some constituents from the irrigation water, and quality of percolated water. Sampling is usually necessary for the applied water, percolate in the vadose zone, and groundwater.

Land Surface Monitoring

Land surface monitoring encompasses an inventory of volumes of water applied to the land surface and other sources of recharge, such as seepage from streams or canals. Evapotranspiration and rainfall rates must occasionally be measured in the field, but can often be extrapolated from nearby areas. Compilation of these data in conjunction with runoff determinations will allow calculation of infiltration rates. Amounts of additives must be inventoried, including fertilizers, soil amendments, and pesticides. Some of these are directly introduced to the irrigation water, whereas others are applied on the land. Estimates for application rates per unit area should be compiled. The chemical quality of applied water must be known or sampling and analysis undertaken. The approximate volumes and quality of other sources of recharge must also be determined. In some irrigated areas of the western United States, preliminary inventories of most of these items have been made for large areas such as irrigation districts.

Vadose Zone Monitoring

Monitoring in the vadose zone includes laboratory and field tests for determination of percolate quality and determination of storage capacity and travel times for water and specific pollutants in the vadose zone. The occurrence of restricting layers in the topsoil and relatively impermeable strata above the water table should be ascertained. Native soil and geological materials may be sampled for determinations such as nitrogen and total dissolved solids. Because return flow is a diffuse source, detailed sampling of percolating water in the vadose zone is impractical over large areas. The major disadvantage of sampling in the vadose zone in the case of a diffuse source of large areal extent is the cost of obtaining a sample representative of the entire system. To compensate for this, selected target areas can be chosen as typical of the larger area. Neutron probe and tensiometer measurements are the most effective method to trace water movement, and water samples can be effectively collected from soil-water samplers in the vadose zone or from wells in the saturated zone. In most cases analytical determination would be limited to the major inorganic chemical constituents, nitrogen forms, and boron. Pesticides, phosphorus, chloride, and potassium could be important in some areas. Sampling frequency in part depends on travel time in the vadose zone. Calculation or determination of travel time can be made based on infiltration rates and storage capacity of the vadose zone. If wells are drilled to penetrate the entire vadose zone and travel time of percolate to the water table is sufficiently slow, sampling during drilling and once every 5 or 10 years thereafter may be sufficient. Where travel times are less than 1 or 2 years, semiannual sampling may be necessary. Where pressure-vacuum soil-water samplers are installed as permanent sampling points, monthly sampling may be done; however, this usually will be unnecessary.

Saturated Zone Monitoring

Monitoring beneath a diffuse source in the zone of saturation should usually focus on sampling existing wells after long-term pumping. Large-capacity wells should be selected in order to provide an integrated sample of the water quality in the area of the well. In areas with few wells, construction of monitor wells may be necessary. Open-bottom cased wells drilled by the cable-tool method in unconsolidated materials may provide the most suitable results. Such wells produce water from well-defined depth zones. Where large seasonal variations in groundwater quality occur, seasonal trends must be established (based on at least monthly measurements to represent the extremes of chemical quality). Thereafter a semi-annual or annual sampling program will usually suffice. Long-term chemical hydrographs can then be plotted to illustrate groundwater quality changes due to return flow. Often, detection of meaningful changes requires chemical analyses for a period of a decade or longer.

An analysis for the major inorganic chemical constituents is advisable in most cases. Total dissolved solids, boron, sodium percentage, nitrate, and hardness are the major concern. Selected pesticides also should be periodically determined. The wells to be sampled should be chosen to reflect the quality of water in the upper part of the aquifer where pollution from return flow will first become apparent.

AGRICULTURAL RETURN FLOW EXAMPLE

Step 2 — Identify Pollution Sources, Causes, and Methods of Waste Disposal

For this example, a 50,000-acre irrigation district in Central California is given as the area in need of monitoring. The source is given as return flow. The area is rural with two towns of population less than 500 each. The area has been intensively farmed for over 80 years. In this case there is no specific method of waste disposal, as groundwater pollution can result from normal crop irrigation.

Step 3 — Identify Potential Pollutants

The chemical quality of irrigation water is known from records of State water agencies. Farmers, farm advisors, manufacturers, and regulatory agencies provide information on application rates of fertilizers, soil amendments, and pesticides. The primary fertilizer elements are nitrogen and phosphorus. The major soil amendment is gypsum and is widely used in only two of the subareas. There are five major types of pesticides in use, including two chlorinated hydrocarbons. The use of pesticides is related primarily to cropping patterns. Two of these pesticides are applied entirely in one subarea because of cropping patterns.

Step 4 — Define Groundwater Usage

In this district, 95 percent of the groundwater use is for irrigation of agricultural lands. The remainder is used for domestic purposes in small communities and rural areas. Despite the fact that the water used for domestic purposes is only a small portion of the total water use, groundwater provides the sole source of drinking water in the area.

Step 5 — Define Hydrogeologic Situation

Subsurface materials are alluvial sediments comprised of interbedded sand, silt, and clay layers. The depth to groundwater ranges from 50 to 200 feet below land surface and the average annual rainfall is 10 inches. Irrigation water is supplied from an extensive system of canals, utilizing surface runoff from nearby areas, and groundwater. Soils range from highly permeable sandy soils developed on sand dunes to low permeability hardpans. The regional direction of groundwater movement is westward through the district toward pumping depressions. Aquifer transmissivities range from 100,000 to 300,000 gpd/ft and irrigation well yields range from 500 to 1,000 gpm.

Preliminary investigation includes calculation of an approximate hydrologic water budget. Surface water inflow and outflow are large items, whereas groundwater inflow and outflow are small items. Data on precipitation and evapotranspiration can be combined with data on the foregoing parameters to compute the water budget. The budget indicates whether there is an imbalance between groundwater recharge and discharge. This in turn indicates whether groundwater levels are relatively constant, rising, or falling. This information is pertinent to the monitoring effort, as the thickness of the vadose zone may vary substantially seasonally and over a period of years or decades. Sources of recharge are seepage from streams and canals, return flow of excess applied irrigation water, and groundwater inflow. Groundwater discharge is primarily through pumping and natural groundwater outflow. Domestic waste disposal volumes are negligible compared to agricultural return flow volumes.

Step 6 — Study Existing Groundwater Quality

Maps prepared based on existing chemical analyses indicate the areal distribution of total dissolved solids, nitrate, and sodium percentage in the groundwater. High values of these parameters are generally related to soil type, cropping and irrigation patterns, and duration of irrigation. Water quality records indicate high total dissolved solids and nitrate contents in the upper 50 feet of the groundwater body, with much lower contents at deeper intervals. Previous studies by the United States Geological Survey indicate the chemical quality of sources of recharge other than return flow.

At this point, available information indicates the advisability of subdividing the study area. As a result, the study area is divided into five subareas for the following reasons:

- Surface water in the district is supplied from two separate sources of differing quality
- Soils in the district can be categorized into several groups on the basis of permeability
- Irrigation methods vary from place to place, but sprinkler irrigation is predominant in some areas and furrow irrigation in others
- Fertilizers, soil amendments, and pesticides are applied at different rates in various portions of the district
- Characteristics of the groundwater basin vary, especially from east to west.

Each subarea has a unique combination of these factors, and thus lends itself to a separate determination of water budgets and salt balance.

Step 7 — Evaluate Infiltration Potential of Wastes at the Land Surface

Determination of the volume of return flow escaping the root zone is the objective of this step. Average applied water volumes per acre for the district are available from a State water agency. Knowlege of the soils, irrigation methods, and cropping patterns enables more accurate estimates to be made for each subarea. Estimates of canal seepage are available from the irrigation district and streamflow seepage is known from streamflow records at various gaging stations operated by the United States Geological Survey. Crop surveys by District personnel and evapotranspiration rates from lysimeter tests at a local agricultural experiment station can be used to determine crop evapotranspiration. Precipitation is measured at several stations in the District. Average annual return flow is calculated for each subarea.

Step 8 — Evaluate Mobility of Pollutants from the Land Surface to the Water Table

Travel time of return flow to the water table is generally unknown. However, preliminary calculations indicate that in cases of shallow water tables, this travel time would generally range from 6 months to 5 or 10 years. In cases of deep water tables, the travel time could range from 5 to 50 years. Application rates of irrigation water are the primary controlling factor.

Because of the pollutant attenuation characteristics of soils and alluvial deposits in the District, forms of fertilizer such as phosphorus and potassium would be adsorbed by soils and geologic materials. The primary form of nitrogen fertilizer is anhydrous ammonia. Ammonia tends to be sorbed to materials in the vadose zone. However, oxidizing conditions in the vadose zone permit formation of nitrate which is subsequently leached to the groundwater. The gypsum contains sulfate which is fairly mobile in the vadose zone. Although calcium may be adsorbed in the vadose zone, it may subsequently be replaced by other cations and reach the water table. Some precipitation of gypsum may occur in the vadose zone. Tests at agricultural experiment stations indicate that only one of the pesticides used is subject to significant leaching; however, its mobility in the vadose zone is unknown.

Step 9 — Evaluate Attenuation of Pollutants in the Saturated Zone

Horizontal movement of pollutants in the aquifer is not of primary concern, in this example, as a diffuse source is being considered. However, the extent of return flow in the aquifer in a vertical sense needs to be approximated. This is necessary in order to effectively utilize existing wells for monitoring purposes. Wells that are perforated too deep may not indicate any effect of return flow. Return flow tends to occur in the upper 50 to 100 feet of the aquifer, as shown by existing well data and chemical analyses. This occurrence is largely due to the layered nature of the alluvium which results in small vertical permeabilities compared to horizontal permeabilities.

Step 11 — Evaluate Existing Monitoring Programs

A brief investigation of the records of the local water resource agencies indicates that there are no existing monitoring programs for groundwater quality in the area except for limited sampling of domestic wells in the two towns.

Step 12 — Establish Alternative Monitoring Approaches

Analysis of the hydrogeologic framework, groundwater quality, and irrigation practice of the district indicates that monitoring at the land surface, in the vadose zone, and in the saturated zone is necessary. Monitoring in the vadose zone is where the test drilling and relatively expensive and time-consuming aspects of monitoring come into play. The cost of monitoring in the vadose zone depends highly on the density of sampling devices.

LAND SURFACE MONITORING. This phase of the monitoring program was previously developed largely in Steps 3 and 7. This monitoring will be continuously updated approximately every 5 years. No additional sampling or analysis will be necessary.

VADOSE ZONE MONITORING. One site in the District is selected for detailed monitoring of percolate in the vadose zone. This monitoring is necessary due to the virtual absence of such data in the project area. The site is 40 acres in size. Soils, irrigation methods, and cropping patterns are judged typical of the larger area. Primary costs of this phase are for well construction, installation of sampling devices, sample retrieval, and chemical analyses and interpretation.

Three alternatives have been selected for monitoring in the vadose zone. The most effective means of sampling and analysis are derived from Everett et al. (1976). Alternative A has two access wells for neutron probes and three holes for pressure-vacuum soil-water sampler nests (Everett et al., 1976, Figure 15). Alternative B has five access wells for neutron probes and ten holes for pressure-vacuum soil-water sampler nests. Alternative C has ten access wells for neutron probes and 20 holes for pressure-vacuum soil-water sampler nests. The access wells for neutron probes are 2 inches in diameter and 150 feet deep. Three pressure-vacuum soil-water samplers are placed at 10-, 25-, and 50-foot depths in a 6-inch diameter hole to comprise each nest.

Neutron probe analysis and lysimeter sampling are carried out on a monthly basis. The percolate is analyzed for the major chemical constituents and boron. For Alternatives A, B, and C, the number of percolate samples collected monthly are 9, 30, and 60, respectively. Vadose zone monitoring is envisioned to be unnecessary after the first 2 years, because this period is believed to be sufficient for determination of rates of water movement and pollutant attenuation.

SATURATED ZONE MONITORING. Due to their large number, existing wells are determined to be sufficient for sampling. A carefully conducted well-data collection procedure is necessary before wells are selected for monitoring. Seasonal variations in well-water quality in the district are generally unknown. A 2-year period is chosen for bimonthly sampling of 300 large-capacity wells. Thereafter a semiannual sampling program is selected for 50 wells chosen from the 300. The major inorganic chemical constituents and boron are determined for the well-water samples. Primary costs of this phase are for sample collection, chemical analysis, and interpretation of results.

Step 13 — Select and Implement the Monitoring Program

Given the alternatives from Step 12, costs are derived based on a companion report (Everett et al., 1976).

LAND SURFACE MONITORING. It is estimated that a person with a B. S. degree in hydrogeology or water resources engineering and a minimum of 2 years of work experience in groundwater (salary $12,000 per year) could collect most of the data required on surface water, groundwater, soils, climatology, and waste loads in about 2 months. Costs for the time of the junior-level individual are calculated by applying a multiplier of 2.5 times the salary. A senior-level hydrogeologist, one with an M. S. degree in hydrogeology and a minimum of 5 years of work experience (salary $18,000 per year) in groundwater, could supervise the monitoring effort. About 1 month of his time would be necessary to review and interpret collected data, interpret hydrogeologic conditions with respect to groundwater pollution, delineate subdivisions of the study area, and to establish monitoring alternatives. Costs for the time of the senior-level individual are also calculated by applying a multiplier of 2.5 times the salary. This phase is primarily a one-time effort, but might have to be periodically updated, depending on future land use, irrigation methods, fertilizer application rates, and other factors. Costs for this phase of the program would be $5,000 for the junior-level individual's time and $3,750 for the senior-level individual's time, or about $8,750. It is estimated that $2,000 per year would cover periodic updating of this phase every 3 or 4 years if necessary.

VADOSE ZONE MONITORING. Costs for access wells for the neutron probe and for soil-water sampler wells are taken from Everett et al. (1976, Figure 18). However, in this case, slightly different well-construction techniques are necessary. Casing is not necessary, but special plugs must be installed to separate the three samplers in each hole. Reasonable estimates can be derived from Everett et al. (1976, Figure 18).

TABLE 1. WELL-CONSTRUCTION COSTS FOR VADOSE ZONE MONITORING

Type of Well	Alternatives (cost in dollars) A	B	C
Access Well Construction (including casing and development)	500	1,100	2,100
Soil-water Sampler Well Construction (including sampler installation)	500	1,750	3,380
TOTAL	1,000	2,850	5,480

In addition, logging test holes and supervision of sampling device installation by the junior-level individual would require 1 month for Case A, 3 months for Case B, and 6 months for Case C. The costs of his time for these alternatives are $2,500, $7,500, and $15,000, respectively.

One neutron probe device with 200 feet of cable is purchased for $3,000 (Everett et al., 1976, p 36). Each soil-water sampler costs $20 and one hand-pump service kit costs $30. Including tubing, the samplers required for each hole cost $70. Only one service kit is needed for all of the sampler wells.

The moisture logging cost per run per well for Alternative A, with a density of one per 20 acres, is approximately $250 using the cost curve of one per acre density (Everett et al., 1976, Figure 9), totaling $500 for the 40-acre tract. Since this cost curve was prepared for point-source application, densities in this example are too low to use the graph directly, and costs must be estimated by extrapolation. The cost per run per well for Alternative B, with a density of one per 8 acres, would be approximately $225. The cost per run per well for Alternative C, with a density of one per 4 acres, would be approximately $200 or $2,000 total. The monthly time for the junior-level individual for sampling soil-water samplers is 0.5 day for Alternative A, 1.5 days for Alternative B, and 2.5 days for Alternative C.

The chemical analyses for percolate obtained from the soil-water samplers include the major inorganic chemical constituents (Everett et al., 1976, p 114) and boron (Everett et al., 1976, Table 14). The cost of analysis of percolate for the major inorganic chemical constituents is $12 per sample and the cost for boron (dissolved) is $10. For purposes of this example, a special group rate of $17 is assumed for a combination of the foregoing. Discounts of 10 percent are applied for total cost over $500 and 20 percent for total cost over $1,000 (Everett et al., 1976, p 113). Analytical costs are $17 per water sample for Alternative A, $15 per sample for Alternative B, and $13.50 per sample for Alternative C. The costs for vadose zone monitoring are given in Table 2.

In order to select the most cost-effective alternative, consideration is given to impacts of pollution on groundwater use. Nitrate and pesticides pose a potential health effect on groundwater used for drinking purposes. No feasible alternative water-supply sources for drinking water are available. Pollution due to return flow also creates economic impacts, as eventually the degraded groundwater can result in decreased crop yields in the District. Assessment of long-term damages is not possible. Another consideration is the net worth of the farm produce. A final consideration is the money available for monitoring in the district and other districts in the region. Consideration of all these factors leads to selection of Alternative B.

TABLE 2. COSTS FOR VADOSE ZONE MONITORING

	Alternatives (cost in dollars)		
	A	B	C
<u>One-Time Costs</u>			
Well Construction and Logging	3,500	10,350	20,480
Neutron Probe and Soil-water Samplers	3,240	3,730	4,430
TOTAL	6,740	14,080	24,910
<u>Annual Costs</u> (first two years only)			
Neutron Moisture Logging	6,000	13,500	24,000
Soil-water Sampling	700	2,100	3,500
Chemical Analyses	1,840	5,400	9,720
TOTAL	8,540	21,000	37,220

SATURATED ZONE MONITORING. The junior-level individual would spend one month in collecting existing well data and groundwater quality data. Ten days would be spent collecting water samples from wells for each round during the first 2 years. Five additional days would be spent by this individual checking chemical analyses and tabulating the results for each round. First-year costs would be $13,750 and second-year costs would be $11,250. The senior-level individual would spend 2 weeks each year for supervision and review of the program. Costs would be about $1,880 each year. A routine irrigation water analysis would be $17 per sample, as calculated previously for analyses of percolate in the vadose zone. For groups of 300 samples, the analytical cost per sample is lowered to $13.50. For the first year, personnel costs would be $15,630 and chemical analyses $24,300. For the second year, personnel costs would be $13,130 and chemical analyses $24,300.

After the first two years, the junior-level individual would spend 2 days collecting samples for each round, and 1 additional day checking chemical analyses and tabulating results for each round. Costs for his time would be $630 per year. Supervision and review by the senior-level individual would be about 1 week each year after the first 2 years, at a cost of $940 per year. For groups of 50 water samples, the analytical cost per sample is $15. For each year after the first two, personnel costs are $1,570 and chemical analyses $1,500.

SUMMARY. Table 3 summarizes costs for the entire program.

TABLE 3. TOTAL COSTS FOR AGRICULTURAL RETURN FLOW MONITORING

	Annual Costs (dollars)		
Type of Monitoring	Year 1	Year 2	Subsequent Years
Land Surface	8,750	2,000	2,000
Vadose Zone	35,080	21,000	0
Saturated Zone	39,930	37,430	3,070
TOTAL	83,760	60,430	5,070

These costs reflect several factors. The greatest costs are incurred during the first 2 years of the monitoring program. One-time costs make the first-year costs almost 40 percent greater than second-year costs. Annual costs after the intensive 2-year monitoring period are only about 10 percent of the average annual cost during the first 2 years.

SEPTIC TANKS

The area selected to monitor depends primarily on the location and configuration of unsewered areas. In general, septic tanks in sparsely populated rural areas are insignificant sources of groundwater pollution. In more densely populated areas, soil conditions, septic tank density, method of disposal, and groundwater characteristics influence the selection of the area to be monitored. The area should be chosen to insure uniformity of as many of these factors as possible. Downgradient areas within 1 mile of the unsewered area should also be included to monitor movement of recharged septic tank effluent. The area selected typically ranges from several hundred to several thousand acres in size.

Nonquality factors to be considered include volume of the septic tank effluent, method of effluent disposal, and soil hydraulic characteristics. Septic tank density, or lot size, is an important factor. Disposal methods range from shallow drainfields where substantial losses due to evapotranspiration occur to seepage pits where this loss is insignificant. Usually the disposal methods are selected on the basis of soil conditions. Percolation rates and the presence of restricting layers influence the impact of septic tank effluent on groundwater quality. Quality-related factors include the quality of septic tank effluent and percolate in the vadose zone. The major sampling required is for effluent, percolate, and shallow groundwater. Soils and geologic materials may be occasionally sampled to determine pollutant attenuation mechanisms, such as adsorption.

Land Surface Monitoring

The most effective type of land-surface monitoring comprises inventoring septic tank densities, volumes of septic tank effluent, water use, and possibly determining a water budget for the area. Data on septic tank densities and volume of septic tank effluent can be determined, for residential areas, from lot sizes in unsewered areas. Special attention should be focused on schools, shopping centers, and other facilities with effluent volumes significantly greater than those for individual households. The volume of effluent has been carefully documented in some areas. Figures for in-home water use are available for most areas. The water subject to septic tank disposal is used in the home for toilets, sinks, garbage disposers, bathtubs, showers, dishwashers, washing machines, and water softeners. In areas where little or no data have been developed, representative households can be chosen for detailed monitoring. The effluent should be characterized as to quality, especially for total dissolved solids and total nitrogen. Sampling of representative effluent may be necessary. The inventory should include pertinent data on the types of detergents used and the extent of the use of water-softening devices.

In the case of shallow disposal, such as seepage trenches, water budget analyses may be necessary in order to determine infiltration of septic effluent. Precipitation and evapotranspiration can be estimated from records in the area. However, judgment is necessary to calculate infiltration, as some seepage trenches may be below the root zones of most plants. In other cases plant uptake of nutrients, such as nitrogen, from the effluent could be significant.

Vadose Zone Monitoring

Determination of storage capacity and travel time for water and specific pollutants in the vadose zone is an important component of the monitoring program. Delineation of restricting layers in the topsoil and relatively impermeable geologic materials above the water table is important. Laboratory and field tests can be conducted to determine the quality changes of effluent during percolation through native soil and geologic materials. Sampling of soil and geologic materials for nitrogen determinations may be necessary where natural sources of nitrogen are present. Because septic tank effluent is a diffuse source over a monitoring area, detailed sampling of percolating water in the vadose zone is impractical in most cases. However, monitoring areas are generally of a size such that several holes could be drilled for sampling in each area.

Neutron probes and tensiometer measurements can be effectively used to trace water movement. Percolate samples can be collected from soil-water samplers in the vadose zone or from wells in the saturated zone. In most cases, analyses of percolate samples are limited to the major inorganic chemical constituents and nitrogen forms. Boron, detergents, stable organics, and bacteriological constituents could be important in some cases. The frequency of sampling depends on travel time in the vadose zone. For wells penetrating the entire vadose zone, and when travel times are very slow, sampling may be necessary only once every few years. However, percolate should be collected from the soil-water samplers generally on a monthly basis. Percolation rates of septic tank effluent often are in the range of 1 to 2 feet per acre per year.

Saturated Zone Monitoring

As septic tanks represent a diffuse source, effective monitoring in the saturated zone usually entails sampling of existing wells after long-term pumping. These wells should be large-capacity wells, if possible, in order to provide an integrated sample. Such wells are often present in urban or suburban areas. Shallow wells should be selected which tap the upper part of the aquifer; an occasional deep well should be included. Seasonal trends should be established in some areas, and a semiannual sampling program will usually suffice thereafter. The establishment of seasonal trends may require monthly sampling for several years. Wells to be sampled include not only those beneath septic tank areas, but upgradient and downgradient wells. Upgradient sampling can provide an indication of water quality unaffected by septic tank effluent. Downgradient sampling indicates the downgradient movement of septic tank effluent in the aquifer. Usually a distance of 1/2 mile or so from the downgradient boundary of the unsewered area will be adequate. This limit is due to pollutant attenuation mechanisms in the saturated zone. Chemical hydrographs can then be plotted to illustrate long-term trends in groundwater quality. Many years of records may be necessary for proper interpretation.

Analysis of well water for the major inorganic chemical constituents is advisable in most cases. Total dissolved solids, nitrate, chloride, and possibly other nitrogen forms are of chief concern. Detergents, boron, hardness, stable organics, and bacteriological constituents may also be important.

SEPTIC TANK EXAMPLE

Step 2 — Identify Pollution Sources, Causes, and Methods of Waste Disposal

In this example, a 2,000-acre suburban area in an alluvial basin of Central California is given as the area for monitoring of septic tank effluent. Septic tank treatment and disposal has been practiced in the area for about 30 years. The area to be monitored includes upgradient and downgradient areas within 1 mile of the unsewered area.

A portion of the water pumped in the area is returned to the groundwater by lawn irrigation return flow and septic tank effluent disposal systems. The method of septic tank effluent disposal used is rather uniform over the area; seepage fields are used that are generally 8 to 10 feet below the land surface. Several schools and small shopping centers are points of heavy effluent discharge, whereas the remainder of the area is residential. Fertilizers used for lawns, gardens, trees, and shrubs may contribute to groundwater pollution. Urban runoff is diverted from the area by storm drains and disposed of elsewhere.

Step 3 — Identify Potential Pollutants

Well water in the area averages about 250 ppm total dissolved solids. Based on analyses of domestic sewage effluent from nearby sewered areas, the dissolved solids content of the septic tank effluent is estimated at 500 ppm. There is no water softening in the area. Chlorides averaging 80 ppm are present in sewage effluent discharged from nearby areas. Boron is introduced through the use of detergents and fluoride is added for health reasons at the well sites. Boron, fluoride, and total nitrogen concentrations in the septic tank effluent are estimated at 0.5, 1.2, and 25 ppm, respectively, based on data in the literature.

Step 4 — Define Groundwater Usage

Groundwater is pumped for municipal use, which includes domestic use and lawn irrigation. One hundred percent of the use is for municipal use, of which about 25 percent is for in-house use (including drinking water), and about 50 percent is for yard irrigation. The remainder is used for cooling purposes (15 percent) and commercial use (10 percent). Additional information on water use is presented in Step 5.

Step 5 — Define Hydrogeologic Situation

The depth to groundwater ranges from 50 to 70 feet, and no perched water is present in the alluvium. The soils are uniform over the area and no restricting layers are present. Water is supplied entirely by groundwater. The aquifer transmissivity is 100,000 gpd/ft, and the water level slopes uniformly to the south. Well yields range from 500 to 1,000 gpm and well depths range from 100 to 200 feet. Wells have usually been drilled by the cable tool method and casings are perforated over short intervals or are unperforated (open-bottomed).

Groundwater recharge is primarily from groundwater inflow and the quality of this water is determined primarily by natural factors. Available studies indicate that this water is of the calcium-sodium bicarbonate type with total dissolved solids content less than 200 ppm. Groundwater discharge is by well-pumping and groundwater outflow. Water levels are relatively stable from year-to-year, although they fluctuate seasonally.

Step 6 — Study Existing Groundwater Quality

Maps have been previously prepared by County agencies based on existing chemical analyses. These maps indicate the areal distribution of total dissolved solids, chloride, nitrate, and hardness in the groundwater. High values are generally found in the central portion of the study area. Chemical analyses of water from shallow wells in the area indicate higher total dissolved solids, nitrate, and chloride contents than groundwater beneath surrounding areas. Deep wells produce water of a chemical quality similar to that in the surrounding area.

Step 7 — Evaluate Infiltration Potential of Wastes at the Land Surface

Calculation of the volume of septic tank effluent percolating below septic system leach lines is the objective of this step. Daily water consumption is available from the water purveyor, since well pumpage and household use are metered. Lawn irrigation is a major use in the summer, but minor in the winter. Based on literature studies and a comparison of water usage in the summer and winter, domestic use subject to septic tank treatment and disposal is calculated. The number and size of lots are available from the County public works department. There are 3,900 lots in the residential portion of the study area (1,850 acres) and the population therein is 8,900.

The average water use in the residential area is 300 gallons per capita per day and the average effluent volume is 75 gallons per capita per day. The total volume of septic tank effluent in the residential area is about 670,000 gallons per day, or 750 acre-feet per year. This averages about 14 inches annually over the part of the residential area not occupied by streets or structures (650 acres). Two schools and two shopping centers are located on a total of about 150 acres within the study area. Annual water use for the schools and shopping centers averages about 90,000 gallons per day. The effluent volume from these four sources averages 100,000 gallons per day during the school year and 20,000 gallons per day during the rest of the year. As the septic tank effluent is disposed of below the root zone of most plants, no loss of effluent to evapotranspiration is assumed; thus no water budget analysis is necessary.

On the basis of winter and summer use, evapotranspiration rates, and irrigation methods, it is estimated that return flow from irrigation averages 1.0 million gallons per day, or about 21 inches per year over the irrigated part of the residential area (650 acres).

Step 8 — Evaluate Mobility of Pollutants from the Land Surface to the Water Table

Previous studies have been undertaken at a nearby Agricultural Research Service site and at the local university. These studies have generally documented travel times of septic tank effluent to the water table and have evaluated the movement of nitrate in the vadose zone. Travel times where effluent application rates are 14 inches per year and the water table is 50 feet deep are about 5 years. Little denitrification occurs because of the aerobic conditions prevailing in the vadose zone and the lack of organic matter. Hence, nitrogen forms in the effluent are oxidized to nitrate and leached to the water table. Bacteriological constituents, including viruses, are removed within several feet of travel in the alluvium above the water table. Phosphorus is strongly retained in the vadose zone due to sorption and chemical precipitation.

For return flow from irrigation, travel times to the water table are comparable to that discussed above. Nitrogen behaves similarly as in the case of septic tank effluent.

Step 9 — Evaluate Attenuation of Pollutants in the Saturated Zone

This step is necessary in order to determine the extent of downgradient monitoring needed. In this case inspection of the maps prepared for well-water quality indicates no detectable effects occur more than 1/2 mile downgradient of the unsewered area after 30 years of operation. The extent of septic tank effluent in the aquifer in a vertical sense also needs to be estimated. This is necessary in order to effectively utilize existing wells for monitoring purposes. In general septic tank effluent tends to occur in the upper 50 feet of the aquifer, as shown by existing well data and chemical analyses.

Step 11 — Evaluate Existing Monitoring Programs

Fairly comprehensive monitoring programs are in effect for all wells for the major chemical constituents (including nitrate, fluoride, and total dissolved solids). One laboratory provides all of the analytical services and the chemical analyses appear to be adequate for monitoring groundwater pollution. No determination for detergents or stable organics has been made. Bacteriological sampling is routinely performed by the water purveyor and analyses for fecal coliform are consistently negative.

Step 12 — Establish Alternative Monitoring Approaches

Analysis of alternative monitoring programs in relation to the hydrogeologic framework, groundwater quality, and waste disposal practice indicates that no vadose zone monitoring is necessary. Routine land surface monitoring and sampling of large-capacity wells can be used to effectively monitor the source. The most cost-effective alternative is selected after consideration of the impact of septic tank effluent on water use in the area and downgradient areas. Nitrate and stable organics in groundwater used for drinking purposes pose a potential health effect. Pollution due to septic tank effluent can also degrade municipal supplies in a monetary sense, especially for parameters such as hardness. Water treatment in the home or by the water purveyor may be necessary to enable the use of the degraded water. A final consideration is the funds available for monitoring in the subdivision and other unsewered areas in the region. Consideration of all of these factors leads to selection of the most cost-effective method.

LAND SURFACE MONITORING. This phase of the monitoring program was largely developed in Steps 3 and 7. No annual updating is deemed necessary.

SATURATED ZONE MONITORING. Because the source to be monitored is generally diffuse and travel times of percolate to the water table are in terms of about 5 years, long-term monitoring of large-capacity pumping wells can be effectively used. Previous monthly sampling has established that peak nitrate concentrations occur in late summer and that the lowest values occur in early spring. Thus, about 25 wells are selected for continuous monitoring and chemical analyses are performed on water samples taken semiannually. Analyses include the major inorganic chemical constituents, boron, and fluoride. Samples are collected annually to determine the stable organic, detergent, and ammonia contents in water from six selected wells.

Step 13 — Select and Implement the Monitoring Program

The monitoring program was already selected in Step 12 based on experience and hydrogeologic judgment. The following costs are then derived from Everett et al. (1976).

LAND SURFACE MONITORING. A person of minimum qualifications (i.e., a B.S. degree in hydrogeology or water resources engineering and 2 years working experience) could collect most of the required data on water use, lot size, septic tank effluent disposal methods, quality of source water and septic tank effluent, and lawn irrigation and fertilizers in about 1 month. Data on groundwater conditions, well data, and historical chemical analyses could also be collected during this period. A one-half week review by a senior individual costs $470. This phase is primarily a one-time effort. No costs for updating have been calculated for this analysis. Total cost during the first year of the program would be $2,970.

VADOSE ZONE MONITORING. Vadose zone monitoring encompasses the review of existing reports and consultations with researchers in the area. The junior-level individual collects these data in 1 week and a senior-level individual reviews and interprets them in one-half week. This phase is a one-time effort during the first year and costs $1,160.

SATURATED ZONE MONITORING. Sampling of water wells is conducted by local agencies at no additional cost. Costs for the major inorganic chemical constituents are given in Everett et al. (1976, p 114) as $12 per sample. Costs for boron and fluoride determinations are given in Table 14 of the same reference as $10 each. A special group rate is assumed for determination of all of these constituents. For the samples collected semi-annually, determinations of the major inorganic chemical constituents, including boron and fluoride, cost $22 per sample, which is discounted to $20 per sample for groups of 25 samples. The annual analytical cost is $1,000 per year. For the samples collected annually, costs per sample are $5 for ammonia (Everett et al., 1976, Table 14), $10 for methylene blue active substances (Everett et al., 1976, Table 15), and $20 for biochemical oxygen demand (Everett et al., 1976, Table 15). A special group rate of $30 per sample is assumed for these annual determinations, or a total of $180. Total analytical costs are thus about $1,180 per year.

Checking chemical analyses and tabulating results requires 1 week each year for the junior-level individual at a cost of $630. Supervision of the program and annual review by the senior-level individual requires 1 week at a cost of $940. Total annual personnel costs are $1,570.

SUMMARY. Table 4 summarizes costs for the entire program.

TABLE 4. COST SUMMARY FOR MONITORING SEPTIC TANK POLLUTION

	Annual Cost (dollars)	
Type of Monitoring	Year 1	Subsequent Years
Land Surface	2,970	0
Vadose Zone	1,160	0
Saturated Zone	2,750	2,750
TOTAL	6,880	2,750

These costs reflect several factors. The annual cost is relatively low due to the use of existing programs for collecting samples. The overall program cost is relatively low due to the lack of well drilling and vadose zone sampling, neither of which are necessary in this example.

PERCOLATION PONDS AND LINED PONDS

Ponds for containment of liquid wastes are potential point sources of groundwater pollution. Two major categories of ponds presented in this discussion are percolation ponds and lined ponds. The first category is represented by large-scale percolation of sewage effluent to remove bacteria and possibly other constituents. In this case large volumes of water are recharged per acre; for example, in the range of 20 to 100 feet per year. The second category is represented by disposal or storage of some oilfield wastes, industrial wastes, and certain toxic materials in lined ponds. Artificial liners have come into wide use to limit infiltration, and small amounts of seepage or leakage per acre usually occur (less than 1 inch to several inches or feet per year). The type of monitoring effective for each category is basically different.

In the case of percolation ponds, water budget evaluation can be effectively used to determine infiltration. Thus nonquality parameters to be measured include rates of waste discharge, precipitation, and evaporation. The infiltration can be calculated by measuring inflow to the pond, storage changes, precipitation, and evaporation.

Artificial liners range from compacted soil or clay to impermeable plastic and rubber liners. "Seepage" may be termed slow-flow through a liner over the entire lined area, whereas "leakage" is flow through breaks or perforations in the liner. Monitoring may be necessary for almost all ponds despite the lining material. Liners can be pierced or joints not carefully sealed during installation. Chemical deterioration is common for some types of liners exposed to toxic wastes. The water budget approach usually is not applicable in this case, as the infiltration rate is usually less than the error inherent in calculating infiltration. Rather, monitoring focuses on the physical integrity of the liner, reactions between wastes and the liner, and detection of leaks.

Factors determining percolate quality in both cases include the waste discharge quality, concentration of pond water by evaporation, dilution of pond water by precipitation, chemical changes in pond water, and dissolution and precipitation reactions in the topsoil and vadose zone. Retrieval of water samples from the waste discharge stream and ponds, percolate in the vadose zone, and shallow groundwater are the most effective sampling methods. Topsoil and geologic materials are sampled where significant retention of some constituents is important.

Land Surface Monitoring

Nonquality monitoring for percolation ponds involves accumulating data for calculation of the water budget. The waste discharge flow can usually be measured at the point of entry to the pond. In some ponds recycling occurs and outputs must also be measured. Flow meters can often be installed in discharge pipes, and weirs and flumes can be installed to measure flow in other cases. Thus a continuous record of waste discharge is available. For large ponds, evaporation and precipitation may have to be measured onsite. To a large degree this depends on the climatological homogeneity of the area. Land pans and floating pans can be used to calculate evaporation from a free-water surface. Extrapolations from nearby areas can be made over climatologically homogenous areas. Daily measurements enable calculation of infiltration. Radioactive isotopes, such as tritium, have been used to directly measure seepage rates. Also, stable hydrogen isotopes are fractionated during evaporation, and thus the deuterium content of pond water can indicate the relative percentages of evaporation and infiltration.

Water samples can be collected from the discharge stream or the open pond. Sampling in open ponds may be greatly hampered by netting or other features designed for wildlife protection. Large fluctuations in discharge stream quality often occur due to variations in plan operational characteristics. Compositing of samples from the discharge stream is thus necessary. Continuous recording devices may be used for some parameters such as electrical conductivity. Sampling open pond-water quality to determine percolate may be more representative than sampling the waste discharge stream. Boats may be used or in some cases special walkways constructed for sample retrieval. Of importance is the collection of a sample that would be representative of water that would eventually percolate. Certain parts of large ponds may be much more favorable for infiltration than others and consideration should be given to this factor when selecting sampling sites. Sample frequency often must be established on a trial and error basis. For composite samples, weekly composites of samples collected at 4- to 8-hour intervals is ordinarily sufficient. For pond samples, weekly, biweekly, or monthly sampling is usually sufficient. The constituents to be analyzed depend on the type and charcteristics of the waste, as well as water use in the area.

Vadose Zone Monitoring

Monitoring in the vadose zone beneath percolation ponds is especially important when percolate travel time from the land surface to the water table is so long (20 to 30 years or greater) as to render saturated zone monitoring ineffective. Where substantial retention of toxic pollutants occurs in the vadose zone, it may also be necessary to obtain soil samples at various depths.

Neutron probes and tensiometers can be used to trace water movement and pressure-vacuum soil-water samplers can be used for water sample collection. Laboratory and field tests can be performed to evaluate the reaction of percolated waste water with soils and geologic materials. For example, the sorptive capacity for various trace metals can be determined. Also, the effect of extreme pH values in percolated waste water on the dissolution of minerals in geologic materials can be evaluated.

Appropriate sampling devices can be installed for artificial liners that may leak. One method is to use two liners separated by a layer of soil and tile drain pipes. The lower liner is graded toward a central point for sample collection. Any leakage through the upper liner tends to accumulate on the lower liner and can be collected. Obviously, the lower liner must be relatively impermeable and carefully constructed for this method to be effective. Sampling of nearby wells can also provide information on leakage.

Saturated Zone Monitoring

Resistivity methods can be used where high salinity wastes are ponded and existing wells are not suitable for monitoring. Specially designed monitor wells tapping the shallow portion of the saturated zone are often necessary. Cable-tool drilled wells that are either unperforated or are perforated over short intervals may be effective in many cases. A number of small-diameter observation wells can be effectively sampled periodically by use of a portable submersible pump. In some cases bailing or air-jetting may be used for sample retrieval. Consideration should also be given to sampling one or more large-capacity wells typical of those used in the area. Such wells may provide data on regional groundwater quality. Once seasonal trends are established, the frequency of sample collection can be determined. In general, monthly or bimonthly sampling is sufficient. The specific determinations depend on the composition of the waste water and the water use in the area.

PERCOLATION POND EXAMPLE

Step 2 — Identify Pollution Sources, Causes, and Methods of Waste Disposal

In this example, a percolation pond for the disposal of toxic industrial wastes in the eastern United States is the source to be monitored. The pond has been in operation for 5 years, is 20 acres in size, and about 5 feet deep. The topsoil has been removed to achieve higher infiltration rates.

Step 3 — Identify Potential Pollutants

The discharged waste is a low pH sodium chloride brine containing some trace metals. Total dissolved solids commonly exceed 10,000 ppm and there are high concentrations of arsenic, cadmium, chromium, barium, and silver. The salinity and trace element content of the waste discharge fluctuates considerably due to plant operation. Pond-water quality shows less fluctuation due to damping by the storage in the pond. Dilution by precipitation falling on the water surface also occurs.

Step 4 — Define Groundwater Usage

There is no use of groundwater in the immediate area. However, County-wide plans indicate the probability of urbanization within 20 years. The future water supply would likely be provided by wells.

Step 5 — Define Hydrogeologic Situation

The average annual rainfall is about 50 inches per year, and glacial till materials about 100 feet thick comprise the aquifer. These aquifer materials are highly permeable and well yields in the region range from 500 to 1,000 gpm. The aquifer is underlain by relatively impermeable igneous and metamorphic rocks. Groundwater flow is to the north at a uniform gradient of about 20 feet per mile. Groundwater flow rates are about 1 foot per day. The regional depth to water is about 20 feet; however, a mound is present beneath the pond and groundwater is believed to be less than 10 feet deep. No wells are in the immediate area. Recharge is from precipitation and groundwater discharge is to streams in the area.

Step 6 — Study Existing Groundwater Quality

Native groundwater in the region is of excellent chemical quality, with total dissolved solids less than 50 ppm. Groundwater quality beneath the percolation pond is unknown.

Step 7 — Evaluate Infiltration Potential of Wastes at the Land Surface

Since no previous measurements are available on which to accurately calculate infiltration rates, a monitoring program will be established for this purpose. However, a preliminary evaluation can be made. Regional data are gathered on precipitation and evaporation from free-water surfaces. It is estimated from the amount of water used by the industry that about 2,000 acre-feet per year of waste water is discharged to the pond. A water budget analysis is used to estimate infiltration. Infiltration is estimated to be about 1,950 acre-feet per year, or almost 100 feet per year over each acre of the pond.

Step 8 — Evaluate Mobility of Pollutants from the Land Surface to the Water Table

There are no significant restricting layers present above the water table to obstruct downward percolation of recharged waste water. There are no field data in the region on the mobility of pollutants in this type of waste.

However, sodium and chloride are generally highly mobile in such situations. Studies in similar areas also reveal that arsenic, cadmium, and chromium may be mobile. On the other hand, barium and silver are not expected to be mobile due to chemical precipitation above the water table.

Step 9 — Evaluate Attenuation of Pollutants in the Saturated Zone

This step is necessary in order to properly determine the location of monitor wells to be drilled near the percolation pond. Physical factors important in the analysis for this step are the water budget of the area, slope of the water table, transmissivity of aquifer materials, and dynamics of groundwater flow. The most valid data are derived from previous pollution studies in other areas of similar hydrogeology. Waste plumes for comparable hydrogeologic situations and for these waste percolation rates indicate detectable salinity increases in the aquifer for a distance of only about 1/2 mile downgradient of the source after 20 years of operation.

Step 11 — Evaluate Existing Monitoring Programs

There are no existing monitoring programs near this site.

Step 12 — Establish Alternative Monitoring Approaches

Analysis of the hydrogeologic framework, waste characteristics, and disposal method indicates that monitoring at the land surface, in the vadose zone, and in the saturated zone is necessary. Alternatives are involved primarily with monitoring in the vadose zone and in the saturated zone. The most effective methods are chosen from a companion report (Everett et al., 1976).

LAND SURFACE MONITORING. Daily precipitation and evaporation rates are measured onsite by use of a standard U. S. Weather Bureau raingage, a Class A land pan, and a floating pan in the pond. In order to estimate evaporation from the free-water surface, corrections are necessary for salinity. The waste flow is continually measured at the inlet to the pond by a propeller type meter installed in the discharge pipe.

Because of the large fluctuations in chemical quality of the discharge stream, an electrical conductivity recorder is installed on the discharge pipe at the pond inlet. This record allows continuous monitoring of the electrical conductivity of the waste discharge. Composite samples of the waste discharge are collected for determination of trace metal content. Weekly composites of the waste discharge samples collected at 4-hour intervals are sufficient to characterize seasonal variations in chemical quality. Monthly samples of pond water are collected in order to evaluate significant differences in chemical quality between the waste discharge and pond water. The primary differences are due to dilution by precipitation and chemical reactions caused by exposure of the waste water to the atmosphere and sunlight in the open pond.

VADOSE ZONE MONITORING. As some trace metals in water percolating from the pond would likely be removed by sorption, chemical precipitation, and other processes, the percolate and geologic materials should be sampled. Soil-water samplers are placed in access holes drilled by power auger beneath the pond. Three alternatives, consisting of 5, 10, and 20 holes, are considered for soil-water sampler emplacement. Three samplers are emplaced in each hole at depths of 5, 10, and 15 feet beneath the land surface depending on the actual depth to the water table. Group seals are used to separate the samplers in each hole. During drilling, the access holes are logged by the junior-level individual and samples of subsurface materials are taken at 2-foot intervals. Exchangeable cations, cation exchange capacity, electrical conductivity, and pH of the saturation extract are determined on selected samples. Percolate samples are taken from the soil-water samplers on a monthly basis and electrical conductivity, pH, arsenic, cadmium, chromium, barium, and silver contents are determined.

SATURATED ZONE MONITORING. As there are no existing wells near the pond, a number of monitor wells are necessary. Prior to the selection of drilling sites, a surface resistivity survey is conducted to delineate the zone of polluted groundwater. Since much of the salinity is due to chloride, and chloride is mobile in this soil-groundwater system, the high salinity zone should generally delineate the maximum extent of polluted groundwater. Other pollutants are generally less mobile and occupy smaller zones in the groundwater. It is estimated that the zone of polluted groundwater extends over 1/2 mile downgradient from the ponds.

From five to ten monitor wells are considered for installation by the cable-tool method. Eight-inch diameter holes are to be drilled and 6-inch diameter steel casing installed.

Under Alternative A, two wells would be located immediately adjacent to the pond in the downgradient direction. One well would be drilled 500 feet upgradient of the pond. One well would be drilled 500 feet and another 2,000 feet downgradient of the pond. Both of the downgradient wells are within the plume delineated by the geophysical survey. Under Alternative B, two upgradient wells would be drilled, at 500 feet distance, three wells near the pond, and five wells from 500 to 2,000 feet downgradient. Wells near the ponds are 50 feet deep and perforated from 20 to 50 feet. Upgradient and downgradient wells are 100 feet deep and perforated from 20 to 100 feet. After development and pump testing for 24 hours, the monitor wells are sampled each month after 24 hours of continuous pumping. A portable submersible pump is purchased for use in all of the monitor wells. The water samples are analyzed for the major inorganic chemical constituents and the five trace metals.

Step 13 — Select and Implement the Monitoring Program

Given the alternatives from Step 12, costs are derived from Everett et al. (1976). A preliminary investigation of hydrogeology, existing water quality, and characteristics of industrial wastes is conducted to meet the requirements of Steps 3 through 6. The junior-level individual spends two weeks at $1,250 and the senior-level individual one week at $940. The preliminary study thus costs $2,190.

LAND SURFACE MONITORING. The costs of a recording precipitation gage, land pan, floating pan, and flow meter are $200, $150, $200, and $100 respectively, including installation. The electrical conductivity instrument costs $700. The annual cost for maintaining these devices is $1,000. Sample retrieval from the waste discharge by the junior-level individual requires 1 day per month and costs $1,200 per year. Analytical costs for electrical conductivity (Everett et al., 1976, Table 14) are $3 per sample. Everett et al. (1976, p 114) list a group rate for analysis of drinking water trace elements. Five of the 12 trace constituents listed are analyzed at a group rate of $25. Analytical costs for the waste discharge are $1,460 per year.

Collection of monthly pond samples is by small boat, requires one-half day per month by the junior-level individual and costs $600 per year. Analyses of the monthly pond samples for the same constituents as are in the waste discharge costs $340 per year. Supervision by a senior-level professional requires 1 week per year or $940. Checking chemical analyses and tabulating results by a junior-level individual requires 2 weeks at $1,250 per year.

Total one-time costs are $1,350 for equipment. Annual costs are $1,000 for maintaining equipment, $1,800 for sample collection, $1,800 for chemical analyses, and other personnel costs are $2,190. Total annual costs are thus $6,790.

VADOSE ZONE MONITORING. Costs for drilling and pressure-vacuum soil-water sampler installation, logging, sampling of geologic materials, chemical analyses of geologic materials, sampling of percolate, and chemical analyses of percolate for the three alternatives (A, 5 holes; B, 10 holes; and C, 20 holes) are given in Table 5. Costs of 8-inch diameter augered holes are determined from Everett et al. (1976, Figure 6). Five holes are $50 per hole, 10 holes are $45 per hole, and 20 holes are $40 per hole. Due to the low density of holes in this example these values are extrapolated from the data on Figure 6 of Everett et al. (1976). Soil-water samplers cost $70 for each hole and one service kit costs $30. Geologic logging and sampling require 1 day for five holes, 2 days for 10 holes, and 4 days for 20 holes, all by the junior-level individual. Chemical analyses of subsurface materials are performed on samples at 5-foot depth intervals, including

TABLE 5. COSTS FOR MONITORING THE VADOSE ZONE

COST COMPONENTS	Alternatives (cost in dollars) A	B	C
One-time Costs			
Drilling and Sampler Installation (including sampler)	630	1,180	2,230
Geologic Logging and Sampling Materials	130	250	380
Chemical Analyses of Materials	500	880	1,600
TOTAL	1,260	2,310	4,210
Annual Costs			
Sampling of Percolate	130	250	380
Chemical Analyses of Percolate	5,400	9,720	17,280
TOTAL	5,530	9,970	17,660

one at the land surface. Cation exchange capacity is $11 per sample from Everett et al. (1976, p 112). Electrical conductivity of the saturation extract is $5.50 per sample from Everett et al. (1976, p 112). The pH of the saturation extract is $2.50 per sample from Everett et al. (1976, p 112). The exchangeable cations are $12 per sample from Everett et al. (1976, p 113). In this case a special group rate of $25 per sample is used. The determinations are discounted to $22 per sample for 25 samples, $20 per sample for 50 samples, and $18 per sample for 100 samples.

Sampling of percolate requires 1 day per month for 5 holes, 2 days for 10 holes, and 3 days for 20 holes, all by the junior-level individual. Costs for analytical determinations of the five trace metals in the percolate are $25 per sample. The trace metals were selected from the 12 listed by Everett et al. (1976, p 114) and a special group rate was applied. Electrical conductivity and pH (Everett et al., 1976, Table 14) are $3 each. A special group rate for all of these determinations of $30 is applied. Chemical analyses for monthly percolate samples are $30 per sample up to 30 samples, $27 per sample for 30 samples, and $24 per sample for 60 samples.

SATURATED ZONE MONITORING. The cost of the surface resistivity survey is determined from Everett et al. (1976, Table 6). The depth to top of the plume is 20 feet and the plume is estimated to be 50 feet thick. The areal extent of the plume is estimated at 50 acres. Based on an electrode spread of 100 feet, six surveys totaling about 18 hours would be required. At $80 per hour, the total cost is about $1,400.

For Alternative A, two monitor wells are drilled near the pond to a depth of 50 feet and the remaining three wells are 100 feet deep. For Alternative B, three monitor wells are 50 feet deep and the remaining seven are 100 feet. Monitor-well drilling costs are calculated from Everett et al. (1976, Figure 19). A 6-inch casing is necessary to permit installation of a 50-gpm capacity pump at the estimated lift of 60 feet (Everett et al., 1976, Table 11). Well drilling costs, including casing and well development, are about $2,600 each for the 100-foot deep monitor wells and $1,700 each for the 50-foot deep monitor wells. Logging requires 1 day of the junior-level individual's time for five wells and 2 days for ten wells. The logging cost is $125 for five wells and $250 for ten wells.

Twenty-four-hour pump tests are run on each monitor well at a cost of $20 per hour exclusive of the junior-level individual's time. His time for pump tests, tabulating and plotting results, and interpretation is 4 days per well. Costs for pump tests including the junior-level individual's time are $980 per well. Chemical analyses are made for pumped water during the pump test. The major inorganic chemical constituents are determined at $12 per sample (Everett et al., 1976, p 114) and five trace metals are run at $25 per sample (Everett et al., 1976, p 114). A group rate is applied for five of the 12 drinking water trace element determinations. Chemical analyses are thus $37 per sample, or $185 for Alternative A and $370 for Alternative B.

A portable 2-hp submersible pump costs $500 (Everett et al., 1976, Table 11). Eighty feet of cable are an additional $70 (Everett et al., 1976, Figure 26). Sample retrieval requires 5 days of pumping per month for five monitor wells, and 10 days for ten monitor wells at $50 per day. Annual pumping costs are thus $3,000 for Alternative A and $6,000 for Alternative B. The monthly samples of water from the monitor wells are analyzed for the major inorganic chemical constituents and the five trace elements. Chemical analyses for the monitor well water are $37 per sample, as determined previously.

Time required of the junior-level individual for sampling, checking chemical analyses, and tabulating results is 1 month for Alternative A and 4 months for Alternative B. Supervision by the senior-level individual is 1 week for Alternative A and 2 weeks for Alternative B. Table 6 summarizes costs for monitoring the saturated zone.

In order to select the most cost-effective alternatives, consideration is given to impacts of groundwater pollution on subsequent groundwater use. In this case, no groundwater is presently used, but it is projected that groundwater will be used for municipal purposes in 20 years. Arsenic, cadmium, and hexavalent chromium pose a distinct health threat to groundwater used for drinking purposes. The high salinity, chloride, and sodium contents could easily render groundwater near the disposal site unusable.

TABLE 6. COSTS FOR SATURATED ZONE MONITORING

COST COMPONENTS	Alternatives (cost in dollars) A	B
One-time Costs		
Surface Resistivity Survey	1,400	1,400
Drilling, Casing, and Development for Monitor Wells	11,200	23,300
Logging, Pump Testing, and Chemical Analyses	5,210	10,420
Portable Submersible Pump	570	570
TOTAL	18,380	35,690
Annual Costs		
Pumping for Monthly Sample Retrieval	3,000	6,000
Chemical Analyses of Monthly Samples	2,220	4,440
Personnel	3,440	6,880
TOTAL	8,660	17,320

Secondly, the net worth of the industrial product has to be considered. A final consideration is the money available for monitoring the site. Consideration of all these factors, in conjunction with experience in monitoring groundwater pollution, leads to selection of Alternative B for the vadose zone and Alternative A for the saturated zone.

SUMMARY. Total costs for the program selected are given in Table 7.

TABLE 7. TOTAL COSTS FOR MONITORING INDUSTRIAL WASTE PERCOLATION POND

Cost Components	Monitoring Costs (dollars) One-Time	Annual
Preliminary Investigation	2,190	---
Surface Monitoring	1,350	6,790
Vadose Zone Monitoring	2,310	9,970
Saturated Zone Monitoring	18,380	8,660
TOTAL	24,230	25,420

SOLID WASTE LANDFILLS

The area selected to monitor above the water table includes the landfill itself. In many areas tens of feet of soil and geologic materials have been excavated and replaced by solid wastes comprising the landfill. Sampling and analysis are done to determine the composition of the solid materials emplaced in the landfill, the leachate, and percolate in the vadose zone. If impermeable layers underlie the landfill, vadose zone monitoring may be necessary for distances of several hundred feet laterally from the landfill. Sampling of leachate and shallow groundwater is almost always necessary. Groundwater should generally be monitored for a distance of at least several hundred or several thousand feet from the landfill. Sampling of topsoil and geologic materials for toxic constituents may be necessary.

Land Surface Monitoring

Land surface monitoring encompasses an inventory of the volumes or weights of solid materials emplaced in the landfill. Rainfall and evapotranspiration rates must be known and can often be extrapolated from nearby meteorological stations. Compilation of these data allows calculation of the potential leachate production. The moisture characteristics of the solid wastes should be monitored, and usually shallow holes drilled by augering will suffice. It is important to determine if aerobic or anaerobic decomposition is occurring at specific locations. This depends on the moisture content of the landfill, depth to groundwater, groundwater inflow, and other factors. Detection of leakage is a prime concern for landfills with liners installed to limit percolation.

The chemical composition of solid materials in the landfill and in the leachate must be determined. The composition of landfill materials can often be broadly characterized, whereas detailed sampling of leachate is often necessary to determine its composition. The frequency of leachate sample collection depends highly on the frequency and rate of rainfall. Rather than a uniform sampling frequency, samples should be collected at intervals based on the rate of leachate production. The approximate volumes and quality of other sources of recharge and groundwater inflow must also be determined.

Leachate analyses should include the major inorganic chemical species, nitrogen forms, total dissolved solids, pH, and oxidation potential. The primary metals in the landfill that may be leached should be determined. Examples are iron, manganese, barium, chromium, lead, selenium, and zinc.

Vadose Zone Monitoring

Monitoring in the vadose zone includes determination of percolate quality, flow rate, attenuation characteristics of soil and geologic materials, and chemical analyses of solid materials. In areas of low rainfall, little or no leachate will be produced and sampling in the vadose zone may be unnecessary. Test drilling is often necessary in or near landfills because of a lack of information on materials comprising the vadose zone. Drilling of test holes can provide geologic information on the vadose zone and permit the installation of devices for water sample retrieval. Neutron probes can be effectively used to trace water movement above the water table when necessary. Analytical determinations for percolate quality include the major inorganic chemical constituents, nitrogen forms, selected trace metals, particularly iron and manganese, and oxidation potential. Cation exchange capacity, electrical conductivity, pH, and exchangeable cations are important analyses for soil and geologic materials.

Saturated Zone Monitoring

Wells have often been successfully used in monitoring groundwater pollution beneath or near solid waste disposal sites. In areas of moderate to heavy rainfall, significant amounts of leachate are produced. Most or all of the leachate can subsequently percolate to the groundwater. Monitor wells may be installed and sampled. Monthly sampling appears to be sufficient in most cases. Several existing large-capacity wells in the area should also be periodically sampled. A portable submersible pump can be used to pump water for sampling from a number of test wells in one area, thus avoiding the cost of equipping each well with a permanent pump. Analyses of water from wells are similar to those for percolate quality, but can be modified to reflect the water usage in the area. As leachate is generally high in total dissolved solids, surface resistivity surveys can be used in some cases to delineate the extent of polluted groundwater. In general the water table must be shallow and groundwater conditions fairly well understood. Remote sensing can provide information in areas where the water table is shallow, and/or the leachate is forced to the land surface.

SOLID WASTE LANDFILL EXAMPLE

Step 2 — Identify Pollution Sources, Causes, and Methods of Waste Disposal

In this example a 20-acre landfill in the southeastern United States is to be monitored. The landfill has been in operation for 10 years. The landfill receives solid refuse from a medium-sized city and a plastic liner has been installed to limit percolation. The other potential sources of groundwater pollution include small amounts of fertilizers, scattered septic tanks and polluted rainfall. Evaluation of these other sources indicates that they are generally insignificant.

Step 3 — Identify Potential Pollutants

The liner has been graded toward a central point so that leachate samples can be collected. Previous analyses of grab samples obtained from a sump drain have indicated that the quality of the leachate is similar to that to be expected from such a source. The leachate contains high total dissolved solids concentrations, some organic chemicals, and selected trace elements. Materials placed in the landfill indicate that chloride, nitrogen forms, potassium, calcium, sulfate, iron, manganese, lead, silver, chromium, cadmium, and zinc are of concern.

Step 4 — Define Groundwater Usage

Wells in this rural area are used primarily for domestic purposes, however, small amounts of groundwater are used for crop irrigation. Of all groundwater pumpage, about 80 percent is for domestic use and the remainder for irrigation.

Step 5 — Define Hydrogeologic Situation

The average annual rainfall in the area is 40 inches. Alluvial deposits about 50 feet thick overlie hundreds of feet of permeable limestone. Both the alluvium and limestone are developed aquifers in the region and beneath the landfill the hydraulic head is lower in the limestone than in the alluvium. A number of water level measurements in wells in the two aquifers are available and indicate the regional direction of groundwater movement. The water table in the alluvium is about 20 feet beneath the landfill and water in the limestone is under artesian pressure. Groundwater in the alluvium tends to move toward a stream about 1 mile downgradient. There is a tendency for downward movement of shallow groundwater into the confined groundwater in the limestone. The extent of the polluted zone in the alluvium has been previously delineated, but the extent of pollution in the lower aquifer is unknown. There are several wells within the polluted zone in the alluvium.

Annual recharge to both aquifers was previously calculated by the U. S. Geological Survey. Annual pumpage from both aquifers in the region is about 20, 000 acre-feet, whereas annual recharge to both aquifers is about 100, 000 acre-feet.

Step 6 — Study Existing Groundwater Quality

Previous studies by the U. S. Geological Survey have delineated the regional groundwater quality. Groundwater in the limestone is calcium bicarbonate in type with total dissolved solids less than 100 ppm. Groundwater in the alluvium has a greater variation in chemical quality than groundwater in the limestone. Alluvial groundwater is generally a sodium-calcium bicarbonate type and total dissolved solids range from about 70 to 500 ppm. Beneath the landfill, groundwater is a sodium bicarbonate-chloride type, with high nitrate, chromium, iron, and manganese contents. Maps are available indicating the regional distribution of total dissolved solids, chloride, and nitrate in both aquifers.

Step 7 — Evaluate Infiltration Potential of Wastes at the Land Surface

Water budget analysis is unnecessary due to the presence of the liner which greatly limits percolation of leachate. The presence of a polluted zone of groundwater beneath the site is ample indication that limited seepage and/or leakage has occurred. There was no inspection of the liner during installation and there has been no monitoring of the liner integrity.

Step 8 — Evaluate Mobility of Pollutants from the Land Surface to the Water Table

Neutron probe moisture logging and soil-water sampling were done in a similar hydrogeologic situation by researchers at a nearby university. This research indicated travel times of leachate to the shallow water table of several weeks to months. Attenuation of bacteriological constituents and some organic chemicals and trace elements was noted. These results could be directly extrapolated to the study area.

Step 9 — Evaluate Attenuation of Pollutants in the Saturated Zone

A surface resistivity survey was previously conducted to delineate the extent of the polluted zone in the alluvium. Several existing wells tap the alluvium, both in and outside of the polluted zone. However, although several nearby wells tap the limestone, no such wells are in the anticipated polluted zone. The extent of the polluted zone determined by resistivity measurements corresponds to high total dissolved solids content. Previous well sampling indicates that high calcium, bicarbonate, and chloride contents also occur in this zone. Several trace metals occur in high concentration, however, over a smaller zone. This is believed to be due primarily to precipitation and adsorption.

Step 11 — Evaluate Existing Monitoring Programs

Existing programs in the area of most direct value are related to monitoring in the vadose zone. There is no routine program for leachate sampling at the landfill, nor is there any for routine well sampling in the immediate vicinity of the landfill.

Step 12 — Establish Alternative Monitoring Approaches

Consideration of information developed in the previous steps indicate that no additional monitoring in the vadose zone is necessary. Routine sampling of leachate, well drilling, and water sampling from wells are deemed necessary. Hydrogeologic judgment is used to select the most effective monitoring program in each case.

To determine cost-effectiveness, consideration is given to water use in areas that could be impacted by the waste disposal. Most of the water use is for domestic purposes, and due to the rural nature of the area, groundwater is considered the sole source of the drinking water supply. Nitrate, chromium, and cadmium pose a potential threat to health for persons drinking water from wells in the polluted zone. The maximum extent of the polluted zone is believed to not exceed 1,000 acres for the alluvium. For the limestone the maximum extent is believed to not exceed 200 acres. Within these areas at present, only three wells are used for drinking water purposes, serving a total of ten people. Given the rural nature of the area and projected land use, this situation should not greatly change in the next 30 years.

Inorganic chemical constituents may also pose a health threat. Chloride, sulfate, calcium, iron, and manganese may degrade drinking water. Increased total dissolved solids from pollution may decrease crop yields in a small area near the pond.

LAND SURFACE MONITORING. As part of the recommended monitoring program, leachate samples will be collected daily for electrical conductivity determinations. In turn, these samples will be composited weekly for analysis. The major inorganic chemical constituents, total nitrogen, COD, dissolved oxygen, iron, manganese, lead, silver, chromium, cadmium, and zinc will be determined.

SATURATED ZONE MONITORING. Monitoring includes routine sampling of water from existing wells and drilling of additional wells in the limestone for water sampling. Three monitor wells are to be drilled into the limestone by the cable-tool method. These wells are 300 feet deep and perforated from 100 to 300 feet. The water level in the wells is only 60 feet below the landfill due to the artesian condition existing in the limestone aquifer. Hole diameter is 8 inches and casing diameter is 6 inches. After development, 1-week pump tests are conducted and permanent submersible pumps of 25 gpm capacity at 75-foot lift are installed. The pump tests provide information on the hydraulic connection of the upper and lower aquifer, as well as vertical permeability of the confining bed for the confined aquifer. The electrical conductivity and temperature of the water discharged are frequently measured. On this basis, five water samples are chosen for routine chemical analyses for each well, including the seven trace metals listed previously.

For the first year, monthly samples are collected from these three wells and five previously existing wells. The major inorganic chemicals are determined, including iron, manganese, chromium, and cadmium. Lead, silver, and zinc are deleted from the program because of attenuation characteristics of materials above the water table. After the first year, quarterly samples from five wells are sufficient.

Step 13 — Select and Implement the Monitoring Program

As the approach has already been determined in Step 12, this step primarily involves determination of costs. A preliminary investigation is conducted to meet the requirements of Steps 3 through 6 including collection and interpretation of records on groundwater conditions, water quality, landfills, and leachate. The junior-level individual spends 1 month at a cost of $2,500. The senior-level individual spends 1 week at a cost of $940. The cost of this phase is thus $3,440.

LAND SURFACE MONITORING. A portable meter for daily electrical conductivity determinations costs $350. Leachate samples are taken by the caretaker at no additional expense. Major inorganic chemical constituents determinations are $12 per sample (Everett et al., 1976, p 114). The seven trace elements determinations are $30 per sample based on a group rate derived from the 12 drinking water trace elements from Everett et al. (1976, p 114). Dissolved oxygen determinations are $5 per sample from Everett et al. (1976, Table 14). Chemical oxygen demand determinations are $10 per sample from Everett et al. (1976, Table 15). Total nitrogen determinations are $10 per sample from Everett et al. (1976, Table 14).

Leachate analyses on a weekly basis are $67, or $3,480 during the first year. Checking chemical analyses and plotting results during the first year requires 1 month of time by the junior professional at a cost of $2,500. Supervision by a senior level professional during the first year totals 1 week at a cost of $940. After the first year, weekly samples are composited and analyzed monthly. Thus, analytical costs after the first year are $804 per year. Personnel time after the first year includes 2 weeks for the junior-level individual at $1,250 and one-half week by the senior-level individual at $470.

VADOSE ZONE MONITORING. Review of existing studies requires 2 weeks by a junior professional at $1,250 and 1 week by a senior professional at $940. Total one-time costs are $2,190.

SATURATED ZONE MONITORING. Drilling costs are about $3,800 each for 8-inch diameter holes with 6-inch steel casing (Everett et al., 1976, Figure 20 - for consolidated formations). The pump tests of 1 week duration for each well are conducted at a cost of $3,500 per well, exclusive of geologist time. The junior professional spends 1 day logging cuttings and 2 weeks for pump tests (including interpretation) on each well. Personnel costs for well-logging, pump testing, and aquifer analysis are $1,460 per well.

Major inorganic chemical constituents are determined at $12 per sample from Everett et al. (1976, p 114). Seven trace elements are determined at $30 per sample from Everett et al. (1976, p 114), applying a special group rate. Chemical analyses are $42 each for the five water samples collected during the pump test for each well. Three 1-hp submersible pumps with 25-gpm capacity at the projected 75-foot lift cost $300 each. Three hundred feet of cable for the pumps costs $240 (Everett et al., 1976, Figure 26). Supervision by the senior-level individual for this phase is 3 weeks at a cost of $2,830. Total one-time cost for this phase of the program is $29,070.

Water samples are collected at no pumping cost, as the monitor wells are also used for water supply in the area. Sampling can be done during normal operation of the pump by the user. Major inorganic chemical constituents are determined for $12 per sample (Everett et al., 1976, p 114). The four trace metals are analyzed at a cost of $17 per sample, applying a discount rate to that given for the 12 drinking water trace constituents from Everett et al. (1976, p 114). Costs for the water analyses are $29 per sample. Monthly analyses during the first year total $2,784. Sample collection, checking chemical analyses, and tabulating results require 1 month of the junior-level individual's time, at a cost of $2,500. Supervision by the senior-level individual requires 1 week at $940.

After the first year, analytical costs are $145 per quarterly sampling round, or $580 per year. The junior-level individual spends 2 weeks annually after the first year at a cost of $1,250. The senior professional spends one-half week at a cost of $470.

SUMMARY. Total monitoring costs are summarized in Table 8.

TABLE 8. MONITORING COSTS FOR SOLID WASTE LANDFILL

	Cost (dollars)		
Cost Component	One-Time	Annual First Year	Annual Subsequent Years
Preliminary Investigation	3,440	---	---
Land Surface Monitoring	350	6,920	1,720
Monitoring Vadose Zone	2,190	---	---
Monitoring Saturated Zone	30,870	6,224	2,300
TOTAL	36,850	13,144	4,020

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APPENDIX

METRIC CONVERSION TABLE*

Non-Metric Unit	Multiply by	Metric Unit
inch (in)	25.4	millimeters (mm)
feet (ft)	0.3048	meters (m)
miles	1.60934	kilometers (km)
acres	0.404686	hectares (ha)
gallons (gal)	3.7854	liters (1)
pounds per square inch (psi)	0.0680460	atmospheres (atm)
parts per million (ppm)	1	milligrams per liter (mg/1)
gallons per minute (gpm)	3.7854	liters (1) per minute

*English units were used in this report because the data obtained were not available in metric units.

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15. SUPPLEMENTARY NOTES

This is one of 5 final reports in a series of 11 documents prepared on monitoring groundwater quality.

16. ABSTRACT

This report is designed to show by example site-specific procedures for monitoring various classes of groundwater pollution sources. The first of five case histories of actual or potential groundwater pollution are presented with the monitoring techniques and their efficacy. The case histories cover brine disposal in Arkansas, plating waste contamination in Long Island, New York, landfill leachate pollution in Milford, Conneticut, an oxidation pond near Tucson, Arizona, and multiple-source nitrate pollution in the Fresno-Clovis, California, metropolitan area. The report concludes with hypothetical illustrative examples for developing and selecting monitoring alternatives based on a cost comparison between other alternatives and hydrologic judgment. The examples illustrated cover agricultural return flow, septic tanks, percolation ponds, and landfills.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Groundwater Monitoring Water quality Water pollution Water resources Water wells Aquifers	Plating waste contamination Landfill leachate Oxidation ponds Brine disposal Nitrate pollution Septic tanks	08H 13B

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