logic environment and environmental safety; (2) specific areas where better knowledge of waste—hydrogeologic interrelations may be needed; and (3) recommendations concerning present practices, or as necessary, for acquiring the information required to evaluate present practices.

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DECISION MAPPING—TOOL FOR UNDERGROUND WASTE MANAGEMENT

Deep-well disposal is one possible method for disposing of waste liquids. Serious concern must be given to the degrading effects on the subsurface environment that such a practice may involve. Yet probably there are geohydrologic basins suitable for injection of waste. At the same time, need for the detailed, and probably very costly, investigations of such basins that must precede injection should not be minimized.

The attractiveness of deep-well disposal usually is related to the favorable costs for injection compared with other disposal methods, such as high-temperature incineration, encapsulization, or others. Presuming that a given sedimentary unit has been evaluated thoroughly and found quantitatively and qualitatively suitable for waste injection, one still must evaluate whether it is more economically desirable to have each operator drill his own disposal-well facility, or whether it is more advantageous to collect the waste of several operators for disposal in a common well or wells. The economic scale advantages of centralized processing must be balanced against the costs of transporting the waste to the centralized facility. The optimal configuration of a centralized disposal system depends on the relative level of these costs. An additional advantage of centralized waste disposal is the greater effectiveness with which local, state, and federal development and operating regulations may be enforced.

We have developed a general mathematical model which allows rough optimization of a multisource, variably distributed system based on limited data. The model is expressed in terms of a decision map which indicates the optimal configuration to serve distributed sources of waste and illustrates the sensitivity of the configuration to important parameters, such as mean-source separation and waste load, which characterize the source population. Application of this economic model provides additional input to the waste-management authority who must integrate these data with environmental factors to produce a final recommendation.

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FEASIBILITY STUDY OF LIQUID-WASTE INJECTION INTO AQUIFERS CONTAINING SALT WATER, WILMINGTON, NORTH CAROLINA

An experimental system to inject liquid industrial waste into deeper sedimentary aquifers containing salt water was installed by Hercules, Inc., at Wilmington, North Carolina, in the spring of 1968, under a permit issued by the State Board of Water and Air Resources. The initial experimental system consisted of 1 injection well and 3 observation wells completed between depths of 850 and 1,050 ft, and 1 observation well completed in the next higher aquifer at a depth of about 700 ft.

The injection zone is an aquifer consisting of sand layers and some thin beds of limestone interbedded with silty sand and sandy silt. The aquifer has low permeability and productivity. The water in the aquifer is salty, with a natural artesian head of about 65 ft above land surface.

The system was placed in operation in May 1968, injecting the by-product from the manufacture of dimethyl terephthalate (DMT). The liquid, deaerated and filtered through 200-μ mesh screen, consisted of water containing acetic and formic acids with some methanol and having a pH of about 4. The maximum injection rate was about 200 gal/minute.

The pressure in the injection and observation wells rose sharply during the first few months of operation. By September 1968, the waste had passed the observation wells which were only 150 ft from the injection well, making the system obsolete for observing the rate and direction of waste movement through the aquifer. By June 1969, the injection well had become plugged with sand, and a new system was designed.

A new injection well and a part of the new observation-well system were completed and placed in operation in January 1971. One of the initial observation wells also was used for injection of part of the waste. Additional observation wells were added, and in 1972 the monitor system consisted of 6 wells completed in the injection zone at distances of 1,500–2,000 ft from the points of injection, 3 wells completed in the 700-ft zone, and 1 well completed in the 300-ft zone. The monitor system and data-collection program have provided much useful information on injection of this type of waste in relatively shallow sedimentary rocks.

The long-term feasibility of such a system appears doubtful, as the aquifer does not appear to be sufficiently permeable to accept the waste at a continuing rate of 200 gpm. Considerable difficulty also has been encountered in maintaining the injection and observation wells.

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HYDROGEOLOGY OF LIQUID-WASTE STORAGE IN FLORIDA

Restrictions on surface-waste disposal practices have caused many to look to subsurface storage of liquid waste in deep saline aquifers as a most practicable and economical alternative. Also, temporary subsurface storage of excess storm runoff and treated sewage as potential sources of fresh water to augment supplies in water-short areas is being investigated. Liquid wastes are being injected into deep, saline, carbonate aquifers at sites in the western panhandle and the southern peninsula of Florida. Additional sites are being considered in the central peninsula. The wastes, including acidic, high-oxygen-demand industrial plant effluents and variable temperature and density, secondary sewage plant effluents, and oil-field brines, are injected into permeable saline zones separated from shallower freshwater aquifers by one or more confining layers which have very little or practically no permeability. There are distinctive differences in stratigraphy between the panhandle and the peninsula of Florida. Hence, the geologic and hydrologic environments for subsurface waste storage also are different.

At a site near Pensacola, in western Florida, acidic liquid waste has, for nearly 10 years, been injected into a 1,400–1,700-ft deep, moderately permeable, carbonate zone of late Eocene age, separated from shallower freshwater aquifers by a widespread, 200-ft thick, nonpermeable, confining, plastic clay layer of middle Oligocene age. The calculated pressure effects of this injection now extend outward more than 30 mi. The waste has improved the permeability of the injection zone near the injection well by dissolution of the limestone. There is no evidence that the confining layer or the carbonate aquifer above this confining layer have been adversely affected by the injection.

In the south part of peninsular Florida, the saline-water-bearing parts of the thick Cretaceous and Tertiary section utilized for waste storage consist almost entirely of carbonate rocks, in part anhydritic. Nonpermeable rock separates the highly permeable, commonly cavernous, injection zones from both shallower and deeper permeable zones. Secondary sewage plant effluent has been injected for about 2 years into a very cavernous limestone of early Eocene age at a depth of about 3,000 ft in the Miami area, with only a slight bottomhole pressure increase during injection. Neither the quality of the water nor the pressure in the overlying permeable zones have been affected by the injection. Hot acidic waste injected at a depth of about 1,500 ft in northwestern Palm Beach County migrated upward to a shallower permeable zone. The injection well was subsequently drilled deeper and cased to about 2,000 ft to confine the waste to the injection zone.

A study of the stratigraphy of south peninsular Florida has delineated 5 discrete zones of high transmissivity in cavernous carbonate beds of Late Cretaceous through Eocene age. Cavities whose maximum vertical dimensions are as great as 90 ft have been found in wells. Zones of high transmissivity are in Upper Cretaceous beds between depths of 5,000 and 6,000 ft and in Paleocene beds between depths of 3,500 and 4,500 ft. A widespread zone in the basal Eocene lies between depths of 2,500 and 3,300 ft in south peninsular Florida, and farther north a zone higher in the Eocene section is at depths of 1,500–2,000 ft. Even younger Eocene zones occur between depths of 1,100 and 1,300 ft in and north of the Lake Okeechobee area.

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SHORT-TERM EFFECT OF INJECTION OF TERTIARY-TREATED SEWAGE ON CONCENTRATION OF IRON IN WATER IN MAGOTHY AQUIFER, BAY PARK, NEW YORK

High concentration of iron in groundwater poses problems both in the operation of wells and in the suitability of the water for many uses. As part of an experimental deep-well recharge program at Bay Park, New York, the U.S. Geological Survey, in cooperation with the Nassau County Department of Public Works, has been studying the geochemical effects of injecting tertiary-treated sewage into the Magothy aquifer, Nassau County's primary water-supply source. Of particular interest are changes in the iron concentration that have resulted from the injection.

Iron concentrations of the injected treated sewage and the native water are relatively low—a range of 0.1–0.4 mg/l (milligrams per liter) for the former and an average of 0.24 mg/l for the latter. However, the iron concentration of the mixed-water (native and injected water) system has exceeded 3 mg/l.

Detailed sampling was made at observation wells 20 and 100 ft from the recharge well. The iron concentration at the 20-ft well began to increase coincidently with the arrival of the injected water front. The iron concentration peaked at 3 mg/l after 3 days and then decreased. After 10 days the iron concentration stabilized at about 0.5 mg/l.

The primary source of iron is pyrite, which is native to the Magothy aquifer. On injection, the reducing environment around the injection well is displaced by a progressively more oxidizing one. The initial response to this change is the oxidation of pyrite, which releases Fe^{+2}, SO_4^{-2}, and H^+ to solution:

$$FeS_2 + 8H_2O = Fe^{+2} + 2SO_4^{-2} + 16H^+ + 14e. \quad (1)$$

Eventually ferric hydroxide precipitates and the Fe^{+2} concentration decreases:

$$Fe^{+2} + 1/4 O_2 + 5/2 H_2O = Fe(OH)_{3(s)} + 2H^+. \quad (2)$$

These reactions account for the iron peak observed at the 20-ft well. Although the reactions agree with those predicted from changes in the Eh-pH conditions in the aquifer, the presence of other constituents in the reclaimed water seems necessary for the iron peak because the iron peak did not occur when water from the public supply was injected.

The iron concentration at the 100-ft well increased to about 2 mg/l after 7 days of injection and then stabilized at this concentration for at least 3 weeks. As the injectant had not completely displaced the native water at the 100-ft well within this time, it is not known whether the concentration would decrease at this well with prolonged injection as it did at the 20-ft well. Also, application of a pyrite-oxidation model to explain any further pickup of iron by the injected water beyond a 20-ft radius is tenuous, as dissolved oxygen in the injectant is reduced within 20 ft of travel and, therefore, is not available to oxidize pyrite beyond that point. Some information about the increase in iron concentration beyond the 20-ft observation well should be forthcoming from a 6-month injection test now being made.

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RADIOACTIVE- AND CHEMICAL-WASTE TRANSPORT IN GROUNDWATER AT NATIONAL REACTOR TESTING STATION, IDAHO: 20-YEAR CASE HISTORY AND DIGITAL MODEL

Industrial and low-level radioactive liquid wastes at the National Reactor Testing Station (NRTS) in Idaho have been disposed to the Snake River Plain aquifer since 1952. The movement and distribution of these wastes have been monitored. The aquifer is extremely large and has a high transmissivity. The total discharge to the aquifer at NRTS has averaged about 1×10^9 gal/year and contained relatively small quantities of tritium, strontium-90, cesium-137, cobalt-60, chloride, hexavalent chromium, various acids and bases, and heat. Tritium and chloride have dispersed over a 15-sq-mi area of the aquifer in low but detectable concentrations and have migrated as much as 5 mi downgradient from discharge points. A remarkable degree of lateral dispersion has rapidly diluted and spread the waste products. The movement of cationic waste solutes, particularly strontium-90 and cesium-137, has been significantly retarded due to sorption phenomena, principally ion-exchange.

Digital modeling techniques have been applied very successfully to the analysis of this complex waste-transport system by numerical solution of the coupled equations of groundwater motion and mass transport. The model includes the effects of convection transport, flow divergence, two-dimensional hydraulic dispersion, radioactive decay, and reversible sorption. The 20-year transport and distribution history of waste chloride and tritium has been successfully simulated by the model.