Distribution of nitrogen and chloride has indicated that the gradual increase in dissolved-solids concentrations in the Marine Corps wells is caused by the use of treated sewage effluent on a local golf course. Areal and vertical mapping of the degraded water indicates that the water supply at the Marine base will be affected if no measures are taken to avoid contamination.

A digital water-quality model of the aquifer was built to aid in evaluating the effects of several alternative ground-water management practices. The model first was verified by comparison with existing hydrologic data and then used to calculate the water-level and water-quality conditions that might occur in the aquifer within the next 20 years. Model results indicated that by 1991 present sewage-percolation practices would result in dissolved-solids concentrations exceeding 900 mg/l in the Marine Corps well field.

Two of the alternative water-quality management practices that were evaluated with the model are:

(1) The oxidation ponds could be lined to prevent further percolation, and the effluent piped out of the study area. The model indicated that this would cause water-level declines in excess of 70% of the saturated thickness of the aquifer in the vicinity of the Marine Corps well field. This is probably unacceptable.

(2) The percolation of treated sewage effluent could be allowed to continue, and a line of barrier wells could be drilled between the sewage-treatment facility and the Marine Corps well field. The barrier wells would be pumped at a lesser rate than the rate of recharge from the oxidation ponds, to lessen the undesirable effects. The model indicated that by 1987 a constant rate of pumping from the barrier wells would effectively limit the movement of the degraded plume toward the well field. However, by 1991 the increasing quantities of percolation from the oxidation ponds would greatly exceed the barrier pumping rate and the highly concentrated parts of the degraded plume would approach the edge of the Marine Corps well field. Judicious choice of barrier pumping rates would probably extend the effectiveness of the barrier beyond 1987.

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Injection of Acidic Industrial Waste into Saline Carbonate Aquifer—Geochemical Aspects

A section of carbonate rocks that includes several highly permeable cavernous zones filled with saline water underlies the south part of peninsular Florida at depths from 1,500 to 4,500 ft. Because these cavernous zones are capable of yielding or accepting large quantities of fluids, they are used for storage of industrial and municipal liquid waste at several places. One such place is at the south end of Lake Okeechobee near Belle Glade, Florida, where the effluent from a sugar mill and liquid waste from the production of furfural processed from sugar cane bagasse have been injected at depths between 1,500 and 2,200 ft. The waste ranges in temperature from 71 to 103° C, in pH from 2.6 to 4.5, and is highly organic (COD 6,000–26,000 mg/l). Since 1966 more than 800 million gal of this waste have been injected. Injection rates range from 400 to 800 gal/minute at pressures of 30–60 psi at the wellhead. The waste is partly neutralized almost immediately to a pH of 5.5 by dissolution of limestone. Caliper logs show localized patterns of dissolution of the carbonate aquifer. Anaerobic degradation of the organic waste begins near the injection well, as indicated by the presence of hydrogen sulfide, methane, carbon dioxide, and nitrogen.

The waste has moved both upward and laterally in the aquifer system, as detected by water quality changes in monitor wells. Upward movement of altered waste into an overlying brackish-water zone was detected by a 1,400-ft monitor well 75 ft away from the injection well. Lateral movement was detected by a monitor well in the injection zone 1,000 ft away. When upward movement of waste was detected, injection was discontinued and the well was drilled and cased several hundred feet deeper. Data collected since the well was deepened are inconclusive regarding the effectiveness of the increased well depth in restricting the waste to the injection zone. Investigations to date at Belle Glade clearly point up the value of a sound monitoring program.

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Role of Borehole Geophysics in Underground Waste Storage and Artificial Recharge

The optimum utilization of underground space for the emplacement and storage of waste and surface water can be achieved through an understanding of the geohydrologic environment. The emplacement of liquid waste and the artificial recharge of aquifers generally requires the drilling of exploration, injection, and monitoring wells. Some geophysical logs are run on almost all wells drilled for deep disposal. Even more information could be obtained, however, by utilization of all available logging techniques. To date, geophysical well logging has not been applied widely to artificial recharge projects; however, borehole geophysics is being used by the U.S. Geological Survey to study geohydrologic parameters related to recharging the Ogallala Formation on the High Plains of Texas.

Geophysical well logs provide preinjection data necessary for the selection of environments for liquid waste or water storage. Logs provide data on the location, thickness, and lateral continuity of storage zones and confining beds, percent and distribution of total or effective porosity, and the relative magnitude of permeability. Intergranular and fracture porosity can be discriminated by crossplotting acoustic velocity and neutron or gamma-gamma logs. The distribution and orientation of preinjection fractures can be determined by acoustic televiewer logs. Logs provide data on the chemical quality of the native fluids and the mineralogy of the aquifer, which are necessary to predict chemical reactions with injected fluids. The temperature and conductivity of the interstitial fluids may be measured directly and their specific gravity and viscosity may be calculated from log data.

Because aquifers overlying injection zones can be polluted by improper well construction or well failure, geophysical well logs should be used to guide the design, construction, and maintenance of injection and monitoring wells. It is important to answer questions such as: are the casing strings and screens properly installed; are they plugged or corroded; does the grout fill the annular space and is it properly bonded to the casing; and, are there leaks through the casing, between pipe strings, or through the annulus?

After waste injection or artificial recharge has started, logs provide *in-situ* measurements of changes in the system. We have found that an increase or decrease in porosity caused by solution or precipitation in pore spaces or cavities may be detected. This type of information not only explains changes in well efficiency but provides the basis for selecting remedial treatment. Accidental hydraulic fracturing caused by drilling or injection can be the reason for vertical leakage through confining beds, and acoustic televiewer logs can locate these fractures. The distribution and velocity of injected water and the location of chemical or thermal pollution may be determined by means of temperature logs. We have used temperature logs to map the horizontal and vertical distribution of injected fluids. Diurnal thermal changes in injected water provide the basis for measuring the velocity of flow and its change with time.

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RETENTION OF DISSOLVED CONSTITUENTS OF WASTE BY GEOLOGIC MEMBRANES

Clays and shales serve as semipermeable membranes, retarding by varying degrees the passage of the dissolved species with respect to water. The relative retardation by geologic membranes of cations and anions generally present in waste solutions was investigated using a high temperature filtration cell. The solutions were forced with varying hydraulic gradients through different clays and a disaggregated shale subjected to compaction pressures up to 10,000 psi and to temperatures from 20 to 90°C.

The efficiencies measured increased with increase of exchange capacity of the material used and with decrease in concentration of the input solution. The efficiency of a given membrane increased with increasing compaction pressure, but decreased at higher temperatures and higher hydraulic gradients for solutions of the same ionic concentration.

The results further show that geologic membranes are specific in that the degree of retardation is different in different dissolved species. The retardation sequences obtained varied depending on the material used and on experimental conditions. The retardation sequences for monovalent and divalent cations were generally as follows:

$$Li < Na < NH_3 < K < Rb < Cs$$
$$Mg < Ca < Sr < Ba.$$

The retardation sequences for anions at room temperature were variable, but at higher temperatures the sequence was:

$$HCO_3 < I < B < SO_4 < Cl < Br.$$

Monovalent cations generally were retarded with respect to divalent cations at the higher hydraulic gradients. This trend, however, was reversed at the lower hydraulic gradients. Extrapolation of the results to average hydraulic gradients encountered in subsurface formations indicates agreement with data obtained from field investigations which show that divalent cations generally are retarded with respect to monovalent cations.

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SALINE AQUIFERS—FUTURE STORAGE RESERVOIRS FOR FRESH WATER?

In the advanced industrial countries the most favorable, least expensive sites for surface reservoirs are already in use or the land already is preempted for other uses and is unavailable for the storage of water. In addition, there are many flat areas in coastal zones, also underlain by saline aquifers, that are unsuitable for water storage although a surplus of fresh water is available in such areas at certain times of year. The lack of a reliable, year-round supply of water has been a major factor in preventing commercial and residential development in these areas.

The storage of fresh water in slightly saline aquifers has been tried empirically several times with some success. To study the physical process in the laboratory we have constructed and operated several miniaquifers and, simultaneously, have devised some approximate mathematical models. The annual cycle of injection, storage, and withdrawal of the fresh water has been found to be feasible under the idealized assumptions normally found in groundwater hydrology—a horizontal, isotropic, homogeneous aquifer of uniform porosity, transmissivity, and storativity. Laboratory experiments on a single-well system built into a miniaquifer constructed of epoxy-consolidated, uniform blasting sand show that the efficiency of the process, per cycle, increases as the number of cycles increases. Our computational procedure verifies this and has enabled us to change inexpensively and quickly such parameters as density difference, dispersion coefficient, input rate and period, withdrawal rate, storage period, *etc.* The studies show that storage of fresh water in an aquifer that contains brine is feasible, if a sufficient number of cycles is considered. The cost, in terms of irretrievable fresh water, is calculable under these conditions.

Additional studies were and are being made on a 9-unit well field. Preliminary results show that although the recovery percentage at the end of the first cycle is smaller than that of a single well operating by itself, by the time the third cycle is reached a multiwell system is more efficient. A greater percentage of the water injected during the third cycle is recovered than is recovered by a single well under the same circumstances.

Most water-bearing formations dip and, in many, a measurable groundwater flow occurs under natural, undisturbed conditions. Each of these circumstances affects the position and configuration of the "bubble" of fresh water. For example, the injected fresh water is lighter than the saline water and should tend to move to the roof of the aquifer and thence updip. This should result in a lower recovery efficiency compared with that from a horizontal aquifer. However, the recovery efficiency depends greatly on the duration of the storage part of the cycle. Single-well experiments in a dipping aquifer verify and quantify this expectation. There are indications that it may be possible to overcome the effect of dip and to stabilize the position of the injected fresh water by constructing and operating a system of injection and withdrawal well updip and downdip from the injection well.

This paper is a progress report on work that is well underway but not yet complete. As to the effect of various combinations of dip, movement of native ground water, and density differences, on the recovery efficiency of a multiwell project, we have some qualitative ideas, but at present are trying to devise a quantitative basis for design that will handle all of the variables simultaneously.

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ASSE SALT MINE, FEDERAL REPUBLIC OF GERMANY—OPERATING FACILITY FOR UNDERGROUND DISPOSAL OF RADIOACTIVE WASTES

All investigations for the disposal of radioactive