change in reflection coefficient. This information then is related to the range of expected changes in reflection coefficient due to the injected waste materials, and subsequently to the feasibility of the seismic monitoring system.

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DEDUCTION OF FLOW PATTERNS IN VARIABLE-DENSITY AQUIFERS FROM PRESSURE AND WATER-LEVEL OBSERVATIONS

In previous potentiometric studies of variable-density aquifers, particularly studies related to oil exploration, certain gravitational effects apparently have been ignored. These include the effects of troughs formed by permeability barriers within the aquifers, and the effects of structural troughs, saddles, anticlines, and synclines. In intermontane regions these gravitational effects probably are negligible in comparison with observed head differences; in most other regions they can change appreciably the heads, or the potentials, that are available to cause flow.

A gradient in potential is not necessarily associated with flow, even though corrections are made for the average rate of change in density of water. Gravitational effects can cause the interface between water and an oil or gas deposit to be tilted, even if the water under the deposit is static. These effects can reduce the rate of flushing of brine by fresh water, or they can prevent flushing.

Previous potentiometric studies should be reevaluated to ensure that all gravitational effects have been taken into account.

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DESIGN AND OPERATION OF LAND-TREATMENT SYSTEMS FOR MINIMUM CONTAMINATION OF GROUNDWATER

The increasing interest in land-treatment systems for sewage effluent and other liquid wastes, as well as some solid wastes, poses a threat to the quality of the native groundwater even though the waste water itself undergoes a marked improvement in quality as it moves through the ground and becomes "renovated" water. To avoid large-scale spread of the renovated water into the groundwater basin, the renovated water should be collected again at some point by wells (deep aquifers) or drains (shallow aquifers) for reuse or release into the surface water. For the Salt River Valley, the effective transmissibility of the aquifer for recharge was evaluated from a pilot project and then used in the design of a full-scale system. This effective transmissibility was less than the aquifer transmissibility.

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UNDERGROUND STORAGE AND RETRIEVAL OF FRESH WATER FROM BRACKISH-WATER AQUIFER

In 1967, the U.S. Geological Survey, in cooperation with the City of Norfolk, Virginia, began a study concerning the injection of fresh water into a confined aquifer containing brackish water. The objectives of the study were (1) to determine whether the host formation would physically accept large volumes of fresh water, (2) to determine the degree of mixing of the injected fresh water with the saline water, and (3) to determine the percentage of recoverable potable water after long periods of storage.

During late 1971 and early 1972, three injection and withdrawal tests were carried out. In test 1, fresh water was injected at a rate of 400 gpm (gallons per minute). The specific capacity of the well decreased from an initial value of 15.4 to 9.3 gpm/ft of drawdown at the end of 260 minutes of injection. In test 2, the initial injection rate of 400 gpm decreased to 215 gpm after 7,900 minutes of injection. The specific capacity dropped from 14.2 to 3.7 gpm/ft during the same time interval. Test 3 began with the aquifer accepting water at a maximum rate of 290 gpm, and the injection rate fell to 100 gpm within 150 minutes and continued to decline to a low of 70 gpm after approximately 1,300 minutes. The specific capacity decreased from an initial value of 3.7 to 0.93 gpm/ft at the end of the test.

Specific capacities during the withdrawal phases dropped from 19.7 gpm/ft at the beginning of test 1 to 6.7 gpm/ft at the end of test 3. All attempts at redevelopment of the injection well failed to improve the specific capacity. Current-meter surveys conducted during injection and withdrawal pumping indicated that the reduction in flow rate and specific capacities was due to a uniform reduction in permeability of all contributing zones in the aquifer rather than to a complete shut-off of flow from selected parts of the aquifer.

All of the hydraulic data collected during the three tests indicated that a physical change of the formation materials had occurred. Specifically, it was felt that the uniform loss of specific capacity of the contributing zones was due to clay dispersion, a phenomenon well known to the petroleum industry. Chemical data collected during the three tests indicated that the sodium-rich clays also were involved in cation exchange. As fresh water was being injected, calcium and magnesium replaced sodium on the clays. During withdrawals, a reversible reaction occurred as the sodium concentration in the mixed fresh and formation water increased. The net effect of the replacement of sodium with calcium and magnesium was to decrease very slightly the tendency of the clays to disperse during the injection of fresh water. The cation exchange activity during both the injection and withdrawal phases had little to do with clay dispersion, which is more nearly a physical than chemical characteristic. However, the exchange activity noted during all three tests did indicate that the clays would readily respond to chemical treatment for the purposes of decreasing or eliminating clay dispersion.

Subsequently, a preflush of 3,000 gal of 0.2 *N* calcium chloride solution was injected in front of the fresh water in injection test 4. The initial specific capacity was 4.3 gpm/ft compared with the ending injection specific capacity of 0.93 gpm/ft in test 3. By redevelopment pumping during injection, the specific capacity was improved to a high of 5.3 gpm/ft. After 4 million gal of water had been injected, an additional 3,000 gal of 0.4 *N* calcium chloride solution was added to the formation. The injection specific capacity increased to a high of 7.12 gpm/ft.

The injection specific capacity fell off with time because only the area around the bore hole was treated to prevent clay dispersion. The data from test 4 indicated a maximum injection rate could be maintained by injecting for periods of 1,200 and 1,400 minutes, then withdrawing water for 30 minutes to remove from the aquifer any sand and clay particles that were clogging the injection zones.

A total of 20 million gal of fresh water was injected in test 4. The water was left in the aquifer for about 6 weeks before beginning the withdrawal phase. It had been determined from the first three injection tests that about 85% of the injection water could be recovered

and remain within the drinking standards of the U.S. Public Health Service.

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ARTIFICIAL RECHARGE—STATE OF THE ART

The largest potential reservoir for the storage of potable water is that which exists in the unsaturated zone. Utilization of this space for the storage and retrieval of potable water is a multifaceted problem which requires application of the best talent from the scientific community. Considerable research has taken place in artificial recharge since the last international symposium on the subject at Reading University, England, in 1970. An increasing demand for economic water supplies created by larger populations indicates a need for much greater research efforts in the near future.

Artificial recharge has many similarities to liquid-waste disposal through deep wells. In both, the problem is to place liquid into a permeable lithologic unit at an economic rate, to predict movement, and the chemical reactions and physical changes that take place while the liquid is in the reservoir. Differences between the two operations are principally in the type of fluid injected and the ultimate objective. In artificial recharge the objective is to store and retrieve water of good quality; in waste disposal the objective is to store permanently water of objectionable quality. In both artificial recharge and liquid-waste storage, the nature of the storage must be known, particularly that of the unsaturated zone. The techniques of investigation for recharge and waste disposal are generally the same.

Water commonly is recharged by surface spreading through basins, induced recharge from adjacent streams and lakes, or through injection wells. Research in recharge through basins has been dominated by mathematical models based on idealized conditions and empirical relations, derived by experimental sequencing of recharge operations, and operational controls in the pretreatment of recharge water. Recharge by injection wells has been undertaken in a variety of hydrologic environments, for example in Israel where efforts have been directed toward the analyses of diffusion and dispersion of the injected water. Much research in the United States has been directed toward the movement of bacteria and organic matter through an aquifer and in the chemical modeling of changes in recharged water as it moves.

Much more research is needed on the basic properties of aquifers, particularly in the unsaturated zone, and on all aspects of recharge water quality. Research and the utilization of data produced are increasingly the responsibility of interdisciplinary teams which consider the geologic, hydraulic, geochemical, bacteriologic, engineering, geophysical, and economic aspects of the system.

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HYDROGEOLOGIC STUDIES AT A SUBSURFACE RADIOACTIVE-WASTE MANAGEMENT SITE IN WEST-CENTRAL CANADA

Nearly all radioactive wastes produced in Canada are stored or disposed of at 2 waste-management sites in shallow Quaternary deposits in south-central Canada. The oldest site and the one which has received most of Canada's radioactive waste is at the Chalk River Nuclear Laboratories (CRNL) in east-central Ontario. The newest site is at the Whiteshell Nuclear Research Establishment (WNRE) in southeastern Manitoba. Both waste-management sites are operated by Atomic Energy of Canada Limited.

Hydrogeologic studies were conducted at WNRE to predict the subsurface behavior of radioactive contaminants, which at some future time possibly could enter the groundwater zone. The site is composed of Quaternary deposits of clayey till above a sandy artesian aquifer which overlies the Precambrian bedrock. The bedrock is 50 ft below ground surface. At present there is no significant contamination of the subsurface hydrologic environment. Hydrogeologic information is being used to facilitiate the design and operation of the waste-management facilities and to assess long-term storage and disposal capabilities of the area.

The hydrogeologic investigations involved 3 main parameters. These are (1) expected residence times of radionuclides which may enter the groundwater flow system, (2) anticipated travel paths and discharge processes, and (3) suitability of the hydrogeologic environment for physical manipulation to achieve greater containment capabilities.

Hydrogeologic studies conducted during the past 5 years have involved field and laboratory techniques such as geologic test drilling, mapping of hydraulic head distributions using wells and piezometers, field permeability tests using single well response tests and long- and short-term pumping tests, mapping of natural hydrochemical patterns in the groundwater zone, tritium tracer experiments, groundwater age dating using C^{14}, and mathematical modeling using digital-simulation programs. Comparisons of the results from the studies indicate that we have attained a reasonable level of predictability in our understanding of the hydrogeologic environment in the area.

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HYDRODYNAMICS OF MOUNT SIMON SANDSTONE, OHIO AND ADJOINING AREAS

The Mount Simon Sandstone (Cambrian), the most favorable stratum for waste injection in Ohio, presently accepts about 250×10^6 gal of industrial waste per year. Concern has been expressed about the transport of these fluids by natural hydrodynamic flow.

The potentiometric surface map of the Mount Simon reservoir of Ohio has a form which mirrors the structural configuration—highest values are in the deeper part of the Appalachian basin and lowest on the Indiana-Ohio platform. Flow direction in central Ohio is indicated to be west or northwest. Head difference is 2–7 ft. Porosity and permeability data combined with this information (Darcy's law) yield velocities of less than 6 in./year.

Because the assumptions involved in determining velocity in this manner are questionable, the resulting values should be considered rough approximations. Nevertheless, the calculations generally show that transport of injected fluids by hydrodynamic flow is not presently a serious hazard in Ohio.

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DAN REGION, ISRAEL, SEWAGE-RECLAMATION RECHARGE PROJECT

The Dan Metropolitan Region, Israel, consists of about 1 million inhabitants, about 50% of whom live in the city of Tel Aviv and the rest in surrounding communities.

The industrial, economic, and commercial growth of this region has been rapid in recent years and the ef-