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:

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

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.

The less conservative cationic solutes also have been successfully modeled. The modeling results indicate that hydraulic dispersion (especially transverse) is a much more significant influence than has been previously suggested by earlier studies. The model may be used to project future waste migration patterns for varied hydrologic and waste conditions.

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ARTIFICIAL RECHARGE IN UNITED KINGDOM, ESPECIALLY IN LONDON BASIN

The Water Resources Board, in its role as advisor to the United Kingdom government on water resources development in England and Wales, prepared regional planning studies setting out the alternative strategies, costs, and consequences for 3 regions covering most of the country. More recently a National Planning Study for all of England and Wales has been completed. The program of research and development includes such subjects as water resources instrumentation, mathematical modeling, desalination, combined use of surface and groundwater, artificial recharge, and ecologic problems.

In England and Wales, about 25% of all public water supplies are taken from groundwater which is recharged naturally by percolating rainfall. In many places groundwater levels have been lowered extensively causing saline intrusion and other problems. In recent years there has been much increased interest in the development potential of groundwater, with the result that some schemes for the combined use of naturally recharged underground resources and rivers are under construction and others are under investigation.

Artificial recharge, considered in the United Kingdom to be the final stage of groundwater development, is not yet used, but it is considered to have major potential both for using underground storage to supplement surface storage and for the partial purification of polluted surface water where suitable aquifers crop out at the surface. The Board's artificial recharge program includes hydrogeologic, engineering and economic, analogue and digital model studies and field experiments in most of the techniques of artificial recharge.

One important example, the London basin, is taken as an illustration. A hydrogeologic study has been carried out to assess the potential for recharge beneath London. The aquifers are the Chalk overlain by the lower London Tertiary strata which comprise the fine-grained Thanet Sands and the sands, gravels, and clays of the Woolwich and Reading Beds. These strata form an asymmetric syncline with an axis striking east-west through London's center. The Chalk crops out in the Chilterns of Oxfordshire and Buckinghamshire in the north, and the North Downs of Kent and Surrey in the south. Over the last 170 years, groundwater levels have fallen, in some areas more than 250 ft, creating a storage volume exceeding 200 billion gal—about 5 times the total surface storage available in the Thames basin. Three areas were identified where hydrogeologic conditions are suitable for recharge.

During the hydrogeologic study, an electrical analogue was constructed to assist in proving the transmissivity and storativity maps calculated from pumping test data obtained during the last 100 years. The model highlighted problems of saline intrusion from the Thames and has been used to illustrate the effectiveness of proposed control measures.

More recently an engineering and economic investigation has been undertaken using 2 main techniques: (1) digital groundwater models of the selected recharge areas, and (2) a digital simulation, using the 84 years' records of daily flows in the Thames. This work has shown that additional yields of more than 70 million gal/day could be made available at low cost without the need of further surface storage.

To substantiate this work further, 2 field experiments have been carried out. One involved the recharge of an existing Chalk well and adit system; in the other, water was injected into a pair of new wells, one open only to the Chalk and one open only to the Thanet Sands. There was a comprehensive program of recharge and water-quality sampling and analysis.

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DEEP-WELL INJECTION OF DESALTING-PLANT WASTE BRINE

The production and desalting of saline waters stored in a deep artesian aquifer, the Mount Simon Sandstone in northeastern Illinois, to aid in meeting projected water deficits for the Chicago region, are being considered. Because of the characteristics of the predicted Mount Simon water quality it would be necessary to dispose of large quantities of desalting-plant waste brine. Evaluation of brine disposal methods led to selection of disposal by injection through wells open to the lower Mount Simon aquifer. As feedwater for desalting plants would be withdrawn from the upper Mount Simon aquifer, injection-well fields were designed to eliminate contamination of feedwater and to keep injection pressures within acceptable limits. Wells capable of injecting 1 million gal/day (mgd) were designed. Injection costs were 12.5–19% of the total cost of producing water. Injection costs ranged from 17 cents per 1,000 gal for injection of brine from a 1-mgd reverse osmosis plant to 58 cents per 1,000 gal for brine from a 5-mgd distillation plant. The effect of brine injection may have a harmful effect on the quality of water withdrawn from existing wells open to the aquifers above the Mount Simon.

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SWISS MODIFICATION OF ARTIFICIALLY RECHARGED WATER

Experiences based on some existing plants, where Pleistocene gravels are artificially replenished by polluted river water and which have recharge capacities of 1–25 mgd, demonstrate the importance of retention time and of oxygen balance in the highly permeable aquifers.

The retention time of the single water particles has considerable variation and depends on hydraulic dispersion which may be proved by tracer investigations. In one case, for a distance of 1,350 ft, the minimal flow time is 3.4 days, the average 22 days. The flow times of the different water particles prove a logarithmic normal distribution function.

The oxygen content of the artifically recharged groundwaters depends on the oxygen concentration and on the biochemical oxygen demand (BOD) of the raw water. From the data the oxygen balance of a groundwater can be evaluated. For example, on an average, a groundwater with 3.4 ppm O_2 and only 0.5 ppm full BOD was obtained from a river water with 12.6 ppm O_2 and 9.7 ppm full BOD (equal to a 5-day BOD of 4.5 ppm) after a retention time of 7 days. As