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 to the oxygen balance, there are no significant differences between a percolative and a direct infiltration, probably because decisive oxygen gas quantities are no longer present after the first percolative seepage of a polluted raw water in an unsaturated zone above the water table. Absence of oxygen in a groundwater will involve the solution of iron and possibly also of manganese. Low oxygen concentrations also retard the elimination of bacteria and of tastes and odors. This elimination results preferably from aerobic biologic filtration. Furthermore, if the oxygen content does not exceed about 5 ppm no sufficient protective scales on the interior of the ferrous water supply pipes are formed. Therefore, poor oxygen balance systems must be improved by different processes of raw water pretreatment.

After the infiltration, the aerobic decomposition of organic matter and the elimination of bacteria mainly take place in short flow times. A case in point is a reduction of an average coliform content from 10^6 per 100 ml to 10 per 100 ml after about 1 day minimal and 7 days average retention time. Other empirical results confirm the excellent biologic filtration of the water during its lateral flow through the gravels. After the beginning of an artificial recharge and the following elevation of the water table, the biologic activity in the inundated natural filter rises only step by step in function of operating time. In the mentioned case, optimal coliform results were obtained at first after an operation time of about 70 days.

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ARTIFICIAL RECHARGE IN COASTAL PLAIN AQUIFER IN ISRAEL—FURTHER FINDINGS

Artificial groundwater recharge operations till the end of 1966 have been described in the *Bulletin* of the International Association of Scientific Hydrology, Annex No. 1, March 1967.

The present paper reviews artificial recharge practices followed in Israel since 1967.

The coastal plain aquifer is at present recharged through 99 wells and through 8 spreading grounds with a total area of 180 acres. The average yearly rate of recharge to this aquifer amounts to about 80 MCM/acre (64,000 acre-ft).

Recharge is practiced mostly during winter months, November through March, and sometimes also during April and October. The main source is mixed Lake Kinneret water, this supplying 68% of the recharged water; about 17% is storm runoff and 15% groundwater withdrawn from a limestone aquifer.

Recharge rates into wells range between 50 and 400 cu m/hour (220–880 gpm) and infiltration rates in the spreading grounds range between 0.2 and 3.0 m/day (0.7–10.5 ft/day), though initial infiltration rates in spreading grounds are usually lower for storm runoff water than for water from Lake Kinneret.

Recharge and infiltration rates decrease during recharge seasons; this decrease varies with the type of recharge installation and the type of water used.

The decrease in well recharge rates is observed mostly when single-purpose wells (unequipped wells drilled for recharge only) are recharged with Lake Kinneret water. Redevelopment of these wells over a short period does not suffice to restore the original recharge rates. The same Lake Kinneret water, when recharged into dual-purpose wells (wells that are normally pumped throughout the summer), causes only a small decrease in the recharge rate during the recharge period. Recharging the aquifer through both dual and single-purpose wells with groundwater from the limestone aquifer causes almost no decrease in recharge rates.

To assist in restoring infiltration recharge rates, the basins are dried out after each season, the upper layer of soil and silt removed, and the basin cultivated. This results generally in restoration of the infiltration rates to their original values.

In the dual-purpose wells, the first batch of water pumped after recharge had ceased for a short period was contaminated. This contamination (odor, turbidity, high counts of coliform bacteria) is due probably to the high content of organic matter in the recharged water. To overcome this pollution, short and intensive pumping for a few hours was carried out and the water discarded. Later, chlorination was applied for a few days.

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UNDERGROUND WASTE DISPOSAL AT NEW JOHNSONVILLE, TENNESSEE

Deep-well disposal of acidic wastes has been employed successfully at the E. I. du Pont Pigments Plant, New Johnsonville, Tennessee, since 1967. In 1965, as part of a program to reduce surface discharge of waste fluids, together with other methods for waste disposal, an investigation of the feasibility of subsurface waste disposal was conducted. Basic data were developed and from this a proposal was made to the state for drilling a deep disposal well. A public hearing, attended by local, state, and federal representatives, was held and all inquiries answered. Under state permit, a 6,700-ft geologic test well was drilled. Receptive zones were found in the middle and lower Knox-Copper Ridge Dolomites (Cambrian). Laboratory studies conducted with rock cores showed that the waste fluids are compatible with the formation rocks and their contained waters. Appropriate state agencies approved completion designs and the well was completed in 1966.

Acidic wastes were injected into the well at design rates and pressures from 1967 through 1971, at which time the well was retired from service. Two additional waste wells have been drilled and are operating successfully. A fourth well is scheduled to be drilled in the near future.

In addition to downhole monitoring systems on each well, the plant monitors many freshwater wells in the surrounding area, as well as 1 deep well on the plant property, for evidence of waste-fluid migration. To date, no vertical migration of waste has been observed.

A second deep monitor well is to be drilled in conjunction with the upcoming fourth waste well. At New Johnsonville it has been shown that a properly installed waste-disposal well system can successfully remove undesirable waste fluids from the biosphere.

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LABORATORY STUDIES RELATED TO ARTIFICIAL RECHARGE

Artificial groundwater recharge, by any method, is subject to limitations caused by some mechanism degrading the hydraulic conductivity of the porous media through which the recharge water is being infiltered or injected. Reduction of hydraulic conductivity may be caused by suspended solids, bacterial growth, chemical reactions of dissolved solids with the porous media or