

WASTE DISPOSAL AND UNDERGROUND WATERS¹⁾

W.A. VISSER²⁾

ABSTRACT

Underground waste management, environmental implications and artificial recharge were the subjects discussed in two symposia, respectively in Houston, Texas, in 1971 and in New Orleans, Louisiana, in 1973. In the present paper the author summarizes aspects of the injection of liquid wastes into reservoir rocks by deep wells in the U.S.A. These aspects concern legislation and policy, statistics and actual conditions in some regionally important disposal zones.

Attention is given to the protection of useful subsurface waters. Ground waters, i.e. those waters that take part in the present hydrologic cycle, and formation waters, i.e. those that are isolated from the present cycle, are distinguished. Disposal in the former constitutes a potential hazard to the environment, in the latter under certain precautions disposal may be considered safe.

In The Netherlands conditions are such, that aquifers that are properly isolated from the present hydrologic cycle occur at depths greater than between approximately 500 and 1000 m. Below these depths disposal prospects are present in sandstone/ claystone alternations of upper Palaeozoic to Tertiary age and possibly in upper Cretaceous limestones. In the northern and eastern parts of the country solid or liquid (including radioactive) wastes could be disposed of in artificial caverns in rock-salt deposits.

INTRODUCTION

The disposal of liquid industrial wastes in porous and permeable rocks is carried out in the United States since 1950. The method is based on experiences gained in the disposal of large quantities of oilfield brines that are produced together with oil and gas. In 1960 there were 25 waste-disposal wells registered, by January, 1972, 225, and by June, 1973 at least 278 waste-disposal wells had been drilled in the United States.

A first symposium on underground waste management was held in Houston, Texas, in September, 1971 (Cook, 1972), a second symposium was organized in New Orleans, Louisiana, two years later (Braunstein, 1973). The author

attended both symposia, and in a former paper (Visser, 1972), dealing mainly with investigations, techniques and safety requirements, he discussed some results of the Houston symposium. In New Orleans a number of contributions were devoted to case histories, and accordingly the present paper contains, though very summarily, some reflections on actual operations in the U.S.A.; it will be restricted to the injection of liquid wastes into reservoir rocks by drilled wells. Another method, the deposition of radioactive wastes in cavities or mines in rock salt, has been summarized elsewhere (Hamstra, 1973; Kühn, 1973; Lomenick and Boch, 1973). Complications on underground waste disposal have been issued by the U.S. Environmental Protection Agency (1973) and in the Netherlands by a study group set up by the Central Organization for Applied Scientific Research TNO (Studiegroep, 1973).

A prerequisite of any method of underground waste disposal is the prevention of contamination of those subterranean waters that now or in the future are potentially useful, of mineral resources and of the surface (Freeze, 1972, Studiegroep, 1973, Visser, 1973). However, if not carried out with proper care, also sanitary landfills, waste ponds or burial on land and disposal at sea, and even incineration may cause pollution of surface and ground water.

LEGAL REGULATIONS AND POLICY

In the U.S.A. the use of the subsurface for waste disposal is legally regulated in several states.

With the exception of radioactive wastes, control of which is in hands of the federal government, the control over subsurface disposal is with the states (Walker and Cox, 1973). As a result there is a wide variety of regulations. Some states have a legislation specifically adopted for disposal wells as Texas (Hill, 1972) or Michigan; others utilize legislation created for other purposes, f.i. water-well or pollution-control statutes. As an example the variation is taken of the specifications of underground waters into which disposal is prohibited. There is general agreement that injection should be restricted to saline aquifers; it is felt that waters of low salinity may be potentially useful and should be protected.

¹⁾ Lecture held for a course engineering geology, University of Technology, Delft.

²⁾ Netherlands Organization for Applied Scientific Research TNO, c/o P.O. Box 285, Delft.

The upper limits of concentration of waters to be protected vary from 1500 mg/l total dissolved solids (Florida) to the concentration of sea water (33000 mg/l, Alabama). New York protects waters to a concentration of 2000, Illinois to 10000, whereas Texas considers potentially beneficial all waters of concentrations between 3000 and 10000 mg/l total solids.

The policy of the U.S. Environmental Protection Agency, as stated in guide lines and decision statements, is aimed at attaining the optimum protection of useful and potentially useful waters, the subsurface and the environment in general. However, the agency has no authority on underground waters; it can make recommendations only (Greenfield, 1972; Hall and Ballantine, 1973). Adoption of strict standards is felt necessary, and through the recommendations of E.P.A. the influence of the federal government is expected to increase. By future legislation the states will keep control, subjected to federal standards.

Misapplication of the technique has in recent years caused discussion and criticism (Barlow, 1973, Lofgren, 1973). Grave concern has been brought by insufficient geological and hydrological knowledge, improper well design and completion, no monitoring of pressures and rates. Control is needed through the awarding of permits for specified cases only and the delineation of factors such as injection pressures and rates, types of materials, tests and monitoring facilities. Although in relation to the volume of sediment suitable for underground waste disposal, the number of disposal wells is small, the capacity of the receiving formations is finite and indiscriminate disposal should not be allowed. Only those wastes should be eligible for underground disposal, if no suitable, for the biosphere acceptable alternative is available (Barlow, 1973; Hall and Ballantine, 1973).

GROUND WATER AND FORMATION WATER

There is an aspect of underground waters that is not generally realized, namely the distinction between those waters that take part in the present hydrologic cycle, here to be designated "ground waters", and those waters in the deeper parts of the sedimentary cover of the earth's crust that do not, the "formation waters". Apart from a negligible amount of juvenile water, all subterranean waters derive ultimately from the surface of the earth, either from precipitation or from sedimentary processes.

The part of the meteoric waters that percolates down into the soil and underlying rocks may emerge at the surface sometimes after a few hours or days, often after a considerable time, hundreds or even thousands of years. Many complicated interactions of chemical, physical and biological nature take place between sediment and percolating ground water, tending to increase the amount of material in solution with respect to the original meteoric water. Concentration and kind of solved substances depend greatly on the character of the sediments, climate and bacterial activity.

Infiltration of sea water in estuaries and coastal areas may change the composition of the ground water, as does the solution of shallow beds of rock salt (Finkenwirth, 1965, Jelgersma and Visser, 1972, Löhnert, 1967). Ground waters, as defined above, show a wide variety of dissolved material; they range from fresh to brackish and even saline. Meteoric influences can generally be detected by a certain admixture of fresh water causing their concentrations to be below that of sea water.

The ground water on its way through the shallow aquifers is in slow movement. With increasing depth the rate of flow diminishes until, depending on local hydrogeological circumstances, a depth is reached below which the water appears to be essentially without flow and where pore pressures are essentially hydrostatic (Piper, 1970). Generally argillaceous beds have an influence on the flow pattern underground, and often an extensive, well consolidated and impervious shale bed may be distinguished, the hydrologic base, that isolates the underlying beds effectively from the hydrologic cycle.

Sedimentation is a process, in which water is withdrawn from the hydrologic cycle, namely sea water in the majority of sediments. The water content in newly laid down deposits is high; in clays 60 to 90% of the total volume may consist of water. Settling, compaction and lithification initially by the weight of the particles themselves, later by the weight of overlying deposits, cause, especially in argillaceous sediments, pore volume to decrease greatly. Part of the original sedimentary water is ejected, part will migrate and in the end be entrapped in the interstices of the rocks.

Where depth of burial and/or impervious beds cause prolonged isolation from the hydrologic cycle, the diagenesis of the original sedimentary water results in high concentrations and changed ion ratios. By various physical and chemical agents, such as ion exchange, sieving action of clays, precipitation of some, solution of other minerals, eventually chemical equilibrium with the sediment will be attained.

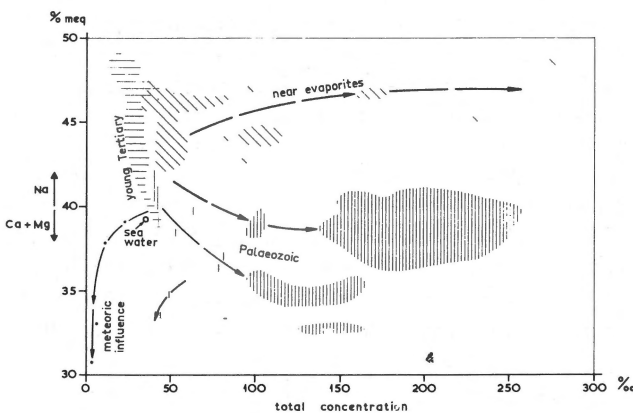


Fig. 1
U.S. oilfield waters (after De Sitter, 1947).

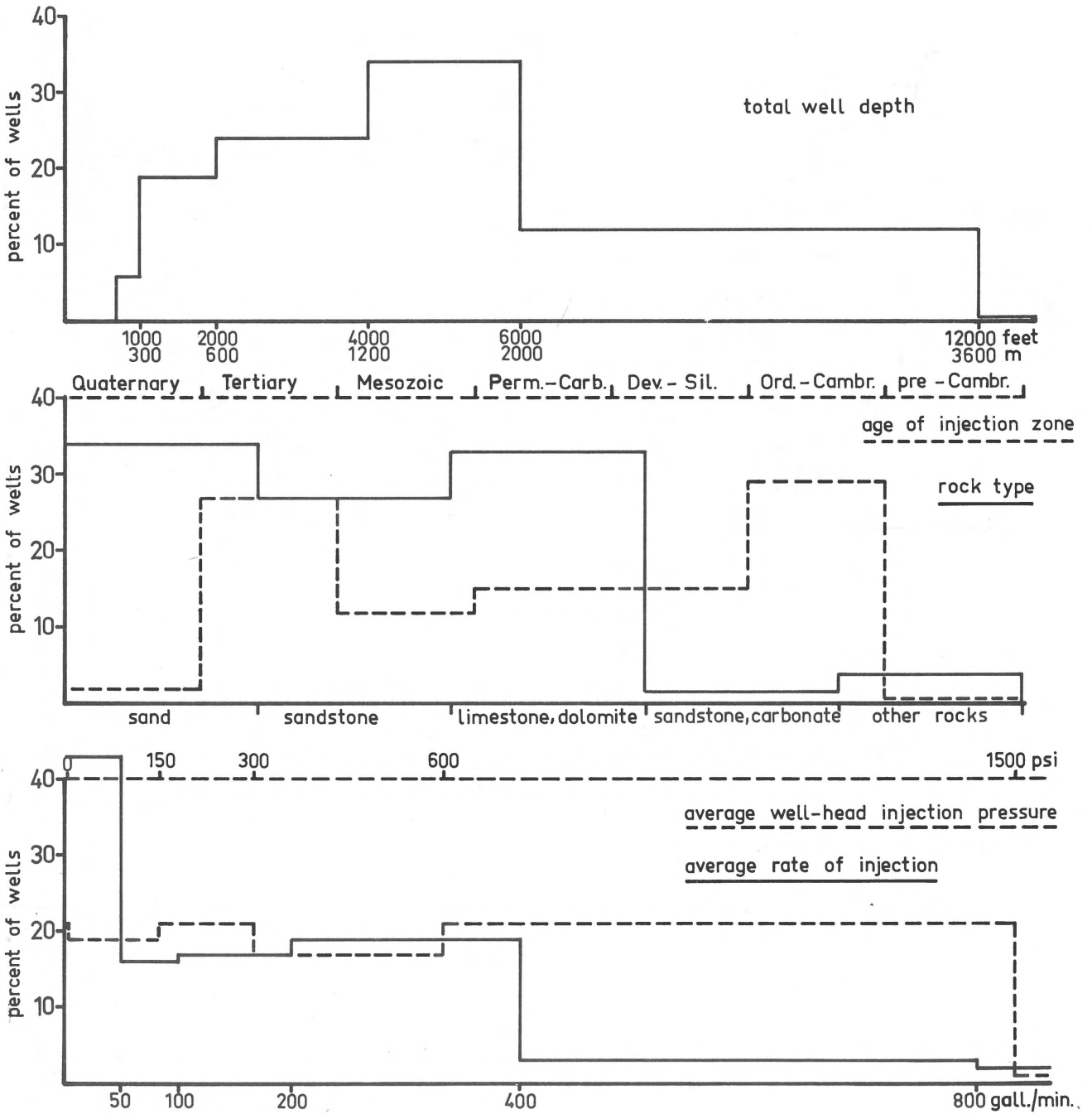


Fig. 2
Disposal-well statistics (after Warner and Orcutt, 1973).

As a rule waters in deep geological formations are different from sea water. A great number of U.S.A. oil field waters has been studied by De Sitter (1947). One of his graphs shows total concentration and the ratio Ca+Mg/Na+K (fig. 1). Extending from the sea water point there is a field of young Tertiary waters with slightly decreased concentrations, but with a relative enrichment of sodium. These are originally sea water, from which calcium, magnesium, sul-

phate and carbonate have disappeared. Toward the lower left-hand corner of the graph the influence of meteoric water is apparent. In contrast, toward upper right high concentrations and enrichment of sodium were found in waters near evaporites. Two fields of high concentration and enrichment of calcium and magnesium belong to waters in Palaeozoic sediments.

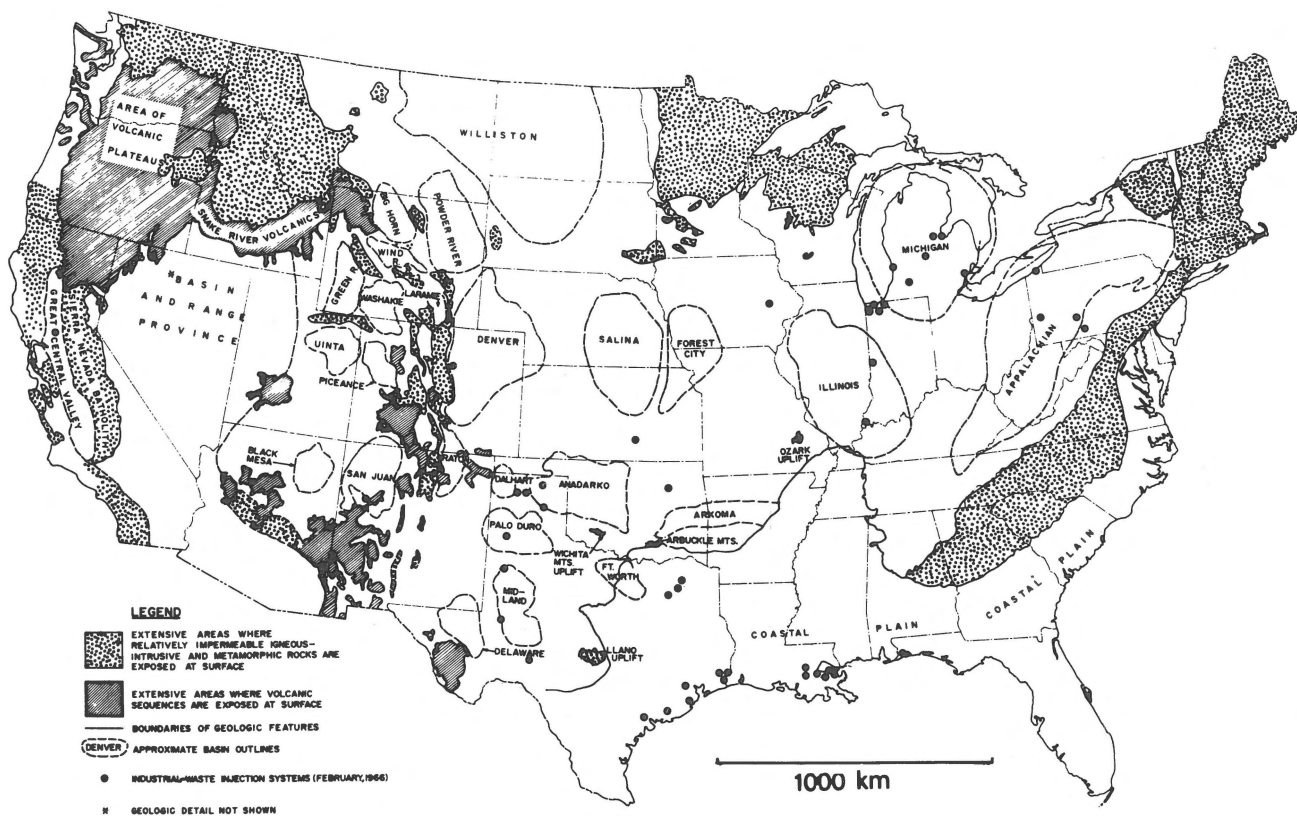


Fig. 3

Sedimentary basins and underground disposal wells in the United States (Warner, 1968; Warner and Orcutt, 1973). The dots indicate sites in 1968; the figures indicate the number of sites per state or basin by June 1973.

Disposal of wastes in beds that are not properly isolated from the hydrologic cycle may constitute a potential hazard to the environment. Disposal in beds that are isolated from this cycle may under certain, strictly controlled conditions be considered safe.

SOME STATISTICS

By June, 1973 at least 278 underground waste-disposal wells had been drilled in the U.S.A.; only 22 had been constructed before 1960; about twice that number by 1964, and since that year an average of about 30 wells have been drilled per year (Warner and Orcutt, 1973). Only 170 wells are presently operating; 25 wells have been operated but are now abandoned and plugged; 11 wells were failures and have never been operated.

Most of the disposal depths range from 300 to 2000 m (fig. 2). Shallower depths are generally inconsistent with safety requirements; greater depths incur greater costs, whereas satisfactory injection zones have frequently been found at lesser depths. Virtually all injection pressures are lower than 100 atmospheres at well head. Considering losses due to friction in the tubing and to viscosity of the waste, the bottom-hole injection pressures are well below well-head

pressures and a fraction only of formation-breakdown pressures. About one fifth of the wells operate with gravity flow, which is possible only, if the native water is flowing or permeability is exceptionally high with low pore pressures. Average continuous injection rates are mostly less than 400 U.S. gall. per minute (about 2200 m³/d); 43% of the wells operate at less than about 225 m³/d. Almost two thirds of the wells have been completed in arenaceous reservoirs, one third in carbonate rocks. The majority of the wells were completed in Palaeozoic sediments (59%), of which about half in Cambrian-Ordovician limestones and dolomites. A large number of wells have been constructed in unconsolidated sands of Kaenozoic age. Of these 70 are located in the Gulf Coast. The 6 Florida wells were drilled in Tertiary limestones. Other important regional injection zones occur in the north-central states south of the great lakes (the basal Cambrian Mount Simon sandstone and its equivalents) and in Kansas and Oklahoma in the Cambrian-Ordovician limestones of the Arbuckle group (fig. 3).

OPERATIONS

A large underground waste-disposal province extends south of the great lakes over an area of about one million

km². Palaeozoic subsidence resulted in a number of basins separated by ridges of relatively slower subsidence. The pre-Cambrian basement ranges in depth from 500 to over 4000 m sub-sea. The Palaeozoic sequence includes sandstones, shales and siltstones, dolomites and Silurian evaporites, covered by thick glacial drift. The latter is a main fresh water aquifer. Disposal zones range from basal Cambrian to upper Devonian. Oil- and gas fields and brine-disposal sites are present.

In this province the basal Cambrian *Mount Simon sandstone* is the most important disposal formation. It is about 300 and locally up to 100 m thick and consists of locally coarse-grained sandstone with lenses of shale and siltstone. Permeability is low, not more than respectively 44, in some cases up to 400 mD. porosity averages 15%. Transmissivity may be up to 120 m²/d. There is a meteoric water intake area in SE Wisconsin; artesian conditions occur in adjoining NE Illinois, where the upper 70 to 100 m of the aquifer yield fresh water (Schicht, 1973). Below this depth concentrations increase gradually with depth to about 88.000 mg/l of total solids (52.000 mg/l Cl⁻) at the base of the aquifer, about 760 m below the top. The feasibility is being studied to develop and desalt saline Mount Simon waters that will bring the necessity of disposing large quantities more concentrated waste brines.

In Ohio about one million m³ of wastes are disposed of through 6 wells (Clifford, 1973). Further disposal operations take place in Illinois and Indiana. Concern has been expressed of the possibility of transport of the wastes by natural hydrodynamic flow. From potentiometric observations in 10 wells Clifford found head differences of 60 to 200 cm after correction for density differences. From these data combined with those on permeability and porosity he concluded that flow, if any would not exceed 15 cm/y, which would not constitute a serious hazard. Apart from observational density that has been far too small to yield reliable results, Bond (1973) pointed out that in variable density aquifers gravitational effects due to permeability barriers and structure may cause potentiometric differences without flow being induced.

It can hardly be maintained that in relation to the huge volume of rock being involved waste disposal in the Mount Simon sandstone on the scale presently being carried out would constitute any hazard to other uses of this aquifer or to other formations, especially if waste is emplaced in the deeper very saline parts. To avoid, however, possible future environmental dangers there is an upper limit to the number of wells, amounts to be disposed of and applied pressures.

Another example is provided by disposal practices in limestones of the *Cambrian-Ordovician Arbuckle group in Kansas*. In the Salina basin of E Kansas and Nebraska the Permian to Cambrian sequence reaches a maximum depth of almost 1400 m below surface. Salt water has been found in all deep formations. To the west on the Central Kansas uplift oil- and gas fields yield large amounts of salt water from the

Arbuckle and other formations. Through 3200 disposal wells about 56 thousand m³ per dag of salt water is returned (Latta, 1973). Of the 30 waste disposal wells in Kansas 25 are completed on limestone beds in the Arbuckle group. Reservoir thicknesses range from 30 to 120 m; disposal depths from 1000 to 1800 m. Due to the high permeability, presumably caused by solution near structural highs, capacities up to 650 m³/d occur without need to apply pressure. The disposal of both, oil-field brines and industrial wastes, is controlled by Kansas state agencies. Underground disposal is considered only for those wastes that cannot be treated and disposed of in other ways; justification should be given why underground disposal is considered the least hazardous method.

The largest concentration of disposal wells in a single geologic province is situated in the *Gulf coastal plains*. This depositional basin that extends over the continental shelf has received continuous sedimentation during the Kaenozoic. Thickness and depth increase toward the south to well over 4000 m. The beds dip very gently in the same direction. Structural deformation is caused by faulting and by salt domes that control the occurrence of the numerous oil- and gas fields. Return of the brines underground is common practice. The depth of the fresh water body may be some 700 to 1000 m in the north, decreasing to about 100 m or less near the coast. The transition, at least in some places, to highly saline waters is abrupt. In the sequence of saline-water bearing, unconsolidated sands and clays there is no gradual increase of salinity with depth. Regionally, waters with a salinity far higher than sea water may occur in beds in a position stratigraphically and geographically higher than layers with waters far below that concentration. The distribution of water qualities may be influenced by clay/sand edges, faulting and by the influence of meteoric waters.

In the coastal zone of Texas and Louisiana – over a distance of about 1000 km – most disposal takes place in Miocene sands and to a less extent in the Oligocene as well. In Alabama farther inland disposal occurs in an Eocene sandstone/claystone alternation. Disposal depths range from about 700 to over 2000 m. Injection pressures are low, up to about 40 kg/cm²; amounts are high: figures of 1500 and 2500 m³/d are quoted. Permeability and porosity are large. It is stated that in 1971 in the whole of Texas 50 active wells were injecting approximately 530 thousand m³ of waste a day into the subsurface (Hill, 1972).

Protection of fresh ground water by cemented casing, monitoring of pressures and injection rates is generally required; supervision is carried out by state agencies. In Alabama and Texas upper limits of concentration of waters to be protected are set. Here again the huge volume of available sediment in relation to the number of wells and amounts of waste disposed of, and the large horizontal and vertical distances provide protection against environmental hazards. Moreover, it is felt that, due to the presence of more or less impervious beds and to the prevailing dip of the beds,

any flow that may occur in the subsurface waters will be downdip. In the very long run the wastes will be dispersed in the sediments below the Gulf.

In Florida disposal of acidic organic waste is varied out in the carbonate platform sediments of upper Cretaceous to Miocene age. The platform extends over the continental shelves on both sides of the peninsula. The beds dip very gently from the inland high towards the coasts. A recharge area is present in the structurally and topographically higher part of the Floridan aquifer (Eocene to middle Miocene) that consists of an alternation of cavernous limestones and dolomites, impervious marls, claystones and dense limestone beds. The fresh water body extends to depths of a few metres along the coasts to about 700 m inland. Through a brackish zone of a few tens of metres the waters quickly become saline. Some flow is considered to be present to presumed discharge zones in the continental slopes (García-Bengochea *et al.*, 1973; Kaufman *et al.*, 1973).

Disposal is carried out in the Floridan aquifer, where it contains waters of more than 1500 mg/l total solids. Capacities are large, up to 450 m³/d; injection pressures are low, only a few kg/cm². Disposal depths are between 450

and 650 m. By caliper logging in disposal and observation wells solution of the limestones and local channelling were observed; leakage to higher zones has taken place. The presence of more than one confining bed, including a thick extensive clay bed, makes contamination of the fresh water zone an unlikely event. At least partial neutralization of the waste by solution of CaCO₃ and denitrification by biochemical reactions may modify the composition of the injected waste (Goolsby, 1972). It is considered most improbable that the waste will ever reach the presumed discharge areas in the continental slopes.

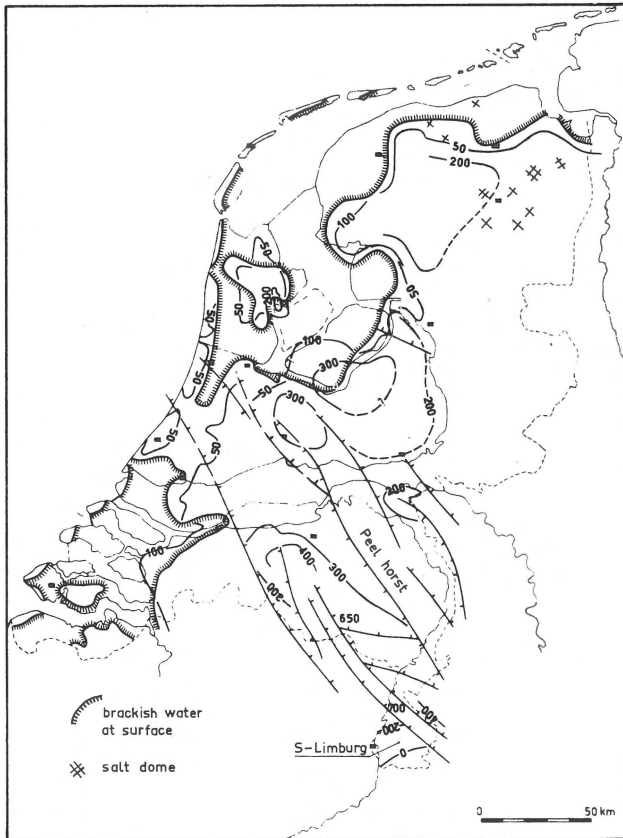


Fig. 4
Depths of the 200 ppm isochlore in The Netherlands.

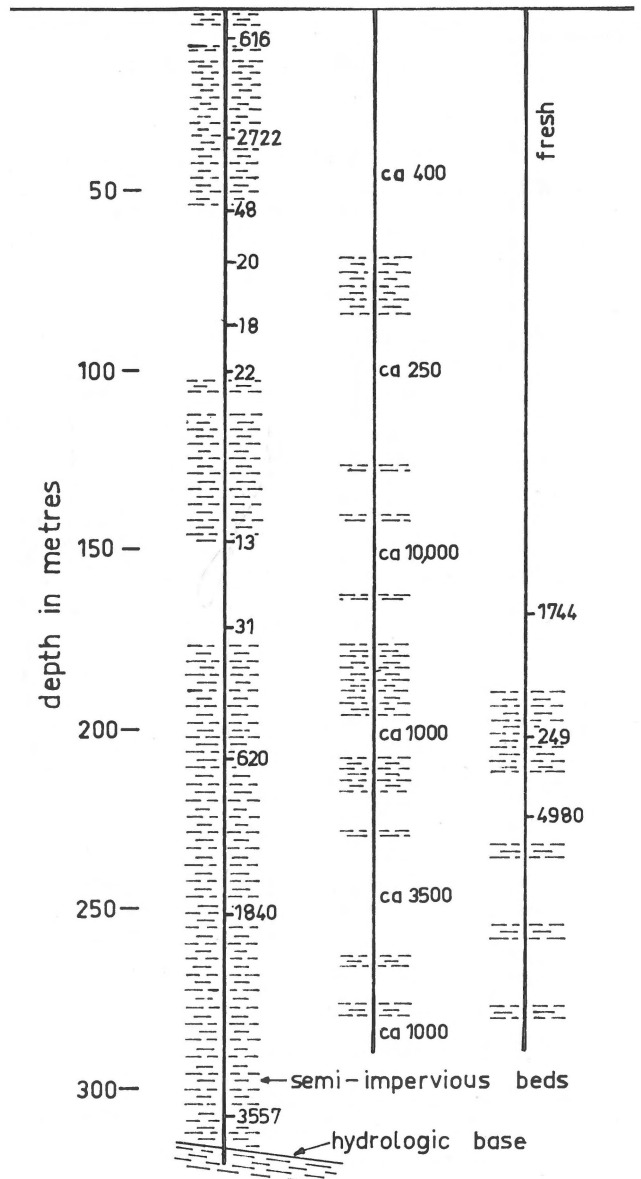


Fig. 5
ppm Cl in wells in the western Netherlands.

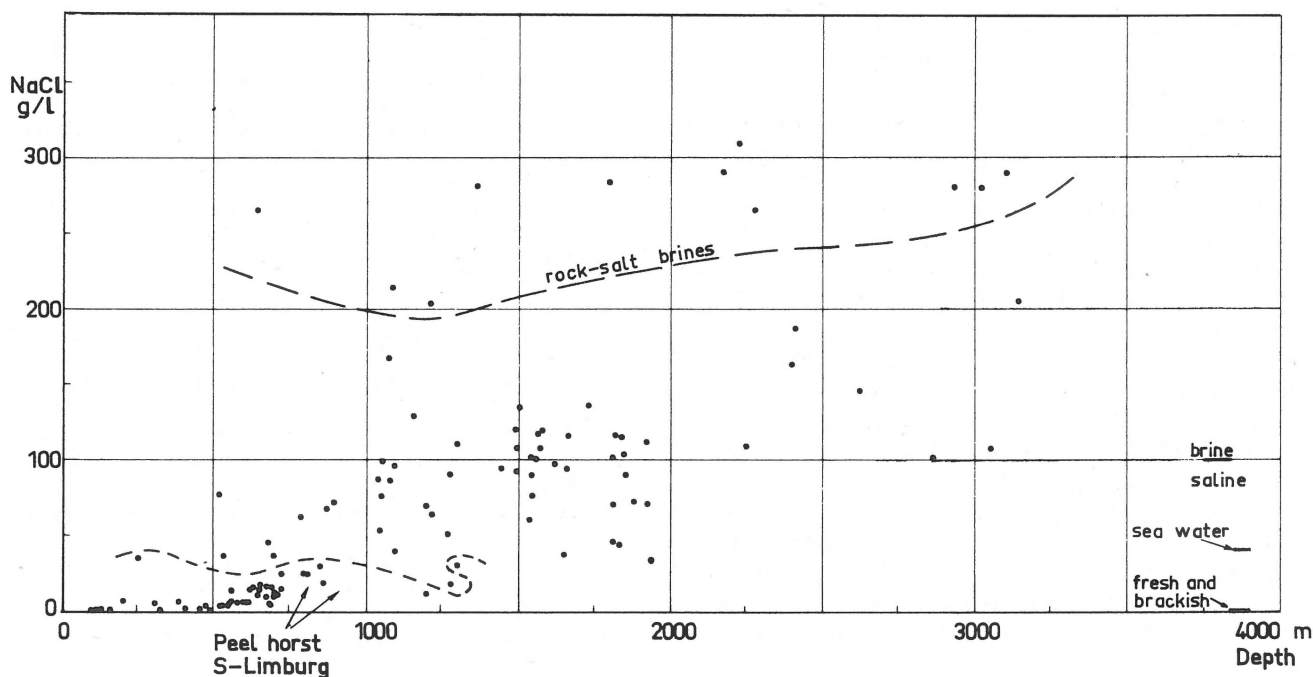


Fig. 6
NaCl contents in subsurface waters in The Netherlands.

In the U.S.A. in many places underground waste disposal is carried out in formations that are not properly isolated from the present hydrologic cycle, and thus may present a future hazard to the environment. Although these operations are in accordance with legal requirements, various authors and federal agencies, have expressed grave concern. The huge size of the sedimentary basins and the huge volume of sediments suitable for underground waste disposal as compared to the small amounts of waste actually disposed of in a small number of installations are doubtless a form of safeguard for the environment; it is not an aspect on which a policy can be built. In this respect it may be worthwhile to have a look at The Netherlands, a densely populated highly industrialized and built-up area of minute size, comparatively rich in mineral resources and where the ground water is a still unpolluted source of industrial, agricultural and household water, a natural resource that should not be endangered.

CONSIDERATIONS ON THE NETHERLANDS

In the coastal areas of The Netherlands, with exception of the dunes along the North Sea, surface- and ground waters are brackish, showing a Cl^- content often far over 200 ppm (fig. 4). From the coasts the 200 ppm-isochlore plane dips inland to depths of about 200 m; in some places only, depths of more than 300 to 400 m are reached; the deepest fresh water known in the country occurs in the lower Triassic of

South-Limburg at 700 m below sea level (Kimpe, 1963). In several places near the coasts tongues of higher concentrated water overlie fresh ground water (fig. 5), clearly indicating the influence of the Holocene transgressions (Jelgersma and Visser, 1972). No evidence has been obtained that the piercement-salt domes in the northeastern part of the country have impaired the quality of the fresh ground water.

In general, fresh ground water is restricted to Quaternary and young Tertiary; in some places along the eastern border and in South-Limburg fresh water occurs in older, mainly Mesozoic, beds. In South-Limburg and the Peel horst, both structurally high areas, uppermost Cretaceous chalks overlie upper Carboniferous strata. No properly confining beds are present, and some faults have been observed to conduct water. There is a considerable influence of meteoric water in an originally saline environment. In South-Limburg the transition from fresh to saline takes place in the Carboniferous; in the deepest part only of the mines mineralized waters of a total concentration higher than sea water have been found (Kimpe, 1963). In the Peel horst the waters in the Tertiary are brackish; in the Cretaceous they are brackish to slightly saline (less than sea water); in the Carboniferous some waters reach a total concentration somewhat higher than sea water (Peelcommissie, 1963).

In other parts of the country NaCl contents are generally higher than those of sea water; they tend to increase with depth (fig. 6). Near rock-salt deposits nearly saturated brines were found. These waters derive almost all from Mesozoic

and upper Palaeozoic sediments that are well isolated from the present hydrologic cycle by impervious clay- and mudstone beds.

These beds are of Tertiary age and as a rule occur at depths between approximately 500 and 1000 m. As a consequence disposal of liquid wastes in reservoir rocks should not be allowed at depths less than about 500 m; at some places disposal would be feasible between 500 and 1000 m, whereas at greater depths disposal prospects are present in sandstone/claystone alternations of upper Palaeozoic to Tertiary age and possibly in upper Cretaceous limestones (Studiegroep, 1973). Furthermore, the extensive rock-salt deposits in north and east, parts of which come within a few 100 m from the surface, liquid or solid, including radioactive wastes could be disposed of in artificial caverns (Hamstra, 1973).

In The Netherlands underground waste disposal should only be carried out, if permits are issued for specified cases only and for restricted duration, and if the preliminary and detailed investigations, the design of the installations, the operations themselves and their abandonment are supervised and controlled by a government's agency (Studiegroep, 1973). Before a decision to carry out underground waste disposal at a certain locality and depth is taken, the consequences for biosphere, mineral resources and ground water should be considered and safety requirements accurately formulated.

If preceded by detailed investigations and conducted with proper care underground waste disposal can be an attractive way, to alleviate a problem of modern industrial society.

REFERENCES

- Braunstein, J., editor (1973) – Underground waste management and artificial recharge, preprints symposium New Orleans, vol. 1, 2, AAPG, USGS, IASH, 931 p.
- Barlow, A.C. – Philosophy of Deep-Well Disposal (Abstract), p. 667.
- Bond, D.C. – Deduction of Flow Patterns in Variable-Density Aquifers from Pressure and Water-Level Observations, p. 357-378.
- Clifford, M.J. – Hydrodynamics of Mount Simon Sandstone, Ohio and Adjoining Areas, p. 349-356.
- García-Bengochea, J.I., C.R. Sproul, R.O. Vernon and H.J. Woodard – Artificial Recharge of Treated Waste Waters and Rainfall Runoff into Deep Saline Aquifers of Peninsula of Florida, p. 505-525.
- Hall, C.W. and R.K. Ballentine – U.S. Environmental Protection Agency Policy on Subsurface Emplacement of Fluids by Well Injection, p. 783-794.
- Kaufman, M.I., D.A. Goolsby and G.L. Falkner – Injection of Acidic Industrial Waste into a Saline Carbonate Aquifer: Geochemical Aspects, p. 526-551.
- Kühn, K. – Asse Salt Mine, Federal Republic of Germany-Operating Facility for Underground Disposal of Radioactive Wastes, p. 741-766.
- Latta, B.F. – Subsurface Disposal of Waste in Kansas, p. 622-633.
- Lofgren, B.E. – Hazard of Waste Disposal in Groundwater Basins, p. 715-730.
- Lomenick, T.F. and A.L. Boch – Site Investigations for a Bedded-Salt Pilot Plant in Permian Basin, p. 634-651.
- Schicht, R.J. – Deep-Well Injection of Desalting-Plant Waste Brine, p. 652-666.
- Walker, W.R. and W.E. Cox – Legal and Institutional Considerations of Deep-Well Waste Disposal, p. 3-22.
- Warner, D.L. and D.H. Orcutt – Industrial Wastewater-Injection Wells in United States-Status of Use and Regulation, 1973, p. 687-700.
- Cook, T.D., editor (1972) – Underground waste management and environmental implications, proceedings symposium Houston, USGS, AAPG, AAPG Mem. 18, 412 p.s.
- Goolsby, D.A. – Geochemical effects and movement of injected industrial waste in a limestone aquifer, p. 355-367.
- Greenfield, S.M. – EPA-The environmental Watchman, p. 14-18.
- Hill, R.B. – Regulation of subsurface disposal in Texas, p. 381-384.
- Finkenwirth, A. (1965) – Deep well disposal of waste brine in the Werra potash region, IAH Mem. VII, p. 123-129.
- Freeze, R.A. (1972) – Subsurface hydrology at waste disposal sites, IBM Jn. of Res., p. 117-129.
- Hamstra, J. (1973) – Mogelijkheden in Nederland voor opberging van vast radio-actief afval in een steenzoutformatie, Atoomenergie, dec. 1973, p. 3-14.
- Jelgersma, S. and W.A. Visser, (1972) – Hydrogeological maps of the Netherlands, Geol. Mijnb. 51, p. 7-10.
- Kimpe, W.F.M. (1963) – Géochimie des eaux dans le Houiller du Limburg (Pays Bas), Trans. R. Neth. Geol. Min. Soc., 21-2, p. 25-46.
- Löhnert, E. (1967) – Hydrochemische Zusammenhänge am Kontakt zwischen versalztem Tiefenwasser und Süßwasser in Norddeutschland, XXIII IGC, 17, p. 127-135.
- Peelcommissie (1963) – Rapport van de Peelcommissie, deel 2, Trans. R. Neth. Geol. Min. Soc., MS 5, p. 47-85.
- Piper, A.M. (1970) – Disposal of liquid wastes by injection underground-Neither myth nor millenium, US Geol. Survey, circ. 631, 2nd print, 15 p.
- Sitter, L.U. de (1947) – Diagenesis of oil-field brines, Bull. AAPG, 31, p. 2030-2040.
- Studiegroep diepe ondergrondse lozing van afvalstoffen (1973) – Vooruitzichten tot ondergrondse verwijdering van afvalstoffen in Nederland, TNO, Delft, 127 p.
- U.S. Environmental Protection Agency (1973) – Ground water pollution from subsurface excavations, EPA 430/9-73-012, 217 p.
- Visser, W.A. (1972) – Experiences in deep well waste disposal, De Ingenieur, 84, p. A891-897.
- Visser, W.A. (1973) – Ondergrondse verwijdering van afvalstoffen. methoden, beperkingen, vooruitzichten, De Ingenieur, 85, p. 800-810.
- Warner, D.L. (1968) – Subsurface disposal of liquid industrial wastes by deep-well injection, AAPG, Mem. 10, edited by J.E. Calley, p. 11-20.