ST/ESA/13

## Natural Resources / Water Series No. 2

# GROUND-WATER STORAGE AND ARTIFICIAL RECHARGE

UNITED NATIONS

ST/ESA/13

Department of Economic and Social Affairs

## Natural Resources / Water Series No. 2

# GROUND-WATER STORAGE AND ARTIFICIAL RECHARGE

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## NOTE

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# FOREWORD

The Economic and Social Council, in its resolution 675 (XXV), requested the Secretary-General to take appropriate measures for the establishment, within the Secretariat, of a centre to promote co-ordinated efforts for the development of water resources. The resolution also singled out ground-water problems as one of the priority subjects in the development of a programme of studies.

Large-scale Ground-water Development, 1/ published in 1960, was the first study prepared in this field by the Water Resources Development Centre. This study, which was issued in English, French and Spanish, met with considerable success, but has been out of print for several years.

In 1963, the United Nations Conference on the Application of Science and Technology for the Benefit of the Less Developed Areas, acknowledged that "there was much interest in underground storage, especially of surface waters, because such storage prevents loss by evaporation. One of the newest techniques discussed was that of the artificial recharge of aquifers, i.e., of water-bearing underground strata". 2/

During the First United Nations Development Decade, many projects assisted by the United Nations Development Programme (UNDP) and other United Nations technical co-operation programmes, were entirely or partially devoted to ground-water prospection, assessment or pilot development. At the same time, however, there was an increased interest in the question of the potential of artificial recharge.

As a result, an expert panel was convened at United Nations Headquarters from 30 September to 11 October 1968 on the subject of ground-water storage. The panel was composed of Gilbert Castany (France), Roger de Wiest (United States of America), Vladimir Kunin (Union of Soviet Socialist Republics), Samuel Mandel (Israel), and Masatugu Murakami (Japan).

A second panel was convened at United Nations Headquarters from 8 to 19 September 1969 on the subject of artificial recharge. The panel was composed of Gilbert Castany (France), Vladimir Kunin (Union of Soviet Socialist Republics), Samuel Mandel (Israel) and Clinton Milne (United States of America).

The fruitful exchange of views that took place at these panel meetings, the numerous papers that were prepared by the panel members, and the subsequent exchange of correspondence between the panel and the United Nations Secretariat, provided the basic material and data that are presented in this study.

The material itself was compiled with the assistance of Ven Te Chow, University of Illinois, United States of America, and James Geraghty, consultant. The final draft was reviewed by Richmond Brown, hydrological consultant from the United States Geological Survey.

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1/ United Nations publication, Sales No. 60.II.B.3.

2/ Science and Technology for Development, vol. I, World of Opportunity (United Nations publication, Sales No. 63.I.21).

In this study, chapters I-IV give an over-all view of scientific, technical, economic and other aspects of ground-water storage and artificial recharge. The text is written so that it may easily be understood not only by ground-water specialists, but by water policy-makers and water management development professionals. To illustrate the general discussion on the subject of recharge, 34 case studies are presented in part two, dealing mainly with artificial recharge projects.

It is hoped that this publication, through the interest it may arouse, will contribute to a better utilization of water resources, especially in developing countries.

* * * * *

The present publication is the second in a series of United Nations publications dealing with water resources. Water Series No. 1, entitled Management of International Water Resources: Institutional and Legal Aspects (ST/ESA/5, United Nations publication, Sales No. E.75.II.A.2), was published in March 1975.

In 1974, another study, entitled National Systems of Water Administration was issued under the symbol ST/ESA/17, United Nations publication, Sales No. 74.II.A.10.

Other United Nations publications dealing with water resources issued over a period of years are listed at the end of the present publication.

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## Explanatory notes

The following symbols have been used in the tables throughout the report:

A dash (-) indicates that the amount is nil or negligible.

A blank in a table indicates that the item is not applicable.

A minus sign (-) indicates a deficit or decrease, except as indicated.

A full stop (.) is used to indicate decimals.

A comma (,) is used to distinguish thousands and millions.

A slash (/) indicates a crop year or financial year, e.g., 1970/71.

Use of a hyphen (-) between dates representing years, e.g., 1971-1973, signifies the full period involved, including the beginning and end years.

Reference to "ton" indicates metric tons, and to "dollars" ($) United States dollars, unless otherwise stated.

# INTRODUCTION

Ground water is the largest source of fresh water available in storage on the earth. While fresh-water lakes hold about 120,000 km$^3$ of water, the estimated amount of ground water, to a depth of half a mile into the crust of the earth, is about 4 million km$^3$. An additional 14 million km$^3$ of water occurs at depths between half a mile and two miles, under less favourable conditions in terms of economic accessibility and chemical suitability for common uses. This underground storage constitutes a vast and almost ubiquitous resource for satisfying water requirements of all kinds. Moreover, additional storage space under the surface of the soil, if properly utilized, increases the available water resources by impounding for future use waters which would otherwise be lost through evaporation or run-off to the sea. Ground water is often the only source of water in arid and semi-arid regions of the earth, and in such regions it is of fundamental importance to any social or economic development. In humid parts of the world, where rivers and lakes have historically supplied much of the water needed by man, the value of ground water has tended to be overlooked. In recent decades, however, as surface-water supplies have been depleted or contaminated, more attention has been given to ground-water resources and, today, ground water constitutes a major source of water-supply in many humid countries. In 12 states of the United States of America, for example, ground water accounts for from 30 to 65 per cent of all water withdrawn for drinking purposes, industrial applications and irrigation.

The technological break-throughs of the past 25 years constitute an important factor that has rendered possible the large-scale exploitation of ground water. In the past, knowledge of ground water was not only meagre but often misleading. The general attitude was that ground water is something hidden and mysterious and that it requires the use of near-magic practices for its prospection. Currently, however, it is well known that effective methods and tools are available for hydrological research and exploitation and, therefore, for the understanding of ground water. Some of these technological achievements are adaptations of methods originally developed for the identification, assessment and exploitation of petroleum and natural-gas resources that are stored underground under conditions similar to that of ground water. As a result, the greatly increased knowledge of the geology and hydrology of the areas investigated, the more detailed understanding of the hydraulics of ground-water flow and recharge, the improved methods of hydrological analysis and the application of electronic data processing techniques to ground-water problems have led to a more accurate quantitative determination of the water resources stored underground and of the nature of their replenishment. Various new tools have been developed for the purpose of collecting field information on ground-water storage. These developments have taken place especially in the field of geophysics, hydrochemistry, remote-sensing, tracers and environmental isotope-analysis.

These advances in technology have also resulted in enormous increases in the extraction of ground water the world over. Formerly, when modern machinery and sources of energy were not available, man obtained ground water from natural springs or shallow drains; or from wells, some of which were dug to great depths into water-bearing materials beneath the land surface. These methods for obtaining ground water were not very productive, and a tremendous amount of human or animal power was required to lift even a modest amount of water to the surface. Currentl in the search for ground water, a wide variety of drilling machines has made it possible to reach a thousand metres and more, even in hard rock, below the land surface, and high-capacity pumps are available that can deliver several cubic metres of water per minute from a single modern well. However, in some areas whe natural replenishment of ground water is inadequate to keep pace with accelerated extraction resulting from growing water demands, the amounts of ground water naturally in storage are decreasing substantially. Although, in many areas, depletion is a slow process, because of the large amounts of ground water in storage, it can eventually cause severe water-supply problems. Over-draught may also result in the alteration of water quality, as it may cause an intrusion of water stored in salty aquifers or an intrusion of sea water in coastal areas. However, in many places more water is available during short periods of time than is naturally recharged to the ground-water reservoirs. Where such excess water is available, the depleted reservoirs may be replenished by means of induced or artificial recharge, thereby utilizing the maximum potential storage capacity of the aquifer.

In general terms, the word "storage", as defined in dictionaries, has the following meanings: the act of storing, the state or fact of being stored, the capacity or space for storing and the price charged for storing. The phrase "to store" means, essentially, to accumulate a commodity in a certain space for future use. Some ground-water scientists prefer to consider ground water either a flow-resource or a stock-resource, depending upon its renewability. As a renewable flow-resource, ground water can be properly and economically developed and utilized indefinitely, within the limits of a "safe yield" corresponding approximately to its natural replenishment; whereas a stock resource can be "mine only once, similar to an ore which is extracted from the earth and, in time, will be entirely exhausted. Unfortunately, these two concepts alone do not adequately convey the full potential of ground water as a natural resource. In this study, therefore, the term "ground-water storage" is emphasized to express techniques that permit a maximum utilization of the ground-water resource. Ground-water storage includes the concept that the subsurface geological formations are to be considered a "warehouse" for storing water supplies that in the main come from sources located on the land surface. The consumers or users of water normally h to take this valuable commodity out of the ground through wells, springs, pits o other facilities. According to the various definitions mentioned above, ground-water storage implies the following:

(a) The act of accumulating water in subsurface geological formations for future use; this act is either natural or due to human effort. The subsequent a of extracting the water also is implied;

(b) The state or fact of this accumulation of water;

(c) The capacity or space that is available in ground-water reservoirs fo storage;

(d) The economic price of ground-water storage, taking into account the f that the storage may be natural, induced or created. In discussing this price, water is to be considered as a public necessity or as a commodity. In the latte case, it is at the disposal of a consumer who needs it and pays a price for it.

In this study, both the technological and the economic aspects of ground-water storage are discussed. It should be observed, however, that while much is known of the economics of surface-water storage in natural lakes or in reservoirs that have been created by dams, the usefulness and economic potential of ground-water storage is less well-recognized. Nevertheless, ground-water storage exists practically everywhere in the world and, in comparison with other sources of water supply, requires a small investment for its use. Moreover, ground water frequently occurs with an enormous capacity and releases a water-flow that is more or less independent of variations in seasonal precipitation.

Ground-water storage, because it is not physically perceptible, is, conceptually, poorly understood by most people. The possibilities and benefits of developing ground-water storage as part of current schemes for water-resources development and management are insufficiently known by government officials, planners and engineers, especially in developing countries. It is hoped that the present report will contribute towards an understanding of these possibilities and benefits.

Part one reviews the features of ground-water reservoirs, their exploitation, artificial recharge methods and their involvement in water-management schemes. Part two contains 34 case studies from countries throughout the world.

# PART ONE

# GROUND-WATER STORAGE AND ARTIFICIAL RECHARGE

# I. GROUND-WATER RESERVOIRS

Water is present in all geological formations; however, the term "ground water" includes only water that can flow through the formation and can be released by it through drainage or pumping. Therefore, the term excludes water which composes the mineral constituents of rocks and also molecular water attached to lithological units by strong capillary forces. The term also excludes water that is contained in closed pores or cavities.

Basically, ground-water flow can occur either in porous media or through cracks and channels. In porous media, the range in permeability of rock units to the flow of water makes it convenient to subdivide the solid geological formations into "aquifers", which are permeable water-bearing and water-releasing formations; "aquicludes" and "aquifuges", which are relatively impermeable formations; and "aquitards", which constitute rocks of an intermediate permeability. The dimensions and the types of interconnexion of the pores in rock formations are the basic factors which determine ground-water flow. The hydraulics in porous media is a subject which is now well known; ground-water hydrologists have at their disposal a number of mathematical formulae and other analytical tools that allow them quite accurately to evaluate the potential yield of ground-water reservoirs and to define the optimum conditions of their utilization. Ground-water flow in fractures and fissures can also be predicted, but owing to the lack of homogeneity, the quantitative expression of flow parameters remains controversial.

When the interconnexion of the cavities containing the water has sufficient extension, this water is considered as forming a "ground-water body" or a "ground-water unit", contained in reservoir rock. This reservoir may involve more than one geological formation and may also include pore water as well as fracture water, but usually a ground-water reservoir corresponds to a defined geological or physiographical structure. Several classifications of aquifer or reservoir systems can be made. For example:

(a) The type of porosity: intergranuler fractures or channels;

(b) The origin of geological formations: igneous; metamorphic; or sedimentary

(c) The lithology: sandstone; limestone; or basalt;

(d) The type of geological structures, such as mesa or syncline;

(e) The physiographical unit, such as plateau, alluvial fill or fan.

The criteria for classification might also be the conditions of natural replenishment of the reservoirs when exploited:

(a) Practically no replenishment;

(b) Potential exploitation exceeds the possibilities of replenishment;

(c) Replenishment potential exceeds the exploitation potential.

Instead of employing a theoretical system of classification, a number of ground-water reservoirs as they occur in the world, in various geological, climatic and geographical conditions is described in the form of case studies. (See part two.) This extensive sampling reveals the existence of certain types of exploited or exploitable ground-water reservoirs.

In the following sections, the general features of ground-water reservoirs and the conditions of ground-water storage are reviewed with respect to physical, physiographical, hydraulic and hydrochemical conditions.

This discussion of ground-water reservoirs and storage is not a repetition of the more general material included in the United Nations publication Large-scale Ground-water Development; 1/ here the emphasis is on technical considerations, specific examples and quantitative data which delineate and illustrate the concept of ground-water reservoirs.

## A. Physical characteristics of geological formations as aquifers

The storage and the release of ground water by a given geological formation are, as previously mentioned, closely related to the type of pore space contained in the bulk of the formation. The nature, dimension, shape and interconnexion of the cavities are quite diverse; they can be observed in the field and measured in laboratory.

The intergranular type of cavity occurs principally in unconsolidated rocks, but may also occur in consolidated and dense formations, amalgamated by means of porous cement.

The dimension and shape of openings in compact rock is related to their origin, whether of a sedimentological, tectonical or weathering nature. Various types of openings can occur, such as faults, crushed areas, microclefts, diaclases, stratification and schistosity joints. These discontinuities in the case of microclefts, may be as narrow as a few microns; or, in the case of faults, as long as 20-50 km or more.

"Porosity" is defined as the ratio of the volume of voids to the volume of aquifer under consideration. Porosity of consolidated materials depends upon the degree of cementation, the extent of fracturing and the size and degree of interconnexion of solution openings. Porosity of unconsolidated materials depends upon the packing of the grains, their shape, arrangement and size-distribution. Small grains will fit into the openings left between grains of large diameter, and thus a medium with a non-uniform distribution of grain-sizes will have a smaller porosity, than a medium in which the grains are well-sorted. Total porosity, expressed as a percentage, is defined as the sum of "effective porosity" (also called "specific yield"); the amount of water which can be drained by gravity from a unit volume of aquifer and "specific retention", which is the volume of voids per unit volume of aquifer that is occupied by water that cannot be drained by gravity. Because of specific retention, the amount of water that can be extracted from an aquifer is always less than the total volume of water contained in the aquifer.

Table 1 presents a summary of the types of porosity and per cent of pore space that occurs in different types of rocks classified on the basis of their origins:

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1/ United Nations publication, Sales No. E/F/S.60.II.B.3.

Table 1. Water-bearing geological formations, type of porosity, average value of total porosity

(Aquifers by origin)

| | Sedimentary | | Igneous and metamorphic | | | Volcanic | |
|---|---|---|---|---|---|---|---|
| | Clastic rocks | | Compact rocks | | | Clastic rocks | |
| | Consolidated | Unconsolidated | Rocks of chemical and biochemical origin (mostly carbonate rocks) | | | Consolidated | Unconsolidated |
| Intergranular porosity | | Gravels sands<br>Clayey sands<br>Sandy clays<br>(up to 65%) | | Weathered zone of granito-gneiss (up to 50%)<br>(more or less consolidated; evoluting towards clastic unconsolidated) | Weathered zone of basalts etc. (up to 20-30%) | | Blocks and thrown-ups;<br>Ashes;<br>(20 to 50%) |
| Intergranular and fracture porosity | Breccias conglomerates: quite variable;<br>Sandstones: (2-30%, average 10-15%);<br>Slates: less than 3% | | Zoogenic limestones;<br>Oolithic limestones;<br>Calcareous grits;<br>(2-35%, average 5-35%) | | | Volcanic tuffs;<br>Cinerites;<br>Breccias;<br>Phtanites;<br>(10 to 50%, up to 85% in pumice) | |
| Fracture porosity | | | Limestones;<br>Dolomites;<br>Dolomitic limestones<br>(up to 10%, often less than 1%) | Granites;<br>Gneisses;<br>Gabbros;<br>Quartzites;<br>Diorites;<br>Schists;<br>Micaschists;<br>(less than 3%, most often less than 1%) | Basalts phonolites etc.<br>(1-10%, often less than 1%) | | |

sedimentary; igneous; metamorphic; and volcanic. The effective porosity and hydrological characteristics of main aquifer formations are reviewed later in this chapter.

Sedimentary rocks can be subdivided into two groups which have quite different storage properties: clastic rocks and rocks of chemical or biochemical origin. The clastic rocks include both consolidated and unconsolidated rocks. All the rocks of the chemical and biochemical group are of the compact type; the main ones are the carbonate rocks.

The unconsolidated clastic rocks are characterized by intergranular openings. The consolidated clastic and compact rocks, and particularly rocks of chemical and biochemical origin, are commonly characterized by fissure-type openings.

Unconsolidated clastic rocks are composed of detrital rock particles of various shapes and dimensions. Their water-bearing properties are determined by the range and proportion of the size of rock particles. Pebbles and gravels, which are somewhat angular and of a size not less than 2 mm are the best aquifers. Thus, the coarse alluvial fills in river valleys are usually good aquifers, except where fine-grained silts and clays limit their water-bearing properties. Sands of from 0.1 to 2.0 mm are good aquifers. Clayey sands, sandy silts and sandy clays can generally be considered as aquitards. Oozes, silts and clays are definitely aquicludes.

Limestones and dolomites are the principal types of rocks of chemical or biochemical origin. In these rocks, the openings are characterized mainly by fractures. Intergranular spaces are either rare (chalk, oolitic limestones) or absent (crystallized limestone and dolomites). When exposed to mechanical erosion and the weathering action of water, the fractures are broadened and an underground network of large cavities and channels is created through a process termed "karstification". Karstic carbonate rocks are excellent aquifers for ground-water storage. They are especially abundant in the Mediterranean area where they are found in Algeria, France (south-eastern part), Greece (including Crete), Israel, Italy, Lebanon, Morocco, Spain (including the Balearic Islands), Tunisia, Turkey and Yugoslavia. Karstic carbonate rocks are also present in many other places, such as the Caribbean area and Thailand.

Compact volcanic rocks are mainly basalts having fracture-type porosity. Basalts are generally good aquifers and are especially abundant in Central America, East Africa and Hawaii. Clastic volcanic rocks may be of a consolidated type, such as volcanic breccias, volcanic tuffs or cinerites; or they may be of an unconsolidated type, such as blocks and ashes. Clastic volcanics, which have an intergranular porosity, often have a wide range of water-bearing properties and may be classified as aquifers, aquitards or aquicludes.

Weathering processes commonly reduce the upper parts of igneous and metamorphic formations by several layers of more or less clayey or granular material. The remaining granular layers may constitute good aquifers, but their thickness is usually moderate, in favourable cases not exceeding 3-5 m. Total thickness of the weathered zone in a tropical humid environment, such as West Africa, is normally in the range of 15-30 m. Igneous and metamorphic rocks are characterized by layers having low permeability and porosity, which, in most cases, are discontinuous and less permeable with increasing depth. However, some fractured zones may yield much larger quantities of water.

As may be expected, porosity is related to the rate at which a formation can transmit water. This rate of transmission is expressed by what is termed the "hydraulic conductivity" 2/ of the formation, which is related more to effective porosity than to total porosity. Indeed, pore size and interconnexion is far more important than total porosity with respect to the water-transmitting capability of a bed. Sands with relatively large rounded or angular grains, for example, may have a smaller porosity than clays, but have greater hydraulic conductivity.

The hydraulic conductivity of an aquifer is commonly indicated by $K$, and may be expressed as $K = k\frac{\gamma}{\mu}$, where

$\gamma$ = the specific weight of water,

$\mu$ = the dynamic viscosity of water,

$k$ = the intrinsic permeability of the medium.

Hydraulic conductivity is expressed in terms of velocity. In the metric system, is expressed as m/day; in British units, it is expressed as ft/day.

The darcy unit, which is used in petroleum engineering as well as in hydrogeology, has been pre-empted as a measure of the intrinsic permeability of $k$. It is defined as

$$1 \text{ darcy} = \frac{\dfrac{1 \text{ centipoise} \quad \text{cm}^3/\text{sec}}{1 \text{ cm}^2}}{1 \text{ atmosphere/cm}}$$

This leads to

$$1 \text{ darcy} = 0.987 \times 10^{-8} \text{ cm}^2$$

$$1 \text{ darcy} = 1.062 \times 10^{-11} \text{ ft}^2$$

$K$ can be evaluated either through laboratory measurements on samples or by analysing the results of field-pumping tests. For the same formation, the results may be quite different because of the larger volumes of rock used in field-pumpi tests.

Some values of intrinsic permeability are given in the following table.

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2/ Also called "permeability", somewhat incorrectly.

## Intrinsic permeability of various types of formations

| Type of formation | Darcy value |
|---|---|
| Metamorphic and plutcnic rocks | Near zero |
| Solid rock | Near zero |
| Metamorphic and highly fractured zones | Several hundred darcys |
| Medium-grained sand | 1,000-30,000 millidarcys |
| Siltstone | 0.1 millidarcy |
| Clay-rich dense limestone | 1 millidarcy |
| Medium-grained sandstones | 1-500 millidarcy |
| Partly cemented coarse limestone breccia | Several thousand darcys |
| Limestone having original porosity | 10-500 millidarcys |
| Alluvium sands (coastal plains) | 10-100 darcys |
| Clay and silt alluvium | Less than 0.1 darcy |
| Dune sands | 5-50 darcys |
| Loess | $10^{-4}$-1 darcy |

## B. Physiographical characteristics of geological units as ground-water reservoirs

Favourable lithological conditions are essential but are not the only factor affecting ground-water storage. Thus, the water-bearing formations must be part of a geological or physiographical unit or structure whose dimensions and shape will retain substantial amounts of water in porous and permeable formations.

The evaluation of the storage potential of an aquifer or ground-water reservoir is invariably based upon knowledge of dimensional data of the reservoir rocks, including their thickness and lateral extent. The thickness of any aquifer is determined by both geological and hydrological limits or boundaries.

All aquifers have geological boundaries which were created by stratigraphic and tectonic processes. Stratigraphy determines changes in the lithology or physical structure of the materials. For instance, a water-bearing formation may be limited down-gradient by a change in facies. In an alluvial bed, gravel and sand may gradually grade to silt and clay; a lens of send may be invaded on its edges by clayey material; sandstone may gradually become richer in thin elements filling the spaces left by larger grains· in a massive of limestone, wide fractures and dissolution channels may be limited to certain areas.

As an example of reservoir dimensions, the Sacramento valley in California has a surface area of some 10,000 $km^2$; it has been calculated that the average effective porosity in the saturated zone between 7 and 70 m deep (the useful oscillation limit in the piezometric surface), is about 7 per cent. Thus, the capacity for water storage in this underground reservoir is about 45,000 million $cm^3$.

Another example is in the vicinity of San Antonio, Texas, where plans now exist for the utilization of an underground reservoir consisting of a bed of limestone 280 km long, 70 km wide and 120 m thick. Since 1962, the extraction of water from this reservoir has been greater than its natural inflow; and in order to compensate for this deficit, it is proposed to replenish the reservoir with the water from surface-reservoir storage of three rivers. The water will be channelled from the surface reservoirs to the underground reservoirs in order to avoid loss through evaporation, which is very large in that area.

Israel is a country where more than 50 per cent of the water resources, some 2,000 cubic hectometres (hm$^3$) a year, are located underground. Only Lake Genazareth, with a regulating capacity not greater than 1,000 hm$^3$ is available for regulating surface water. This is insufficient, so consideration is being given to utilizing as a reservoir, the aquifers presently being tapped. These aquifers are made up of calcareous sandstone, limestone and basalt and have a storage capacity estimated at several thousand cubic hectometres.

Another example of ground-water storage is the underground reservoir formed by the alluvial and deltaic deposits of the Besos and Llobregat rivers near Barcelona, Spain. The total quantity of water contained in these aquifers exceeds 1,000 hm$^3$. By artificially recharging and discharging these aquifers, it might be possible to use them as a surface-water reservoir having a capacity of about 200 hm$^3$, with the added advantage that this reservoir is located within the very centre of the consumption area and is already in existence. In Central Asia (Union of Sovet Socialist Republics) ground-water storage under the vast alluvial plains of Kara Kum and Kyzyl Kum has been estimated at several thousand cubic kilometres. These are only a few examples among the considerable number of ground-water reservoirs which are known in the world.

In determining ground-water storage conditions, not only dimensional but geomorphological factors should be considered. Such physiographical data as topography, location of hydrological stations and the effect of particular geomorphological features should not be overlooked. These parameters may be particularly significant, or typical, in controlling ground-water storage, as in the case of dunes and dune-complexes, which are most commonly located in coastal areas. For example, the dune formations of the Netherlands are 160 m thick, and storage may exceed 80 hm$^3$ of water in the Amsterdam region. Alluvial plains and deltas may be found close to existing streams; or they may be distant from such streams, having originated by vast spreadings of clastic deposits by ancient streams, such as that under the Crau plain in southern France. Ancient alluvial plains developed by rivers are particularly significant in their effect on natural recharge. They rarely exceed 20 m, but because of their large surface area they permit natural recharge of large volumes of water and provide a significant amount of storage. For example, in France 150 hm$^3$ of water are stored in the alluvial aquifer at Montereau and 120 hm$^3$ in the Crau; 30 hm$^3$ are stored at Biskra in southern Algeria.

The glacial and fluvio-glacial formations may have low hydraulic conductivity, owing to the amount of fine-grained materials they contain, but because of their great thicknesses these formations offer substantial storage facilities. This is the case in Canada, Federal Republic of Germany (northern part), Norway and Sweden. Basins and topographic depressions, originated by erosion processes and filled recently with clastic sediments, may provide local ground-water storage facilities in regions where bed-rock formations are poorly permeable, as in the depression of Lake Aleg in Mauritania, where the volume of water storage is 8 hm$^3$.

In arid zones, thick piedmont or foot-hill formations such as alluvial fans in the United States and proluvium in the Soviet Union offer potentially good conditions for infiltration. Geological structure may also have an important effect on storage. Faulted and crushed areas, large syncline areas with moderate dips and synclines or synclinoriums are structures favourable for the storage of ground water.

## C. Hydraulic factors

As may be expected, many hydraulic factors are associated with the occurrence of ground-water reservoirs. The main factors are:

(a) Amounts of water available for storage, which are closely related to the abundance and distribution of rainfall and infiltration areas;

(b) Hydrological properties of the aquifer related to the ground-water flow. This includes hydraulic conductivity, transmissivity, specific yield and storage coefficient;

(c) Hydrological boundaries of the ground-water reservoirs.

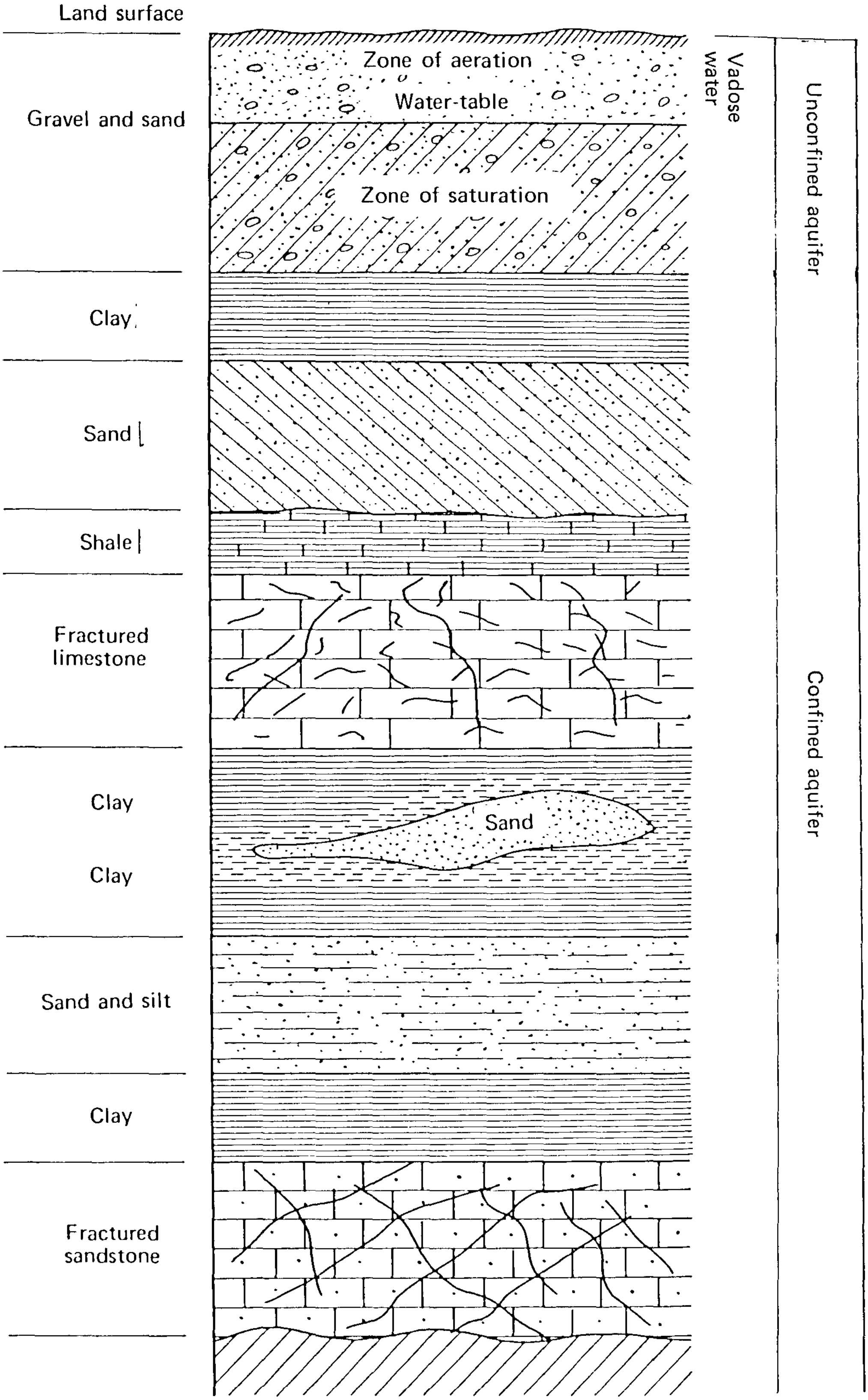
Some fundamental principles regarding the presence of ground water in geological formations should be mentioned here. (This subject is discussed in greater detail later in the report.)

As shown in figure 1, water underlying the land surface generally can be considered as subdivided into several unit types. The "water-table" is the surface below which all openings in the geological formation are saturated with water. The "zone of aeration", which is sometimes called the "vadose-water zone", exists above the water-table and contains water in various forms. Under dry conditions, the aeration zone, near the water-table, holds locally some water which is contiguous with the water in the saturated zone. Above this "capillary fringe", water in liquid form is scattered in tiny pockets in the ground. Lastly, in the upper parts, near the ground surface, water is present in the form of moisture vapour, moving upwards owing to the process of evaporation. The thickness of the capillary fringe is related to the nature of the geological materials and to the climatic environment; it does not exceed 2-5 cm in gravels; but may reach 30 m, or even more, in silts and clays.

Among water-bearing units capable of yielding water to wells, springs or streams, a classic distinction is made between "unconfined" or "water-table aquifers" and "confined" or "artesian aquifers". Unconfined water is found in the zone of saturation whenever the upper surface of the zone forms a water-table under atmospheric pressure, free to rise and fall with changes in the volume of stored water. Confined water is found in saturated aquifers that are separated from the zone of aeration by layers having markedly less permeability.

The distinction between confined and unconfined water is based chiefly upon the differences in permeability found in the bulk of geological formations. Such differences are commonplace, and although there are many exceptions, large bodies of unconfined water may locally have some degree of confinement. Since permeability is a relative term, confinement is also relative. Rocks with identical characteristics may form an aquifer in one location; elsewhere, when overlying a much more permeable aquifer, it may form a confining bed.

Figure 1. Vertical distribution of ground water



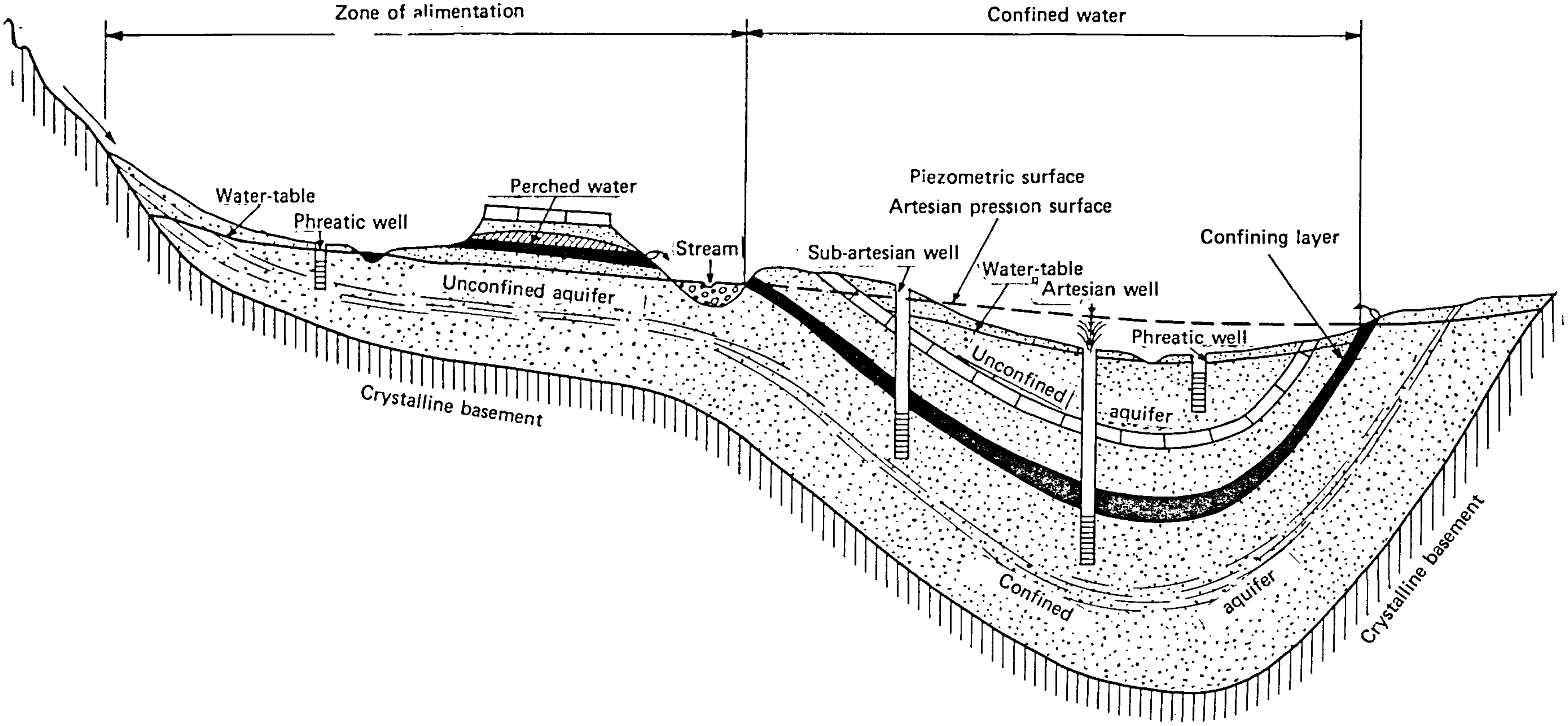
An artesian well is one in which the water level rises above the top of the aquifer in which it is encountered. If the water rises above the land surface, a flowing well is formed. When an artesian well is pumped, reduction of pressure occurs rapidly in the aquifer over time and in terms of distances from the discharging well, resulting in rapid piezometric pressure changes in other wells tapping the same aquifer.

For the hydrologist concerned with quantitative determination of ground-water storage and movement, an important reason for distinguishing between confined and unconfined water is that the hydraulics of flow differ and require different testing techniques and formulae. The difference between confined and unconfined water, may in many respects, be likened to the difference between flow in pipes and open-channel flow. It should be noted that the conditions of confinement can be changed by man's activity. Pumping from wells in confined aquifers may eventually de-water the upper part of the aquifer, first in the immediate vicinity of the wells and then in progressively broader areas, until the confined water in the entire aquifer may no longer be confined. The reverse may also occur in recharge operations, where water is injected into aquifers overlain by less permeable rocks.

Waters available for storage may originate from various sources. In natural conditions, ground water mainly originates from the infiltration of rainfall and from infiltration of snow-melt waters and surface run-off. In fact, natural storage of water underground constitutes an important part of the "hydrological cycle" of the earth, which is the path travelled by all waters of the earth, including both surface water and ground water. The oceans may be considered as the basic reservoirs of the earth in which most water originates and to which it returns. In the complete cycle, water evaporates from the oceans and forms clouds which move inland, the clouds condense and fall to the earth as precipitation. From the land, the water runs into the oceans through river channels and underground. Although no water is destroyed in this process, neither is any generated, and not all water particles complete the entire hydrological cycle. For example, there are built-in short circuits or partial cycles in which water evaporates from land and returns to land as precipitation, only to evaporate again, and so on. The time elapsing between infiltration from precipitation and discharge back in to the atmosphere varies within the widest of limits. Downward movement of water to the water-table may take from a few days to a few weeks, and even a few months or years.

The three variables controlling this downward movement are: (1) the supply of water infiltrating; (2) the vertical permeability of the materials between the surface and the water-table, and (3) the depth to the water-table. The residence-time of ground water within the zone of saturation, once that zone has been reached, may vary from a short to an extremely long time. Water in shallow zones of saturation in humid regions normally moves to discharge in springs, or directly into beds of streams, in times varying from a few days to weeks, months or, at most, a few years. On the other end of the scale, water may remain within a ground-water reservoir for tens of thousands of years. Age-dating of water in the great reservoir beneath the Sahara and beneath Arabia, for example, shows that the water infiltrated during rainy periods of the ice-age, as much as 30,000 years ago. For aquifers in northern Europe (Federal Republic of Germany, German Democratic Republic and the Netherlands), the age would be from 8,000 to 10,000 years. The residence-time for water within an aquifer system depends upon such variables as distance from the point of infiltration to the point of discharge, hydraulic gradient within the reservoir, and permeability of the reservoir materials.

Figure 2. Confined and unconfined aquifers



Development of the reservoir by man adds additional points of discharge, thus unnaturally depleting the reservoir and shortening the residence-time. Ground-water recharge may also occur from such surface-water bodies as natural or artificial lakes and ponds. It must be emphasized that the surface-water bodies may be perennial, temporary, natural or artificial and that the hydraulic connexion between these bodies and the water-table within the unconfined aquifers is often very close. Such connexions also exist between rivers and streams and confined aquifers, and also between confined and unconfined aquifers, as the confining beds allow water to percolate through them. In fact, in the earth's crust, almost any ground-water reservoir is more or less related to atmospheric and surface water. In addition, sea water may intrude inland into the aquifer by infiltration, in order to maintain equilibrium with decreased head in the overlying fresh ground water.

Apart from surface sources, ground water is supplied secondarily by subsurface inflow into the aquifer from adjacent areas of higher head. Ground-water storage may be increased by artificial recharge by spreading of water on the surface of the ground or by injection of water into wells. The storage underground of desalinated waters has been envisaged in some special cases. Ground water may also be recharged by seepage of waste water injected into the aquifer for disposal purposes.

The quantities of waters which will be available for future storage depend upon environmental conditions, especially such climatic factors as the amount of rainfall, rate of evapo-transpiration and run-off. These factors vary extensively from one climatic area to another. In arid zones, the annual potential evaporation is considerably higher than the average annual precipitation. However, when precipitation occurs, it is often in the form of short and heavy rainstorms. Therefore, during a short period each year, precipitation exceeds the potential evaporation ratio. During these short periods, soil moisture is replenished, while surface run-off of flood water is intense. In humid, tropical areas, rainfall generally exceeds the potential evaporation, in spite of the hot climate. However, very intense rainfall often alternates with dry seasons, in which a temporary deficit of water occurs. In very cold regions, such as within the Arctic Circle, perennially frozen ground, or permafrost, is extensive. The permafrost may not be continuous, but it profoundly affects the infiltration and the circulation of ground water and, in extreme cases, makes the recovery of ground water virtually impossible.

For practical purposes, the amount of flood water available for storage in a defined ground-water reservoir is extremely variable from one area to another; usually the capacity of the reservoir is the limiting factor, except in some desertic and very arid locations. The discharge characteristics of run-off waters are of special importance for flow occurring in arid zones; this discharge is commonly in the form of major floods that occur within a short period of time. Therefore, a large volume of surface flow does not necessarily imply a large amount of infiltration potential. However, the flow of surface water available for storage may be more regular in other situations; for example, surface waters supplied by a canal, by a waste-water treatment plant or by a desalination plant. However, the quantities of such flows are far less important.

Mention was previously made of hydraulic conductivity, $\underline{K}$, in which the capacity of a given aquifer to transmit ground-water flow is expressed as a measurement of velocity, specifically, metres per day. The transmissivity coefficient is more commonly utilized because it is directly obtainable by means of field-pumping test and because it is easily interpreted through the use of graphs. The transmissivity coefficient is the product of hydraulic conductivity and the averag thickness of the saturated aquifer, expressed in $cm^2$/sec or $m^2$/day. "Specific yield" or "effective porosity" is the volume of water which can be drained by gravity from a unit volume of the aquifer.

The ground-water flow that is induced by a depression created in the aquifer by means of pumping a well occurs under quite different conditions in confined and unconfined aquifers. When a well in an unconfined aquifer is pumped, the water-table declines in the vicinity of the well in the general form of an inverted cone, called the "cone of depression". The water being discharged from the well comes from water stored in the pores of the materials within the cone of depression. Generally, a large portion of the pore-water may lag behind, draining slowly downward into the cone of depression. In a confined aquifer, a pumping well will cause a pressure-surface on the confined water, termed the "piezometric surface", to decline in much the same way as water levels declined in the unconfined aquifer. In other words, a cone of depression develops on the piezometric surface. However, in the usual situation, the original piezometric surface and the developed cone of depression are both above the top of the confined aquifer, which means that the aquifer is still brim-full with water, even when the well is being pumped. The explanation for this apparent anomaly is that the reduction of hydraulic pressure in the aquifer caused by the pumping results in an extremely slight compression of the aquifer materials, and a slight expansion of the water in the aquifer. In other words, the aquifer becomes a bit thinner during a pumping operation, and a certain amount of water is thereby released from the aquifer materials. The compaction of the aquifer at any one point would be too small to detect normally, which means that only a very small amount of water is squeezed out of storage from a vertical column of material having, say, a 1 $m^2$ cross-section. Since the pumping well is extracting a relatively large amount of water, the cone of depression in the piezometric surface must become large enough so that the sum of all the contributions from all of the 1 $m^2$ columns is equal to the well discharge.

The relationships outlined above are expressed technically in terms of a "coefficient of storage", which reflects the amount of water derived from storage in the reservoir, as the water-table or piezometric surface is lowered by pumping. This coefficient is highest for unconfined aquifers, where it generally ranges from 0.01 to 0.2. In confined aquifers, the coefficient is much smaller, and tends to be in the range of from 0.005 to 0.00005. The coefficient of storage of a confined aquifer can be expressed as $S = \gamma b(\alpha + n\beta)$, where $\alpha$ = vertical compressibility of the granular matrix of the rock,

$\underline{n}$ = porosity,

$\beta$ = compressibility of the water,

$\gamma$ = specific weight of the water,

$\underline{b}$ = aquifer thickness.

The coefficient is significant only for elastic aquifers. The fact that confined aquifers are, apparently, all more or less compressible and elastic, was recogni by several American hydrologists, who introduced the concept of coefficient of storage, defined as the volume of water, measured in cubic feet, released from storage in each column of an aquifer having a base 1 $ft^2$ and a height equal to the thickness of the aquifer, when the water-table or other piezometric surface is lowered 1 ft. The storage coefficient is, therefore, a "dimension-less" number. In the metric system the coefficient of storage has the same definition with cubic metres, square metres and metres substituting for cubic feet, square feet and feet. The knowledge of the value of the coefficient of storage is essential in order to assess the over-all and maximum capacity and economic value of a given ground-water reservoir. It is essential to know the safe yield, but this is less hydraulic than economic, as it expresses the quantity of water which can be extracted "safely" from an aquifer, i.e., without diminishing in time the water resource, in quantity or quality.

The value of the coefficient of storage is not constant for a given aquifer; it may change with changes in the piezometric surface resulting from pumping. It is essentially equal to the value of effective porosity, when water is unconfined. Under water-table conditions, slow drainage of the aquifer takes place with time, so that there is an apparent increase in the value of the effective porosity with time. As an example, pumping tests in France, in the Durance valley alluvium, revealed an increase of the storage coefficient from 4 to 14 per cent. A "coefficient of replenishment" might be considered for characterizing the natural or artificial replenishment of an aquifer, as a homologous value of the coefficient of storage. Such a coefficient of replenishment might be defined as the volume of water, in cubic metres, which can be put into storage in each column of an aquifer having a base of 1 $m^2$ and a height equal to the thickness of the aquifer, when the water table or other piezometric surface is raised 1 m.

The boundaries of a ground-water body are not only of a physical or physiographical nature; hydraulic boundaries also constitute limiting boundaries of flow. These boundaries are determined by the head and physical position of contiguous water bodies. Discharge boundaries of constant head include spring outlets, hydraulic ground-sills and the level of underground overflows related to geological boundaries. Variable-head boundaries, that may serve either as recharge or discharge boundaries, include rivers, lakes, ponds, seas, pumped drains and wells and drainage and irrigation canals and ditches. Another type of boundary is represented by the contact inside an aquifer between two fluids having different specific weights, for example, an interface of fresh water/salt water.

The position of hydraulic boundaries can be either constant or varying. Their movement is related to head change. This movement is important in artificial recharge, because the recharge increases the head and therefore moves the boundaries. A provisional study must be made to predict the effect of shifting hydraulic boundaries that might take place as a result of recharge. Such shifts might either be favourable or unfavourable to artificial recharge schemes.

## D. Chemical factors

It is well known that the quality of ground water is closely related to the chemical composition of water-bearing materials, and especially to the nature and the amount of soluble substances contained in these materials. In addition, the chemical compositions both of the aquifer and the water may exert some influence

Table 2. Specific yield versus porosity

| Rock-type | Formation | Porosity (percentage) | Specific Yield (percentage) |
|---|---|---|---|
| Consolidated clastics | Normal sandstone | 37 | 27 |
| | Thin-grained sandstone | 33 | 13 |
| | Siltstone | 35 | 12 |
| Unconsolidated clastics | Coarse gravel | 28 | 21 |
| | Medium gravel | 32 | 24 |
| | Fine gravel | 34 | 28 |
| | Coarse sand | 39 | 30 |
| | Medium sand | 39 | 32 |
| | Fine sand | 43 | 33 |
| | Dune sand | 35 | 30 |
| | Glacial sand and gravel | 28 | 15 |
| | Eolian sand | 45 | 38 |
| | Silt | 45 | 20 |
| | Loess | 49 | 18 |
| | Clay | 42 | 6 |
| Compact carbonated | Limestone | 30 | 14 |
| | Chalk | 30 | 2 |
| | Tuff | 41 | 21 |

Source: Sampling and measurements by United States Geological Survey.

Figure 3a. Examples of geological boundaries

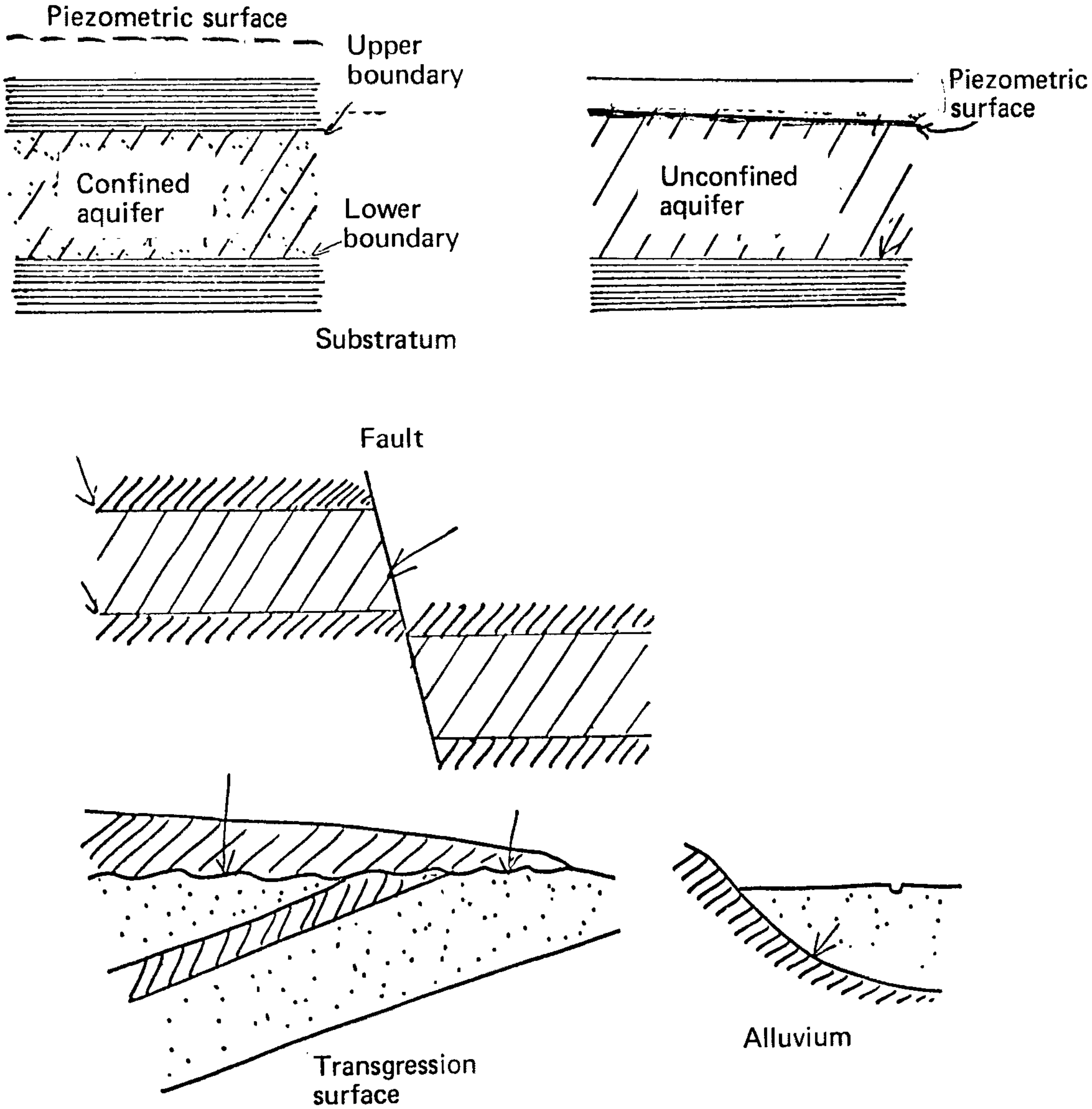
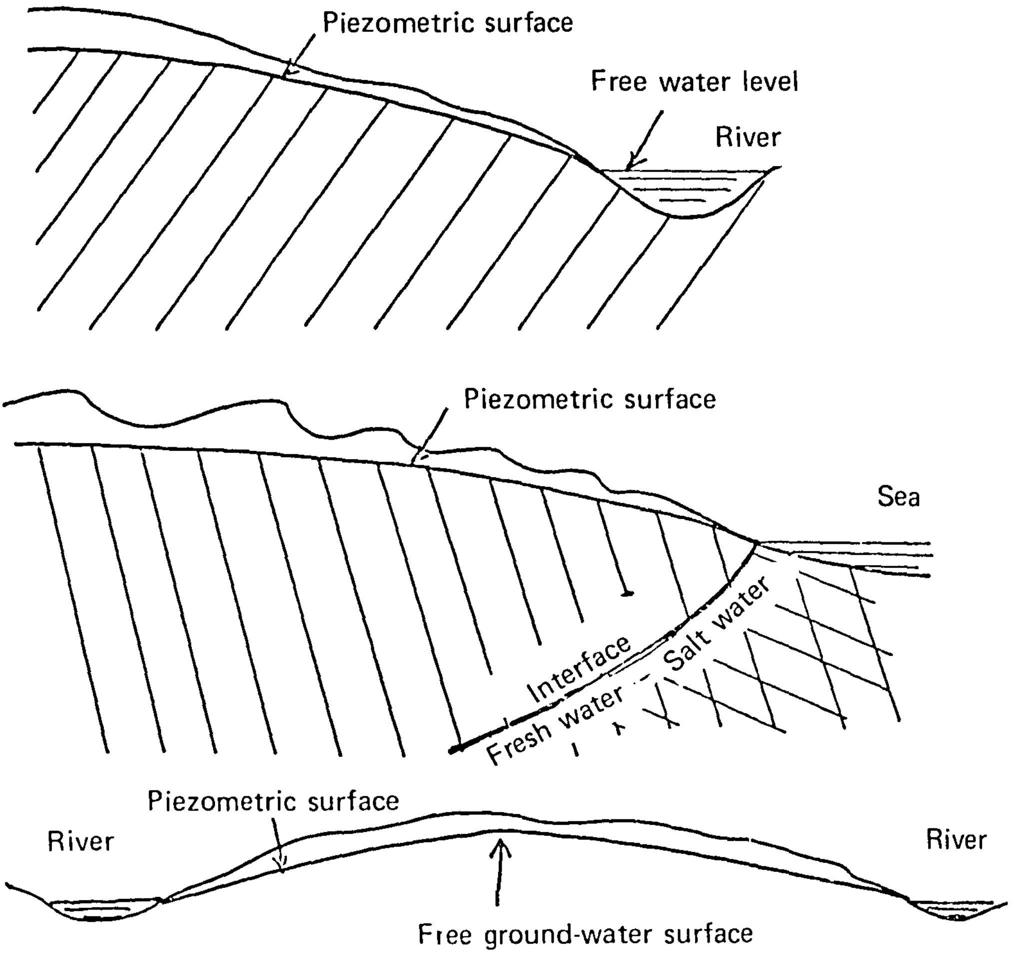


Figure 3b. Examples of hydraulic boundaries



on the ground-water flow itself. The chemical content of ground water is closely related to the lithology of the aquifer. The concentration of dissolved solids in ground water is related to the duration of contact of the water with the aquifer; thus, it is a function both of the extent of the aquifer and of the velocity of ground-water movement. During the flow, the mineral content of the water is modified by chemical processes, such that there may be changes in the concentration of dissolved solids, base exchange and sulphate reduction.

The rate of change in the chemical composition of infiltering meteoric water is more rapid when moving through unconsolidated porous media than when moving through fractures in consolidated rocks. However, chemical changes may be relatively rapid when moving through fractured carbonate rocks. In the zone of aeration, water may dissolve certain salts through infiltration. For example, iron may turn into solution as a result of the alteration of ferro-magnesian and ferric minerals; this process takes place in agricultural soil under the action of micro-organisms on organic material. Iron in solution, in the form of ferric compounds, enters the aquifer (saturated zone), it is then oxidized and precipitated. The velocity of the movement of the ground water, and the distance travelled between the recharge and discharge areas across various geological formations determine the time of contact of the ground water with the aquifer and the amount of dissolution and precipitation that takes place. Meanwhile, several hydrochemical changes can be developed in succession, down-stream.

Concentration of dissolved solids in ground water is mainly due to the solution of soluble substances contained in geological formations and, locally, by evapo-transpiration. High evapo-transpiration can be caused by high air and ground temperature. This is particularly significant in the arid zone. Solution of solid soluble substances occurs in the aeration zone as well as in the saturated aquifers, depending upon lithology, air and ground temperatures, hydraulic head or pressure, duration of contact of water with the water-bearing material, amount of water and its temperature and degree of saturation of the formation.

The major ions found in solution in ground water are Ca, Mg, Na, Cl, $SO_4$, $HCO_3$ and $CO_3$. The most common soluble combinations of these ions are calcium carbonate in limestone, magnesium carbonate in dolomites, calcium sulphate in anhydrite or gypsum and sodium chloride and potassium chloride in saline rocks. Other constituents such as silicates or silica are soluble in trace amount but are rarely found in significant quantities. The study of the chemical contents of ground water is very important for the determination of its origin and circulation. Generally, the concentration of dissolved constituents increases with depth, temperatures of water and soil, fineness of materials and distance to replemishment areas.

The time required for the process of concentration through solution relates proportionally to the undersaturation of major ions in the water. Therefore, total concentration of dissolved solids is roughly a parabolic function of the time of contact of ground water with the aquifer and is, thus, roughly related to length of ground-water flow-paths. Evapo-transpiration is the chief cause of concentration of dissolved solids in ground water, especially in the arid zone. The resulting precipitation may take place in the following order: first, calcium carbonate, carbonated crusts and carbonated tuffs; secondly, gypsum and gypseous crusts; and lastly, sodium carbonate and sulphate.

## Table 3. Central Tunisia: quality of ground water at various locations of ground-water flow

(From upstream to downstream under arid climate conditions)

| Name of outlet | Location | Concentration percentage (approximate) | | | | | | Total dissolved solids (Parts per million) |
|---|---|---|---|---|---|---|---|---|
| | | Ca | Mg | Na | Cl | $SO^4$ | $CO^3$ | |
| Ain El Kiss (spring) | Feriana (foot-hill of mountain) | 44 | 3 | 3 | 12 | 18 | 20 | 550 |
| Ain Djedidi (spring) | Gafsa | 22 | 12 | 16 | 10 | 33 | 7 | 1,780 |
| Lalla (bore-hole) | Gafsa (about 65-70 km downstream from Ain El Kiss) | 21 | 14 | 15 | 12 | 27 | 11 | 1,112 |
| Tozeur (spring) | About 150 km downstream from Ain El Kiss | 16 | 15 | 19 | 19 | 27 | 4 | 2,077 |
| Nefta (spring) | About 180 km downstream from Ain El Kiss | 18 | 12 | 20 | 21 | 26 | 3 | 2,881 |

However, the concentration of dissolved solids does not always increase with increasing lengths of ground-water flow-paths. On the contrary, in some cases, especially in shallow aquifers, dilution may occur owing to the addition of less concentrated water, for example, through infiltration of rainfall or irrigation water. Ground water is usually in contact with aquifer material for a long time at the contact with hydrochemical zones. Thus, the concentration of dissolved solids generally increases with depth. The presence of saline water (connate water) will, for example, further increase the concentration in the aquifers in the sedimentary basin of Paris. It also should be noted that when evapo-transpiration takes place from a shallow aquifer, the vertical distribution of concentration is altered, especially in the arid zone.

Certain aquifer materials have the property to absorb and exchange their soluble constituents with those contained in ground water. This phenomenon is known as "base exchange" and takes place mainly in certain clay minerals such as montmorillonite, vermiculite, zeolite, organic substances, glauconite etc. These exchangeable bases will effect the characteristic proportions of metals in solution in ground water, and in particular the ratios of K/Na, Na/Ca, Na/Mg and Mg/Ca.

Certain hydrochemical anomalies should be carefully considered. For instance, the ionic component in sulphates may be very small, or even nil, whereas the contents of hydrosulphide, sulphur and hyposulphite may be very high. This phenomenon is due to the extensive presence of organic material in the aquifer or in discharge areas, as in the case of peaty terrains, where wells are polluted by animal excretion. The presence of sulphite, sulphur and hydrogen sulphide in water is often a sign of pollution. It is assumed that the reduction of sulphates, in most cases, is due to the action of specific anaerobic micro-organisms that exist in fresh and moderately brakish waters. A typical example, where ground water is enriched with sulphur and hydrogen sulphide due to the action of micro-organisms, is in the mineral springs of Enghien, near Paris. The high sulphate-confined water from Cenozoic gypiferous limestone percolates through a peaty capping that is rich in bacteria. This capping, covering the bottom of a lake under 3-7 m of water, provides thermal springs that are rich in sulphur and hydrogen sulphide.

Deep aquifers often have a high content of dissolved solids. They are not exploited when this content renders the waters unusable for human consumption, irrigation or industrial use, except if water is needed for such uses as oil drilling, road construction or water desalination. In unconfined, shallow or intermediate-depth aquifers, water quality is not a problem, in most cases, because the content of dissolved solids in rainfall and run-off waters is often very low.

Certain physical characteristics of ground water that result from its movement or storage underground are closely related to its chemical composition. Thus, electrical resistivity measurements indicate the salinity of water, and measurements of pH indicate the corrosion-power of water on metals. Ground-water storage exerts a remarkable regulating effect on water temperature. In Frankfurt it has been observed that in shallow alluvium, at 10 m depth, for a ground-water flow of 0.8-1.3 m/day, the temperature is uniform after 70-140 days. Water temperature increases with depth; in deep artesian aquifers, waters are sometimes too hot to be utilized for such purposes as irrigation. Conversely, shallow waters often have a moderate temperature that renders them fit for many uses, and are generally free of most adverse biological actions. Ground water is sometimes turbid, because of suspended particulate matter, or coloured with organic or colloidal matter. Turbidity and colouring are due, in part, to contact of water with clayey beds or peat bogs. Red colours sometimes indicate a ferric content. In the vicinity of some mines, ground water is often polluted by waste water. Flood waters often contain suspended matter; silts, clays and other material which may, in some cases, hamper infiltration and clog artificial recharge works.

Under certain conditions, the biological and chemical quality of surface waters can be improved, if the water if infiltrated underground, with the geological formations acting as a natural filter. Where recharge water is very high in dissolved solids, a storage of short duration may show a noticeable decrease in total hardness, carbon dioxide, iron and manganese, and an increase of dissolved oxygen and in pH; this means that the aggressiveness of water is lowered. A longer period of storage may result in an increase in carbon dioxide, iron and manganese. In Goldstein, Federal Republic of Germany, waste waters are injected underground because of their impurities. After 38 days, which corresponds to a path of 20 m, the impurities have been destroyed; after 190 days, corresponding to a path of 100 m, the colour, bad taste and odours disappear.

A knowledge of the chemical content of ground water and of the water bearing formations are essential in order to select the proper treatment process for artificial recharge waters; precipitation, oxygenation or sterilization may be required to protect the infiltration grounds or injection wells against clogging, and to increase the effectiveness of renovation.

## E. Structure of ground-water reservoirs

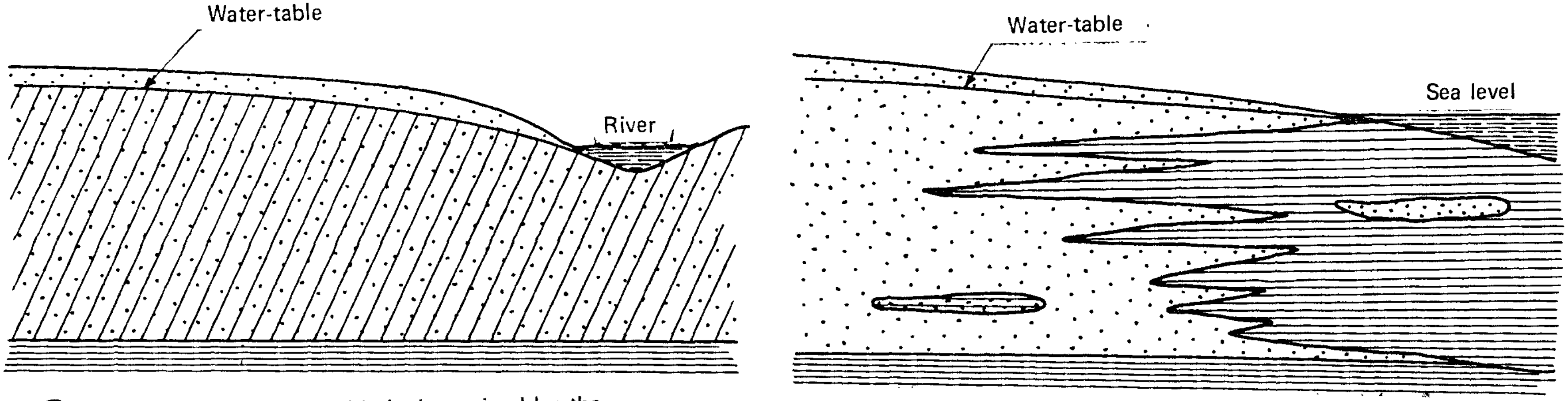
The structure of a given ground-water reservoir is determined by geological and hydraulic boundaries. Confinement commonly exists where the boundaries are low-permeability formations, where aquifers are unconfined and where the base level of the outlets is a surface water-body, such as a stream, lake or sea. These hydraulic boundaries effect the greatest control on movement of water within the aquifer.

All ground-water bodies are limited downwards by an impervious or semi-pervic substratum. Where aquifers are confined, the upper limit is a low permeability layer; where aquifers are not confined, the upper limit is the water-table. The position of lateral boundaries is often the chief consideration in assessing the capacity of a reservoir, as most aquifers are not economically exploitable for the whole of their thickness.

Unconfined reservoirs are "perched", if there is unsaturated flow between the perched water body and the continuous water table. Discharge may take place from the top of the low permeability bed. When discharge is in contact with the bottom of the aquifer with a low permeability bed, two cases may be considered: (1) if there is no aquifer below the level of the outlet of the aquifer, and (2) an aquifer below this level. In other situations, the level of discharge may be located considerably above low permeability formations; under these conditions, surface discharge can be caused by the presence of a natural underground obstacle or dam, such as a low permeability substratum or a faulted zone, as may be found in the limestone reservoirs of Jbel Zaghouan in eastern Tunisia.

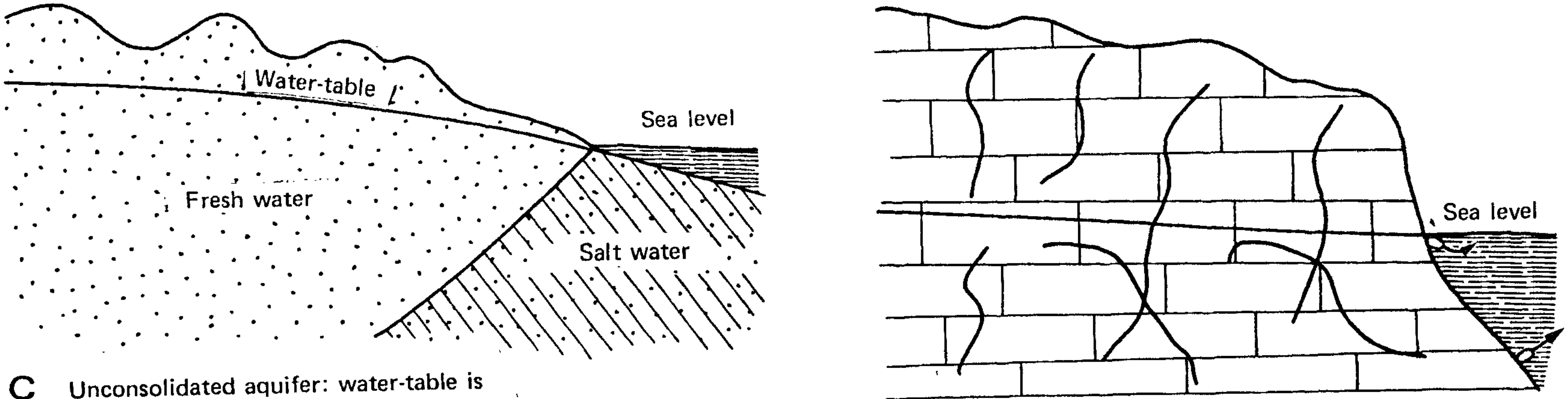
Artesian basins often have overflowing outlets at their edges and at the li of confined waters in storage and unconfined waters in replenishment areas. As

Figure 4. Sustained aquifers



a Alluvial aquifer: water-table is determined by the level of surface-water flow

b Delta aquifer: water-table is determined by a change in lithology



c Unconsolidated aquifer: water-table is determined by sea level

d Karstic aquifer: water-table is determined by sea level opposed to "perched" and "sustained" reservoirs, aquifers are closely connected with surface-water sources. In this case, the position of the water-table of the reservoirs "sustained" by the existence of an open-water surface, such as a river in an alluvial plain or the ocean in coastal areas (deltas, dunes) is determined by the drainage pattern. The "perched" and the "sustained" reservoirs may be defined as "open structures", as opposed to the "closed structures" represented by overflowing reservoirs, corresponding to grabens, subsident basins, depressions etc.

The aquifers which are "sustained", or recharged, by surface-water bodies, often provide significant storage. Replenishment is by means of infiltration of surface water to underlying aquifers. In a permanent river that recharges an alluvial aquifer, there is a hydraulic connexion between the river and the aquifer. The altitude of the bottom of the river-bed, above the base of the aquifer, determines the potential maximum storage in the system. The interrelationship between river and aquifer is considered as:

(a) Free and permanent, when the whole of the aquifer is cut by the river-bed and an impervious substratum is exposed at the bottom of the river. A hydraulic connexion exists through the river-bank only;

(b) Temporary or periodical, where the river-bed cuts the impervious substratum down to a certain depth and the water-level of the river rises above the substratum level only in high-water periods;

(c) Non-existent, when the water-level of the river is permanently below the level of the aquifer.

The ground-water flow which occurs in the alluvia ground-water reservoirs may generally occur in three directions:

(1) Towards the river. The river is a drain of the alluvia aquifer, the low-water flow of the river being supplied by flow from the alluvium. This case is most common;

(2) From the river towards the alluvium. The alluvium is replenished by the river; this replenishment is the hydraulic system where recharge is induced by intense pumping from the alluvial aquifer;

(3) In parallel to the river (this case is exceptional).

Similar situations develop when the ground-water reservoir is in contact with a lake or with sea water.

## F. Discharge, replenishment, storage

The discharge from a ground-water reservoir is carried through various kinds of outlets, natural and artificial. The main natural outlets are: springs discharging into surface streams; plants and evaporation areas directly connected with the aquifers, yielding ground water to the atmosphere in the form of vapour termed "evapo-transpiration losses"; and underground water-losses to other areas or to the sea. Wells and drains are the main artificial outlets.

The stream-flow (or "run-off") which occurs in a river is often the sum of surface run-off and ground-water flow that reaches the stream. Ground-water reservoirs contribute what is termed the "base flow" or "dry-weather flow" of rivers; therefore a study of the interrelationship between surface water and ground water is often indicated and, in many projects, measurements of surface discharge are the only means of indicating the amounts of ground water available. Surface run-off equals precipitation minus evapo-transpiration and infiltration. Infiltration is the passage or movement of water through the surface of the soil and is to be distinguished from ground-water flow. Surface run-off is a function of precipitation, type of vegetation, area of drainage basin, distribution of precipitation, stream-channel geometry, depth to water-table and the slope of the land-surface. Surface run-off is commonly represented in the form of a hydrograph, which is a time record of stream-surface elevation or stream discharge at a given cross-section of the stream. In general, a hydrograph is a plot of the discharge from a hydraulic or hydrological unit or system, such as a river or drainage basin, *versus* time. In the case of perennial streams, in periods of drought, when no direct overland flow reaches the river, the hydrograph is a line which slopes gently down. The stream-flow is made up entirely of ground-water flow, also called "base flow".

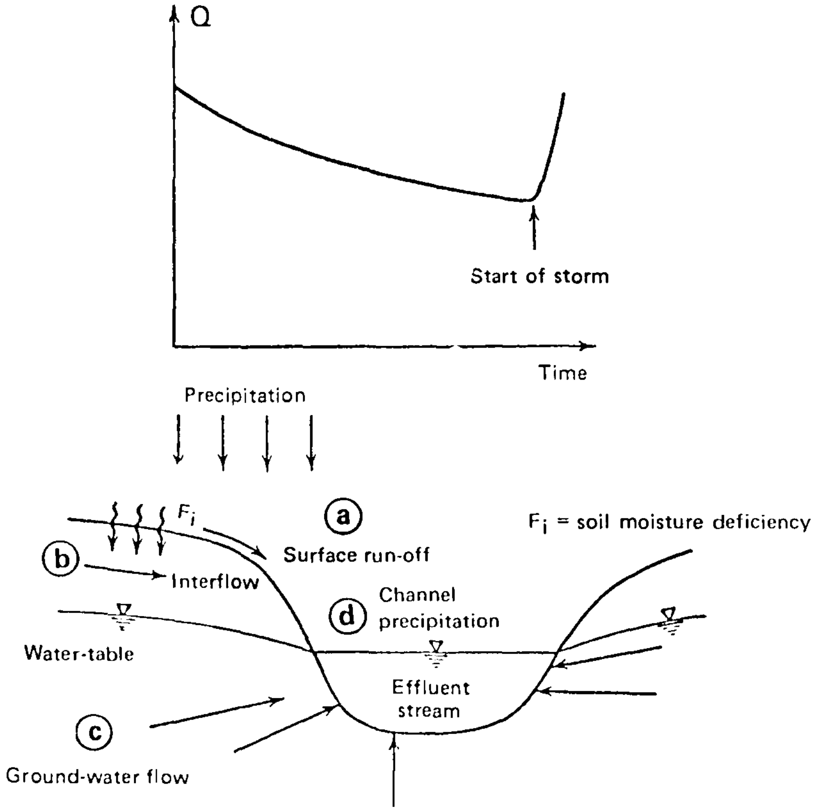
The run-off portion of the hydrological cycle includes the distribution of water and the path followed by water after it precipitates on the land and until it reaches stream channels, or returns directly to the atmosphere through evapo-transpiration. The relative magnitude of the various components into which the total amount of precipitation of a given storm may be broken down, depends upon the physical features and conditions of the land, natural and man-made, as well as upon the characteristics of the storm. At the beginning of a storm, a large amount of precipitation is caught or intercepted by trees and vegetation. Water thus stored on vegetation is usually well exposed to wind and offers large areas of evaporation, so that precipitation from storms of light intensity and short duration may be entirely depleted by interception and by the small amount of water that would infiltrate through the soil surface and fill puddles and surface depressions.

For water to infiltrate, the surface of the soil must be in the proper condition. When the available interception and depression storage is completely filled, and when the storm is such that the rainfall intensity at the surface of the soil exceeds the infiltration capacity of the soil, "overland flow" begins. The surface of the soil is then covered with a thin sheet of water, called "surface retention". Once the overland flow reaches a stream channel, it is called "surface run-off".

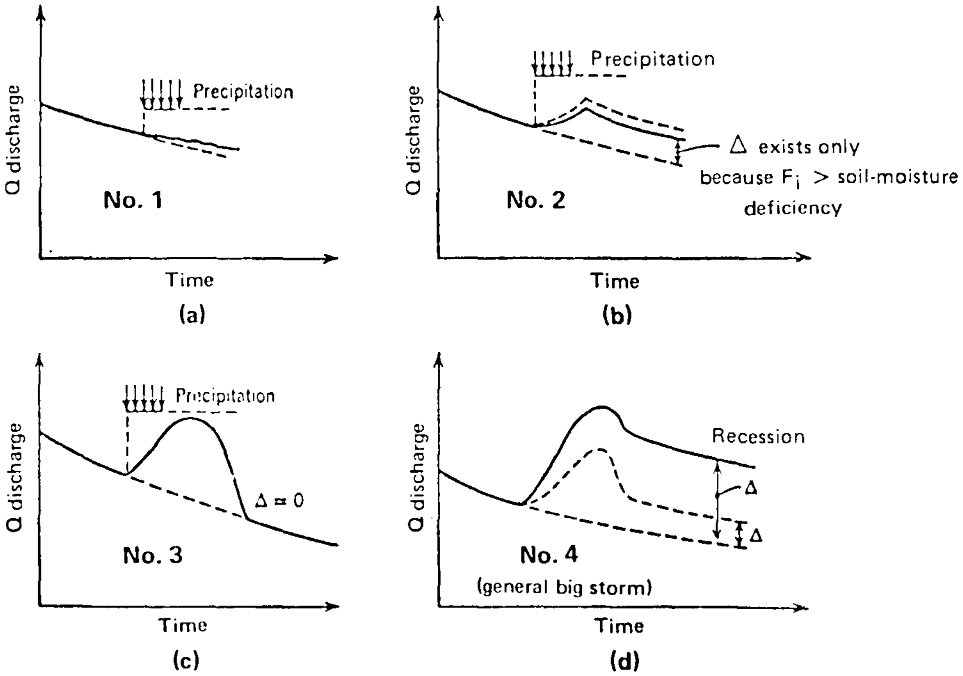
Part of the water that infiltrates into the soil may continue to flow laterally as "interflow" at shallow depths, owing to the presence of relatively impervious horizons just below the surface of the soil; this interflow reaches the stream channel at this horizon. Another part may percolate to the ground-water table, and eventually may reach the stream channel to provide the base flow of the stream; and still a third part may remain above the water-table, in the zone of unsaturated flow.

The infiltration capacity of a soil, $f_p$, is defined as the maximum rate at which a given soil can absorb precipitation in a given condition. The infiltration capacity decreases exponentially, in time, from a maximum initial value to a component rate. The actual rate of infiltration, $f_i$, is always smaller than $f_p$,

## Figure 5. Hydrograph



Hydrograph of effluent stream before storm. Run-off contribution starts after the storm.



Hydrograph composition ((a), (b), (c), (d)) except when the rainfall intensity, i, equals or exceeds $f_p$; it also decreases exponentially with time, as the soil becomes saturated and in situ clay particles swell. The amount of water that reaches the ground water is equal to the total infiltration minus the amount of water retained in the vadose zone. Thus the moisture content of the soil, prior to a precipitation event, is an important factor affecting ground-water recharge.

The flow of ground water through geological formations is governed by well-defined physical principles conveniently expressed by differential equations which can be solved when sufficient data are available for a given problem. As in classical isothermal fluid mechanics, three velocity components plus pressure and density at any point of the fluid are the five unknown quantities in problems of ground-water flow. In general, water is assumed to be incompressible, except in the calculation of the storage coefficient of a confined aquifer, where the expansion of water is responsible for a significant percentage of water released from storage. This means that the equation of state reduces to an expression of constant density and only four unknowns (three velocity components and pressure) exist in a single-phase flow having a three-dimensional pattern. Storage conditions differ, depending upon the type of aquifer considered.

Confined aquifers are saturated with water under greater-than-atmospheric-pressure. The water is progressively less confined toward outcrop areas, where it is unconfined and subject to water-table fluctuations. If there is a natural discharge, water flows from the outcrop area, where the head is highest, to the regions of the lower head, to other formations or to the atmosphere; if there is artificial discharge, it flows from the outcrop area through pumping. When a confined aquifer is pumped, the withdrawal of water is usually so fast that replenishment through the outcrop area and the body of the aquifer between outcrop and point of withdrawl cannot keep pace with the withdrawal. In this case, water is released from storage to satisfy the demand. Pumping results in a decrease in head and, therefore, in a decrease in water pressure. The granular matrix of the rock must compensate for this decrease in water pressure and bear an increase of pressure or stress of the same magnitude. In many cases, when the granular matrix is deformable, compaction of the aquifer and subsidence of the land surface result. The aquifer has effectively lost some storage capacity.

When the aquifer is not completely confined between low-permeability strata, it may exchange water with underlying or overlying water-transmitting geological units, from which it is separated by flow-retarding or low-permeability formations. The aquifer is called "leaky" and the drawdown for the case of an infinite aquifer, tapped by a single well of constant discharge Q, is given by an equation similar to that used for confined aquifers, but including a coefficient B, called "the leakage factor". It has the dimension of a length, small values of B meaning high leakage, and vice versa. Where B becomes infinitely high, the aquifer becomes completely confined. The graphical method devised by Theis to determine T and S remains adequately valid for most tests.

However, there are excellent examples of the deficiency in the present methods of determining T and S for carbonate rock aquifers. One should be aware of the discrepancies between theory and practice in such aquifers and of the restrictions on the correctness of solutions of the differential equations. Whatever set of values of S, T and B are found, in view of the discrepancy between ideal conditions and actual field conditions, the results should be tested against practical considerations, such as observed drawdown at a far distance from the pumping centre, observed subsidence and boundary effects.

The concept of storage in unconfined aquifers is much simpler than that related to confined and to leaky aquifers. In unconfined flow, the coefficient of storage for long periods of pumping is approximately equal to the specific yield of the material through which the water-table falls and, therefore, is independent of the thickness of the aquifer.

## G. Ground-water reservoir systems

Natural drainage of water takes place through two large classes of drainage systems: surface drainage systems, such as rivers and glaciers; and ground-water drainage systems. In most cases, both classes of systems are closely intertwined; however, for the sake of clarity, it is useful to compare two ideal cases, i.e., a river-channel which carries only surface run-off from rainfall and a ground-water aquifer which is replenished by rainfall only. For both idealized drainage systems, it is obvious that, in the long run, inflow and outflow must balance in any natural drainage system. It should also be mentioned that rivers, as well as ground-water systems, hold a certain volume of water in storage, though in the case of rivers this fact is often overlooked. However, a salient difference between the two classes of drainage systems is expressed by the storage/discharge ratio, which may be defined as the volume of water in storage divided by the annual discharge of the system. It will be noted that the storage/discharge ratio, thus defined, has the dimension of years.

In the case of a river, the volume of water stored in the river-bed is almost negligible compared with the annual discharge of the river (lakes and artificial reservoirs are, of course, excluded). In a ground-water system, the volume of water in storage is usually much larger than the annual discharge from the system. The following examples will illustrate this point:

(a) Case No. 1: River-system discharges 6,000 million $m^3$/year; this may be represented by a channel 100 km long, 3 m deep and 60 m wide.

Storage discharge ratio (river) = $18 \times 10^6 / 6 \times 10^9 = 3/1000 = 0.003$ year

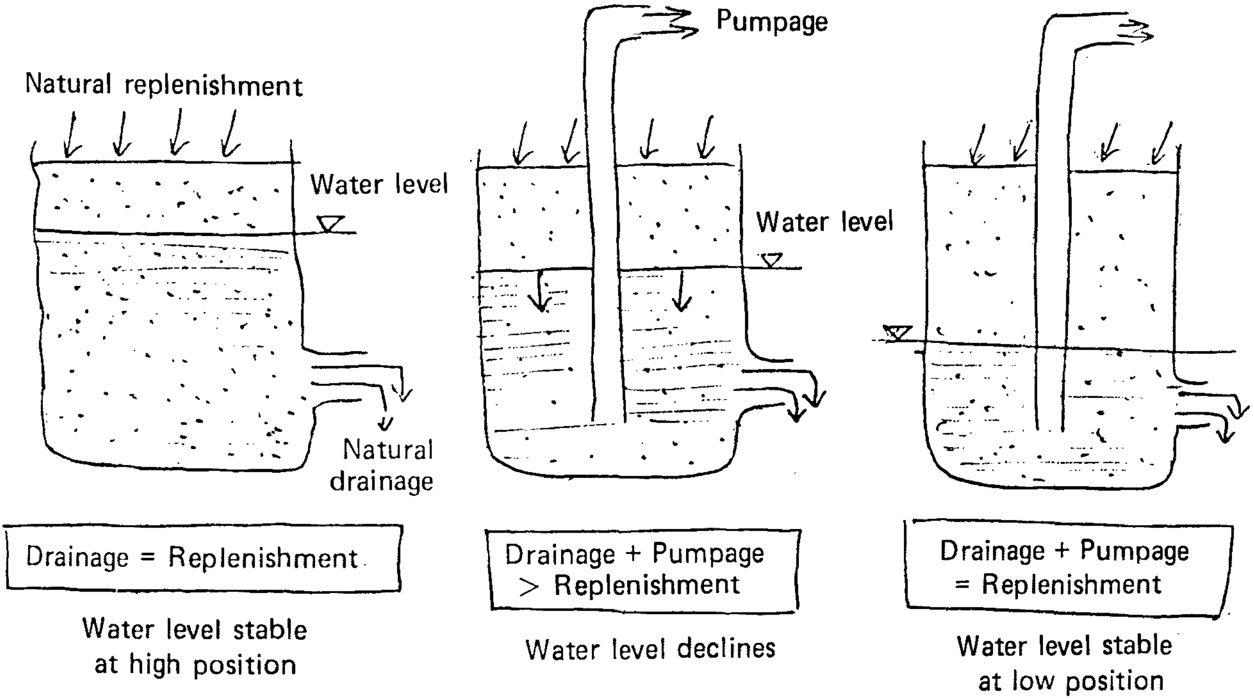
(b) Case No. 2: Comparatively small aquifer (the data conform roughly to the coastal aquifer of southern Israel) having an annual discharge of about 100 million $m^3$/year. It is 50 km wide, 10 km long, 60 m thick and has an effective porosity of 15 per cent.

Storage discharge ratio (ground water) = $4.5 \times 10^9 / 10^8 = 45/1 = 45$ years

The following, more visual, meaning can be given to these results: in the absence of any rainfall, if waters were extracted from the system at a rate corresponding to their respective average annual discharges, the river system would dry up in about one day, but the ground-water system would dry up only after about 45 years. In fact, the storage/discharge ratio, as defined above, is an expression of the time which a drop of water takes, on the average, to travel through the system, from the point of intake to the point of outlet. This "transit-time" is an important concept in ground-water studies.

A simple example of a ground-water system is presented by an unconfined, or phreatic, aquifer. The aquifer contains water which is in a state of continuous flow and discharges through seepages and/or springs into a river. The energy that makes the water flow stems from elevation head and pressure head. The

Figure 6. The tank model



elevation of the water-level above the outlet, measured at any point, indicates the energy available at that point. The ground water in the system is replenished by rain, a certain part of which infiltrates downward to the water-level.

The exploitation of ground water by pumping wells lowers the water-level and also locally deforms the shape of the water-table by creating cones of depression around the wells.

A ground-water reservoir can be conveniently represented by a tank of irregular shape filled with granular material and provided with a lateral outlet somewhat above its bottom. The irregular shape simulates the boundaries of the phreatic aquifer, the granular material simulates the aquifer and the outlet simulates the mechanism of natural discharge. Replenishment is simulated by pouring water into the tank from the top. The tank fills up, the water-level slowly rises and water begins to issue from the outlet. If it is assumed that replenishment is continuous and constant (i.e., disregarding the seasonal and yearly variations of replenishment), the following condition expresses the state of natural equilibrium that is, a constant water-level:

(a) Natural outflow = natural replenishment: If pumpage is simulated by withdrawing water through a vertical pipe at a rate of 75 per cent of natural replenishment, release of water from storage causes a lowering of the water-level, or, in other words, a decrease of the hydraulic head; and this, in its turn, diminishes the outflow. Lastly, a state of modified equilibrium is reached and natural replenishment is attained by pumpage plus diminished outflow;

(b) Pumpage + diminished outflow = natural replenishment: It is quite clear that with pumpage amounting to 75 per cent of inflow, the new equilibrium condition will be reached only when the outflow has been reduced to 25 per cent of its natural value. In view of Darcy's law, this will occur only when the driving-head, which governs outflow, is reduced to 25 per cent of its initial natural value. In order to reach this point, about 75 per cent of that part of the reserves that were above the level of the outlet (the so-called "regulative reserves") have to be removed.

In most natural aquifers, the regulative reserves are very large and it takes a considerable number of years to reach a new equilibrium state. During all these years, the water-levels continue to decline and the ground-water system is in a state of non-equilibrium characterized by the inequality,

Pumpage + slightly diminished outflow > natural replenishment.

A few important insights are gained from the above, seemingly trivial considerations.

(a) The behaviour of a phreatic ground-water system is determined to a large extent by the relationships,

Discharge = function of head = function of storage;

(b) Any release of ground water necessarily diminishes storage;

(c) Water which is artificially recharged to the aquifer can be stored underground over considerable, though not indefinite, periods. This can easily be seen by considering what happens if the inflow into the tank is increased after some of the storage has been withdrawn by pumpage.

The fundamentals expressed above are put into practice in the exploitation of ground-water storage and the artificial recharge of ground-water reservoirs.

# II. EXPLOITATION OF GROUND-WATER STORAGE

The exploitation of ground-water storage is a long-term operation to be developed in progressive stages. The first phase should be to investigate the features of the natural ground-water reservoirs and survey and evaluate quantitatively their characteristics. This will pave the way for a second phase, which is to assess the potential of the ground-water reservoirs for storage, replenishment and discharge of ground water, the selection of further operational schemes and, ultimately, the design of specific waterworks which will be incorporated into the projects.

## A. Investigations

In a previous United Nations publication, Large-scale Ground-Water Development Development, 3/ an over-all view has been provided of the methods involved in ground-water investigations. In this section, some factual examples, data and practical procedures are discussed.

In assessing ground-water storage, two main types of data, geological and hydrological, have to be collected and further processed and analysed with a view to defining the occurrence and movement of ground water in the area being considered. The geological data that are necessary are related to surface as well as subsurface geology. In particular the thickness, volume, structure, depth, degree of fracturing, fissuring, weathering and chemical composition of the various geological formations have to be known in detail. It should be mentioned that the geology of aquifers focuses on lithological units, even if such units cover several geological periods. In other words, the age of the formation is not the main concern, as it is for stratigraphers; hydrogeologists are concerned with the rock composition, rather than with the faunae. The lithological character of the rocks and their structure determine the hydrological characteristics of the aquifers, the discharge and recharge of the ground-water reservoirs under various conditions and the physical and chemical characteristics of the waters.

A variety of methods and techniques are available for the collection of such data, their analysis and their interpretation. Most of these methods and techniques deal with diverse geological and hydrological aspects of ground-water reservoirs, either from a qualitative or from a quantitative point of view. Data collection requires remote-sensing surveys; and such surface investigations as hydrogeological reconnaissance and water-points inventory, measurement of rainfall, discharge of springs, run-off and evapo-transpiration. Also required are such subsurface investigations as geophysical surveys, drilling of bore-holes, test-pumping, use of tracers, determination of the speed of the ground-water flow and analyses of ground water.

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3/ See, in particular, annex III, "Ground-water exploration".

The methods and equipment utilized in ground-water investigations are described at length in many manuals and technical books, and need not be discussed here. The following considerations apply to those techniques and equipment which are specifically used in ground-water storage investigations:

(a) The concept of utilizing ground-water storage can be applied only to areas which have been identified through a reconnaissance survey as a hydrogeological unit of a measurable surface and volume, and which is likely to be able to store and release a significant amount of ground water during an extended period of time;

(b) The investigation made in such an area should be as detailed as possible in terms of the distribution of geophysical profiles, drilling of exploratory and test wells, pumping tests and other subsurface investigations, including water-quality studies;

(c) In addition, a detailed study of natural ground-water discharge from springs and rivers existing in the area, or its vicinity, is essential. Such studies should be made for a significant number of "hydrological years". An elaborate analysis of the hydrographs is usually necessary to assess the natural rate of ground-water outflow.

(d) The fluctuations of the piezometric surface must be measured accurately, often and at many locations. The piezometric surface must be matched with the various possible factors which may have an effect upon it, such as rainfall, evaporation, pumping, infiltrations of floods or irrigation waters;

(e) When the physical features of the reservoirs are known, the study of these fluctuations is the final and the most important part of the over-all investigation. Since many factors are involved, a mathematical simulator or analogue model which combines all the relevant factors may be used to better analyse possible relationships of the many factors.

## Reconnaissance surveys

The results of a hydrogeological reconnaissance are normally presented as follows:

(a) A set of index cards is prepared, each one referring to a well, bore-hole, spring etc. indicating water quality, depth to water-table, use of pumped water, output and elevation of the piezometric surface. This is the procedure used in France and in French-speaking Africa. The members of the British Commonwealth record bore-hole data in a register.

(b) A set of maps showing the aquifers and aquicludes must be prepared. In many reconnaissance hydrogeological maps, three main classes of geological formations are represented: aquifers with intergranular porosity; aquifers with fracture and channel porosity; and formations having relatively low permeability.

(c) In addition, the maps often bear such information as:

(i) The main springs, bore-holes, wells and other outlets with their discharge;

(ii) The availability of ground water in terms of gallons per minute per square mile, or litres per second per square kilometre;

(iii) The countour lines on the piezometric surface;

(iv) The depth to ground water from land surface and the chemical content of ground water. They may be complemented by small-scale maps and graphs showing rainfall, run-off and evapo-transpiration and also by tentative cross-sections and descriptive and explanatory notes.

Such a preliminary survey will serve as a basis for the selection of the most promising ground-water reservoir areas, where more detailed and sophisticated methods will be applied for investigation purposes and, especially, for determining the storage potential of an aquifer system.

## Geophysical surveys

Resistivity surveys and seismic refraction surveys are the two conventional methods of geophysical prospecting for hydrogeological studies that are conducted at ground level. However, spontaneous or induced potential surveys, electromagnetic surveys and gravity surveys also give good results, particularly with such difficult problems as those involving low permeability beds and karstic carbonate rocks. The electrical resistivity surveys, utilized especially for investigating ground-water conditions at shallow or moderate depths, are well-adapted to the study of lithology, the location of aquifers and the investigation of rocks underlying ground-water bodies. The resistivity of rocks and soils depends essentially upon lithology, water content and chemical content of the ground water. Variations in resistivity according to these properties can be utilized to give valuable interpretations, as shown in table 4. The most difficult operation consists not in the measurements but in the interpretation and translation of such results into geological terms. This work requires a good geological knowledge of the region, which can be obtained only through a detailed field study and the drilling of reconnaissance bore-holes. Close co-operation between the geologist and the geophysicist is essential if effective results are expected from electrical prospecting methods.

Successful utilization of electrical resistivity surveys requires two favourable geological conditions. First, the various geological layers have to present contrasting resistivity characteristics; secondly, a limited number of formations should be involved, at most three to four. The electrical-resistance method gives good results for horizontal or gently dipping formations and can be successfully applied in the study of a stratigraphic unit comprising two or three layers. For example, electrical resistivity surveys can identify: the prospection of alluvium in a sedimentary basin, including the determination of the thickness, the depth and shape of an underlying bed rock, the depth of weathered zones in crystalline areas and the boundaries of areas with salt-water intrusion. The cross-sections and maps constructed from resistivity surveys help in identifying strata, indicating steep dips, locating faulted areas and horizontal variations in the lithology of formations.

The "seismic-prospecting method" utilizes the subsurface propagation of shock-waves produced by means of an explosion. The parameter measured is the time (duration) it takes for the shock-wave to travel to the adjacent land areas. This

Table 4. Electrical resistivity as a function of lithology, of water content and of chemical composition of water contained

(Ohm per metre)

| | Resistivity |
|---|---|
| Lithology | |
| Marls | 0.5-20 |
| Schists and shales | 50-1,000 |
| Limestones | 100-5,000 and above |
| Sandstones | 60-10,000 |
| Quartzites | 20,000 |
| Granites | 300-15,000 and above |
| Alluvium (sands and gravels) | 100-1,000 |
| Eruptive rocks (compact) | 500-20,000 |
| Eruptive rocks (weathered) | 100-1,000 |
| Rock salt | $10^{15}$ |
| Water content | |
| Dry sand | 10,000 |
| Saturated sand | 50-100 |
| Chemical composition of water contained | |
| Sand with fresh water | 50-100 |
| Sand with saline water (marine) | 1-4 |
| Clays (fresh water) | 1-100 |
| Clays (brackish water) | 1-10 |

time-interval is related to the elasticity of the subsurface rocks. The speed of the shock-waves varies from 100 to 600 m/sec in sedimentary formations, increasing with the density of the rocks. Many geological formations can be identified by a specific speed, and important differences noted for various formations in many cases enable a reasonable differentiation to be made between unconsolidated formations and compact rocks. For examples, sands and gravels transmit shock-waves at a rate of 600-800 m/sec; clays and clayey sandstones at 1,200-1,800 m/sec; marls, schists and shales at 3,200-3,800 m/sec; and limestones at 5,600-6,000 m/sec.

The "seismic-refraction method" is applied to refracted waves, which are most suited for shallow- and intermediate-depth prospecting. For shallow and moderate depths, the equipment needed is quite simple and is not cumbersome; the explosive charges which produce the waves are small and are buried at a shallow depth. Features which are not revealed by electrical prospection can be frequently identified through seismics. For instance, an alluvial complex which has a resistivity of 100-200 ohm/m overlaying a limestone substratum at 200-250 ohm/m cannot be individualized using the resistivity method only. However, it can be identified, and its thickness can be measured, by means of seismic refraction because the velocity of the refracted wave is 800 m/s in the alluvium and is 5,000 m/s in the limestone. Similarly, a lens of sand holding salt water (40 ohm/m and 600 m/s) cannot be distinguished from clay (50 ohm/m and 2,000 m/s). In many cases, and especially when prospecting to a depth not exceeding 200 m, it is recommended that both the seismic prospecting and seismic refraction methods be co-ordinated. This co-ordination can be accomplished by a single team of technicians using light-weight equipment. This combined method is called "electroseismic". Therefore, the results of the two methods are compared, matched and reciprocally checked. The co-operation of the geologist, the rating of the speeds in varied formations and the actual knowledge of geolithological data acquired through the drilling of some bore-holes, which allows a checking of the computed cross-sections, are, in all cases, essential for obtaining reliable results.

## Bore-hole investigations

The electrical-logging method is used for measuring the variations of the electrical resistivity of formations and their spontaneous potential. The logging is conducted in an uncased bore-hole containing a homogenous mud while in an "at rest" condition. The interpretation of the electrical logging "film" or chart that is obtained leads to an evaluation of:

(a) The resistivity of the formations found in the bore-hole;

(b) The lithology of the strata and an accurate measurement of its depth;

(c) The porosity and the order of magnitude of hydraulic conductivity;

(d) The chemical content of ground water;

(e) The location of the areas through which ground water reaches the hole.

The induction-wireline logging method measures the conductivity of formations by using a dry bore-hole having no casing. It is suitable for the identification of conducting strata incorporated in a resistant environment.

The principle of radio-active-logs can either be used to measure the natural radio-activity of the rocks encountered by a bore-hole, or to measure the radio-activity resulting from neutron bombardment. Therefore two types of sensors are incorporated in the same apparatus; one for "gamma ray" logging and the other for "neutron" logging. The logging can be performed in a bore-hole either with or without a casing. The measurements are little affected by variations in temperature or by the resistivity of the mud. These logs lead to the identification of porcus strata and the separation of sand layers in marls and clays, or of marls in limestone.

Measuring temperatures within bore-holes is accomplished by means of a thermo-electric log or "thermistance" log that may be incorporated within the same apparatus as the electrodes used for measuring resistivities and spontaneous potentials. Temperature logs may show the presence of ground water in the bore-hole.

## Areal investigations

The potential of natural or induced currents in the subsurface geological formations is measured by spontaneous polarization, or the natural-potential method; and by the provoked, or induced-polarization method. These are new methods which have already been used with success and are marked for wide development in the near future. Data with respect to ground-water infiltration and flow, particularly information about compact fractured rocks, may be collected directly by these methods, and the data does not require further interpretation.

The gravimetric prospecting method is often considered a technique which should be used only when making structural investigations at great depths. However, recent studies have shown that, under favourable conditions, it can be used for shallow-depth ground-water reconnaissance surveys as well, particularly since it has the advantage of being much less costly than electrical or seismic prospection. This method has been successfully used, for example, in France in the study of the Sedimentary basin of Rennes, which overlays basement crystalline formations in Brittany.

The airborne geophysical prospecting method allows a rapid survey of vast regions, or of regions into which access is difficult due to a thick vegetal covering, such as tropical regions. As a rule, most of the methods which are utilized on the ground are adaptable to airborne surveys. However, for ground-water prospecting only airborne electromagnetics is utilized. This method measures the variations of the magnetic fields of the earth and phenomena related to the conductivity of the rock. Since drilling bore-holes is expensive, the maximum amount of data must be collected from them with various geophysical measuring techniques. The main types of measurements that deal directly with ground water are wire-line electrical logging, induction wire-line logging, radio-active logging and thermometry.

Following is a summary of the geophysical techniques of investigation and their objectives for ground-water studies:

(a) The dimension of the aquifer stratum (resistivity, seismic refraction and, particularly, gravimetry);

(b) The internal structure of the aquifer stratum (resistivity, electromagnetism of limestones, gamma radiation, gamma spectrometry, thermal conductivity, in-hole neutron activation and, on occasion, seismic refraction);

(c) The physical characteristics of the aquifer (resistivity, electromagnetism, neutron, gamma-gamma, natural gamma and seismic refraction).

However, the efficiency and the accuracy of geophysical prospecting depend upon three essential conditions: firstly, a close co-operation must be developed between geologists and geophysicists; secondly, several geophysical methods (except electroseismics) must be used in combination, and; lastly, geophysical prospecting should be carried out simultaneously with geological investigations and drilling.

## Drilling

Of the various investigation methods available to hydrogeologists, exploration drilling is the most direct approach for gathering information about a ground-water reservoir. However, it must be realized that this type of operation may be long and expensive; an exploratory drilling programme must be prepared with great care, taking into account all the factors and prospects which have become evident as a result of previous surface and subsurface investigations. A geological reconnaissance drilling programme will usually result in the collection of exact (not computed or hypothetical) data with respect to the thicknesses, depths and extents of the water-bearing formations. However, in most cases, such a drilling programme, which will involve small-diameter bore-holes only, does not provide a quantitative appraisal of the ground-water storage, though it renders possible a determination of the order of magnitude of the hydrological characteristics of the aquifers resulting from preliminary tests performed with small-diameter pumps.

The hydrological features of a reservoir can usually best be ascertained through a programme of test well-drilling and test pumping. Test drilling is carried on to test specific water-bearing formations which have been previously identified by other means. Usually, such operations are initiated when the natural depth and thicknesses of such formations are known or estimated with a reasonable degree of accuracy (10-30 per cent). In particular, the final depth of the bore-holes must be approximately known. As such an operation is costly, it is recommended that the results of the drilling be reviewed on a daily basis by the hydrogeologist and that no risk be taken of clogging the aquifers with natural or artificial drilling mud. In addition, undesirable transfer of water should not be induced through the holes between several aquifers containing waters under different heads and having different chemical compositions. Cementing operations must be carried out in proper time. In most cases a test bore-hole is drilled in order to set a casing of from 6 to 10 in, 8 in being the average. This casing is slotted or properly fitted with screens, at the level of the aquifers that will be tested. A gravel-pack filter may be laid down between the casing and the surface of the bore-hole in order to provide a transitional zone for the ground-water flow between the narrow channels existing in the aquifers and the openings (slots or screen spacings) of the casings. Many types of materials have been utilized for the fabrication of casings. Casings should be capable of resisting corrosion and mechanical pressures exerted by the terrains, including metals, wood, plastics and other materials. In some developing countries in the Far East and Central America, large-diameter bamboo rods have been used as casings.

A number of drilling techniques are utilized in ground-water exploration. They are described later in this chapter. However, it should be mentioned now that a test well can be used as a pilot exploitation well if it gives positive results in terms of the yields obtained through pumping tests.

## Hydro-indicators

A new and fruitful scientific method has recently been developed in the Union of Soviet Socialist Republics for studying the occurrence and distribution of ground water by means of a variety of surface data; botanical as well as other data are utilized. This method is termed "landscape hydro-indication". It is likely that it will gradually become more quantitative and will combine with geophysics and satellite surveying. Landscape hydro-indicator investigations have as their objective obtaining knowledge of the hydrogeological conditions of a certain area based upon studying the morphological and other components of a given environment and establishing hydro-indicator regularities, i.e., the hydro-indicator significance of these components. The main theoretical basis of landscape-hydro-indicator investigations is the intrinsic interconnexion and interdependence of all landscape components.

As a result of landscape-hydro-indicator observations, using data on the character and distribution of typical components of the landscape, the ground-water availability, quality and depth for a certain area may be estimated. In this case, elucidation of the conditions of formation, transit and discharge of unconfined ground waters, and their areal distribution, is of particular significance. This method is of importance to the search for fresh unconfined ground waters over vast areas with complex structural features.

Thus, the principal feature of landscape-hydro-indicator studies is the estimation of the hydrogeological conditions of the area under investigation, using a number of direct and indirect landscape-hydro-indicators that are combinations of certain topographic forms and plant communities, within the framework of certain typological units of natural aerial complexes. While separate specimens of phreatophytes may indicate only the existence of shallow ground water, geobotanical indices, i.e., plant communities, lead to an evaluation of the depth and the chemical composition of ground water, and the collection of data on the character of the salinity and the lithological composition of superficial deposits, with a 70 per cent reliability.

Another characteristic feature of landscape hydro-indicator studies is the hydrological trend of the landscape analysis of an area, on the basis of general theoretical concepts of ground-water occurrence and exploration in deserts. Only the ground water of the first unconfined aquifer, as well as ground-water flows and perched water of the lens type, are covered by hydro-indicator investigations. The water of deeper aquifers, including artesian aquifers, may be partially characterized, if natural ground-water outlets are found having characteristic features of the terrain, e.g. gravity springs. In landscape hydro-indicator studies, the recharge and discharge areas of unconfined ground water and fresh-water lenses are commonly defined. The areas of recharge and temporary transit of unconfined ground water are characterized, as a rule, by indirect hydro-indicators. In such areas, vegetal cover is often absent or represented by ombrophilous plant communities. In contrast, the discharge areas of unconfined ground water and artesian waters are characterized by a distribution of direct hydro-indicators, primarily phreatophyte communities, which discharge water by "pumping" to evapo-transpiration. By use of landscape-hydro-indicator investigations, large areas can be investigated for their ground-water resources, while keeping drilling programmes and expenses at a minimum.

Data for landscape hydro-indicator studies may be used for preliminary estimates of the availability of water of the area as well as for locating areas with fresh ground water. In practice, using indicator regularities, it is advisable to carry out landscape hydro-indicator studies in conjunction with conventional hydrological and geophysical investigations. The best results may be obtained by using such a combination during the early stages of hydrogeological reconnaissance and surveying, when hydro-indicator interpretation of topographical maps and aerial photographs is essential.

### Remote sensing

The use of remote-sensing methods has increased considerably in the past few years. These methods use instruments carried by aircraft and space craft to collect or transmit different images or numerical data related to the hydrological environment and the terrain. In a relatively short period of time, a large area can be surveyed. A wide range of remote-sensor systems has been developed, in addition to the classical methods of panchromatic and infra-red photography. Multispectral photography may be useful in differentiating vegetation types as indicators of ground water. Colour photography provides a sharp contrast for geologic mapping. Infra-red radiometry and imagery are utilized for locating points of ground-water discharge into streams. Radar imagery and infra-red colour photography have a less direct application for checking ground-water data.

### Water-quality surveys

Water-quality analyses constitute one of the most important elements in an investigation of ground-water storage. These analyses are used to evaluate the suitability of the water for different purposes; to check the variation of water quality under different conditions of exploitation and replenishment; and, to deduce from hydrochemical data, information regarding the circulation of ground water in the geological formations, and especially data related to the type of porosity, the presence of clayey lenses and the speed of the ground-water flow. The chemical features of ground water are generally established by means of testing the water for such components as $CO^3$, $SO^4$, Cl, Na, Ca, Mg, K, the total dissolved solids (TDS) and hardness. A significant nitrate content generally indicates pollution of water with organic material. This type of pollution can be most accurately checked by means of microbiological analyses. When the water supplies of human communities are involved, and when certain drinking-water standards are required, "minor-elements" analysis are carried out, with a view to measuring the amount of such harmful components as lead, iron, boron and flourine. In any case, water-quality analysis can give important leads as a "by-product" to mineral investigations, and should also be encouraged for this reason.

Environmental isotope studies

A new type of water analysis has been successfully experimented with in the last few years. It is applied to the isotopes of hydrogen and oxygen, which are found in waters under natural conditions. The stable isotopic components of water are $HD^{16}O$ and $H_2{}^{18}O$. (D = deuterium.) They occur in natural water, in concentrations of about 320 parts per million (ppm) and 20,000 ppm, respectively, and can be measured by means of a mass spectrometer. The isotopic component of a water sample is expressed in terms of the per mil deviation of the isotope ratio from that of a standard. The stable isotope content is related to the period during which the recharge occurred. In the arid regions, these analyses have shown that the last recharges occurred mainly during a specified "pluvial" of Pleistocene times. These analyses are sometimes able to reveal if ground water has been subjected to heat; they give indications of the latitude, altitude and vicinity of the sea of the recharge area and, therefore, may reveal that there is no local recharge.

Reliable results in the determination of the age of water have been obtained using two radio-active isotopes, tritium and radio-carbon. For example, $C^{14}$ has been used in estimating the age of artesian water in Sakhara, in the Union of Soviet Socialist Republics. Many specialists were surprised by the fact that the age of waters of various artesian basins in Sakhara ranges from 7,000 to 25,000 years. These figures should be considered as being only the order of magnitude, but they none the less agree with palaeoclimatological data related to "younger" waters. At present, the recharge of artesian basins in Sakhara is insignificant. Therefore, non-renewable ground-water resources are being developed in this area. This conclusion is of importance in the selection of methods of ground-water development.

The use of isotopes as indicators gives important information on water flow. The following example is taken from a project of the United Nations Development Programme (UNDP), which was carried out with the participation of the International Atomic Energy Agency (IAEA), in the region of Antalia, in south-western Turkey. It had been assumed that some large coastal springs in this area were recharged at the expense of seepage from lakes located to the north of Taurus, on the inner plateau, by means of a hydraulic connexion through fractured Mesozoic limestones. In fact, deuterium and $O^{18}$ determinations in water samples from lakes and springs have shown that the waters of these bodies were of a different origin and that the springs were recharged by precipitation falling on this region. The variation of tritium concentration in lake water was caused by the variation of tritium content in the atmosphere, owing to nuclear tests. Thus, it was determined that the water in the springs and lakes was not related.

The study of the isotope content of surface and ground water, in conjunction with that of precipitation, provides a new and reliable method for hydrograph separation, as well as for the determination of the subsurface component of stream-flow, and the role of the latter in ground-water storage-recharge. It is likely that, in future, this method will involve the use of artificial isotopes for an accurate determination of the time and path of water circulation. Nuclear methods can help greatly in assessing the relationship existing between several aquifers. They are also a very useful tool for the study of the movement of water and vapour through the unsaturated zone, when infiltration and evapo-transpiration take place.

## B. Assessment

A quantitative evaluation of water supply may be made of any portion of the hydrological cycle, whose components of input and outgo are subject to separation and measurement. This evaluation is given different names by hydrologists in various parts of the world, the most common phrases being "hydrological balance", "hydrological budget" and "hydrological equation". Although the first of these phrases is used here, the meaning of all is similar: the amount of water going into the region or zone under consideration in a given time equals the amount of water going out of the region or zone in the same period, plus or minus the change of storage within the zone during the period.

### Hydrological balance

A drainage basin is the region for which a hydrological balance is most commonly assessed. The items of input and outgo are:

| Input | Outgo |
|---|---|
| 1. Precipitation | 1. Evapo-transpiration |
| 2. Surface inflow | 2. Surface outflow |
| 3. Subsurface inflow | 3. Subsurface outflow |
| 4. Imported water and sewage | 4. Exported water and sewage |

Input + decrease in storage = outgo + increase in storage

In the foregoing equation, "storage" includes surface storage, ground-water storage and storage in the vadose zone. Obviously, the change in storage may be zero on one or both sides of the equation. Other terms in the list of items of input and outgo may also be zero. In most basins in developing countries, import and export are either zero or negligible. However, in certain basins in some developed countries these items are significantly large and must be considered. Care must be taken not to omit any items, such as subsurface inflow and outflow or change in storage. If the item or items omitted are sufficiently large, serious errors are introduced.

In the general equation for the hydrological balance, as given here, both surface water and ground water within a basin are entirely covered, although change from one to the other within a basin is not shown separately. A hydrological balance for the ground-water reservoir only is outlined below.

Many variations exist in the statement of the equation of the hydrologic balance. However, all equations which consider all possible items of the hydrological balance, with respect to both ground water and surface water, should reduce to the equation given here; or if the concern is with ground water only, the equation should reduce to that which is given below. In fact, it is frequently desirable to compute a balance for the ground-water reservoir alone. Only items of input and outgo for the saturated zone are considered. The ground-water reservoir is thus treated as engineers treat a proposed surface reservoir, that is items of supply to and disposal from the reservoir are carefully measured, along with the changes in the amount of storage within the reservoir. This type of appraisal is obviously essential for adequate understanding of a ground-water reservoir. It is necessary for calculation of safe yield and for operation and management of the reservoir.

The items of a ground-water balance are as follows:

Input

1. Infiltration from precipitation
2. Infiltration from bodies of surface water (streams, lakes or ocean)
3. Infiltration of artificial discharge (return of irrigation water etc.)
4. Artificial recharge
5. Subsurface inflow

Outgo

1. Natural discharge to the surface (springs, streams, evapo-transpiration direct from ground water)
2. Artificial discharge (wells, drains)
3. Subsurface outflow

Input + decrease in ground-water storage = outgo + increase in ground-water storage

Accurate hydrological and geological information on a ground-water reservoir makes it possible to obtain an accurate ground-water balance. Infiltration is generally obtained by solution of the equation.

Infiltration = precipitation - run-off - evapo-transpiration

Of the terms in this equation, data on precipitation and run-off can be measured directly using standard procedures, and evapo-transpiration can be estimated by the Blaney-Criddle or other methods. Infiltration from streams can be measured by a number of methods, the simplest of which is to measure the flow of the stream at both the upper and lower ends of the reach in which infiltration occurs. Making correct allowance for evapo-transpiration (a very uncertain procedure), the loss of the stream-flow is due to infiltration. Where flood-flows or large volumes of stream-flow render this method inapplicable, other more sophisticated methods are necessary. Where the stream-bed is permeable and saturated with water, there may be saturated flow between the base of the stream and the water-table. In such a case the following method is satisfactory: the gradient of the water table is measured at right angles to the stream; and Darcy's law is used to compute ground-water movement away from the stream. The form of Darcy's law most convenient for this purpose is:

$$\underline{Q} = \underline{KIA}$$

In this formula, $Q$ is the volume of flow measured in cubic metres per day (or gallons per day in the British system) passing through a cross-sectional area, $A$, measured in square metres (or square feet) of the aquifer, with hydraulic conductivity, $K$, measured in cubic metres per day per square metre (or gallons per day per square foot), under a hydraulic gradient $I$, which is non-dimensional. Flow away from a lake, although not too common, may be determined by the same formula.

The form of Darcy's law utilizing transmissivity is frequently more convenient, particularly where large bodies of water such as the ocean are involved:

$$Q = TIL$$

In this formula, $Q$ and $I$ are as defined above, and $T$ is the coefficient of transmissivity, measured in cubic metres per day per metre (or gallons per day per foot) and $I$ is the width in metres (or feet) of the cross-section through which the discharge occurs.

Infiltration of surplus irrigation water can be computed by a variation of the equation for infiltration:

Infiltration = water applied - evapo-transpiration - run-off

Infiltration of artificial recharge water applied to the surface can be computed similarly. The volume of any water artificially recharged through wells should be measured before injection.

Subsurface inflow to a basin, or subsurface outflow, therefore, may be computed at the basin boundaries, utilizing Darcy's law in one of the forms above. Values of the transmissivity or permeability coefficient can be obtained from standard pumping tests. The hydrological gradient is measured by comparing water levels in wells.

Natural discharge to the surface can be measured directly in the case of springs, and discharge to streams may be measured in the same manner as infiltration from streams, as described above, although in this case the stream will gain in flow. Evapo-transpiration directly from ground water can be measured by using such available formulae as the Thornthwaite or Penman formulae for potential evapo-transpiration. Artificial discharge is normally measured directly. Yield of wells, kanats or drains are measured, and are normally totalled on an annual basis.

Change in ground-water storage is simply measured by the rise or fall of the water-table and a calculation of the changes in storage for the volume of the zone of change, using known values for specific yield or effective porosity. In reservoirs where confinement is regional, the change in storage is equal to the change in level of the piezometric surface, multiplied by the storage coefficient, $S$, of the confined aquifer, the value of $S$ being very small in the case of a confined aquifer.

The specific-yield values can be obtained on site through a pumping test and give a quantitative evaluation of the potential yield of the aquifer. In most tests, pump-yield and water levels in observation wells are recorded. In general, in order to develop an accurate solution for any aquifer test, where data is developed by a point source, such as a well, it is necessary that the aquifer be reasonably homogeneous. For tests involving steady, radial flow, without vertical movement, it is assumed that the water-table surface and the base of the aquifer are parallel and horizontal, and that essentially all water is moving toward the well. In the case of non-steady radial flow, without vertical movement, further conditions must be met. The aquifer must be homogeneous and isotropic; the body of water must be of infinite areal extent; the discharging well must penetrate the entire thickness of the aquifer; and the water removed from storage must be discharged instantaneously, with decline in head. In addition, certain field procedures should be followed to assure valid results:

(a) The output should be uniformly maintained during the test and must be of sufficient duration to satisfy theoretical conditions;

(b) The water level should not fluctuate appreciably in the pumped well;

(c) The pumped water should be diverted to a point sufficiently far from the area in order to avoid infiltration to the water level in the vicinity of the bore-hole.

If such conditions are obtained, the data thereby collected, i.e., drawdown versus time and yield, can be utilized for the calculation of the hydraulic characteristics of the aquifers, namely, hydraulic conductivity, transmissivity and storage coefficients.

Soviet specialists conduct three categories of pumping tests.

(1) "Preliminary pumping tests" are conducted in single-test or observation-production wells, with the object of making preliminary estimates of their yields and of obtaining reliable information on availability of water at separate small areas and from disrete aquifer zones. Preliminary pumping tests are conducted at one or two pumping rates during two or three working shifts;

(2) "Pumping tests per se" are conducted in single-test and test-production wells, and also in groups of wells which include one or two observation wells. The purpose is to obtain the relationship between yields of the well and drawdown, in order to construct the so-called "yield curve" and to determine the coefficient of hydraulic conductivity and the storage coefficient. Step-drawdown tests should be run in each area. Not less than two or three pumping rates should be tested during from five to eight working shifts. The minimum duration of pumping should be determined by analysis of data collected during the test; under water-table conditions this duration might normally be for 72 hours at two or three pumping rates;

(3) "Production pumping tests" are carried out in test-production wells with the objective of obtaining more reliable data on productivity of the well, possible zones of production and ground-water quality. These tests are carried out at a maximum possible yield for a long period of time (from one and a half to two months and more). The best data is obtained from production-pumping tests in which either a constant well-yield is maintained, and the water level in the well lowers with time; or the water level is held constant, and the well-yield lowers with time. Such tests usually give data sufficiently precise to predict, with acceptable

accuracy, the effects of prolonged production pumpage. As compared with shorter-term tests, the results of production-pumping tests make it possible to estimate more reliably the aquifer transmissivity and to estimate other parameters needed for calculation of safe yield.

In recent years, as hydrological observations of ground water proceeded, and relevant data accumulated, total analysis of a stressed system has given increasingly reliable results for solving hydrological problems without pumping tests. Automation of observations as well as the development of data-processing centres and computer programmes which select optimal parameters all may ultimately replace pumping tests as a means of determining hydraulic parameters. However, pumping tests are currently necessary in most hydrogeological investigations.

## Modelling

The ground-water balance is the ultimate basis for evaluation of the use of a ground-water reservoir for storage, and for the continuing operation or management of that reservoir. Because all of the items of the balance can be expressed quantitatively, it is possible to construct a model of the ground-water reservoir. The various types of ground-water models include physical, electric analogue and mathematical models.

Physical tanks filled with sand have frequently been used to model ground-water behaviour. Through glass or clear plastic-sided tanks, direct observation can be made of ground-water movement and occurrence. Such models are particularly useful where such liquids of different densities, as fresh water and sea water, are utilized and coloured with different dyes. Tank models are most useful for investigating limited, but carefully controlled, ground-water conditions, rather than complete ground-water reservoir operations.

Electric analogues of various kinds have been utilized, in which current represents water flow, potential represents head and resistance represents length of travel. The most sophisticated of these are resistor-capacitance networks. These networks have been considerably utilized in recent years by the United States of America Geological Survey.

Resistor-capacitance analogue models usually represent a ground-water basin by a series of nodes, each of which contains a capacitor and is connected with adjacent nodes by resistors. Ground-water movement is modelled by the flow of current through the electrical network. The flow of current varies according to Ohm's law, and infiltration or extraction of water is modelled by the appropriate addition or subtraction of current at the nodes. A model of this kind is easy to understand and demonstrate and, in part, for these reasons has great value. However, the built-in resistors and capacitors are generally not variable. Any possible errors in transmissivity or storage capacity at the various nodes are thus "built-in", and must be physically replaced if their values are found to be incorrect during testing of the model or as a result of subsequent field work.

More complex modelling techniques have been developed using digital computers. These models solve simultaneous differential equations based on Ohm's law and Darcy's law. Mathematical models are more easily adjusted for the effects of changing water levels and changes in storage than are analogue models. Mathematical models, like analogue models, should be verified in accordance with the known past behaviour of the ground-water reservoir. Known inputs, from precipitation etc., are properly entered into the model; and outgo, in the form of pumping etc., is extracted. The water level representing the storage capacity of the mathematical model is then checked and compared with known water levels in the basin during the period being verified. Discrepancies require adjustments, which may be necessary in recharge or discharge rates, transmissivity or storage capacity. After discrepancies have been "adjusted out" for reservoir response, which has been determined from historic data, a model may be considered accurately to simulate the actual ground-water reservoir. The model may then be utilized to predict variations of ground water in storage and variations of water levels that would occur with any proposed future pattern of ground-water replenishment and extraction from the reservoir, within the part of the aquifer tested by the historic data. In accordance with expected inputs of the reservoir, optimum location, depth and discharge of wells can be planned. If artificial recharge is to be necessary, the response of the model to various amounts and locations of recharge can be tested. A verified mathematical model of a ground-water reservoir is probably the best available tool for planning and managing future ground-water storage.

## Sources of information

In concluding this section, it should be emphasized that a significant amount of preliminary and detailed information regarding the assessment of ground-water resources, including ground-water storage, is available in a great number of countries, and is continually increasing. The selection of case studies included here is intended to give a sample of world-wide information. The main sources of information and documentation are the national agencies, the international associations and a number of private firms. In most of the industrialized countries, including France, Japan, the Union of Soviet Socialist Republics and the United States of America, the national geological surveys deal with ground-water problems. In some countries ground water is the concern of the ministry of public works, or a ministry of water and power or a ministry of natural resources (as in a number of countries of Africa and in Iran). Elsewhere, such specialized agencies as the Egyptian General Desert Development Organization (EGGDO) and development corporations in Latin American countries are involved in ground-water investigations and development.

Usually, the results of the most complete and advanced investigations are published and are available. Exchange of publications between most of the geological surveys of the world is now a routine procedure. The United Nations, through the regional economic commissions and the specialized agencies have issued publications which deal directly or indirectly with ground-water storage problems. The publications of the International Association of Scientific Hydrology and of the International Association of Hydrologists provide abundant data concerning ground water. Other symposia also provide pertinent information. In this respect, the International Conference on Waters for Peace, held in Washington, D.C., May 1967, deserves special mention owing to the number of participants and to the value of the material presented and published. Numerous engineering and geological firms engage in ground-water work throughout the world. Reports of these firms are generally restricted, as they are usually given only to clients such as national or local governments.

### C. Drains, wells and pumps

Exploitation of ground-water storage may imply the closing of the natural outlets of a ground-water reservoir or the creation of new artifical outlets, sometimes including the construction of artifical recharge works.

Several methods of construction may be used: building of underground dams; permanent or temporary obturation of springs; or the cementing or grouting of underground outlets or leaking areas. Some examples are given in part two, the most significant one being the exploitation of the limestones of Jhel Zaghonan, in Tunisia, for the water-supply of the city of Tunis.

The new artifical outlets include either drains or pumped wells that may be dug, drilled or sunk.

In ancient times, the construction of drains was widely utilized for the exploitation of aquifers in Central Asia and in the Middle East. Owing to the high cost of such works, their difficult and expensive maintenance and their relatively low yield, this type of construction was abandoned in favour of the construction of wells equipped with mechanical pumps.

In general, wells dug by hand do not produce high yields. Their depth usually does not exceed an average of from 30-50 m, as a maximum. Under normal conditions, they do not penetrate more than one aquifer and cannot be driven more than a few metres in to an aquifer, even if powerful jackhammers and sump pumps are used for their construction. However, there are essentially no technical limitations to the depths of drilled wells or tube-wells; the limiting factor is the cost. The rate of penetration of a drill may vary widely per 8-hour shift from a few inches using a conventional cable-tool rig in hard rock such as quartzitic gneisses or boulders, up to several hundreds of metres using a rotary rig in soft consolidated terrain.

The various well-drilling methods and equipment were, for the most part, developed to meet special conditions in major hydrogeological environments; consequently, each method or type of equipment is particularly suitable for a limited range of conditions. Accordingly, various attempts have been made to design combination rigs employing two methods, so that one or the other can be used according to the drilling conditions encountered. One type of combination rig widely used is that employing percussion and core-drilling, but other combinations can be designed according to conditions anticipated. Manufacturers offer combination rigs that can be equipped for percussion, rotary, jet hollow-rod, core or auger drilling.

Another recent development of combination methods, designed for drilling in hard rocks, is the rotary-gun drill, or down-the-hole air-hammer tool, which is a percussion tool used with rotary equipment. It works on the principle of the pneumatic drill, in which the cutting head vibrates rapidly by compressed air. The compressed air also serves to blow the cuttings from the hole. Holes can be drilled to a depth of about 300 metres with this equipment.

A summary of the diverse drilling methods and of their advantages and disadvantages is provided in table 6.

Table 5. Information characteristics of various drilling methods

| Quantitative and qualitative characteristics of geologo-hydrogeological information | Drilling methods | | | | | |
|---|---|---|---|---|---|---|
| | Rotary with mud | | Rotary with air circulation | | Percussion-cable | Combined (auger and percussion-cable) |
| | Non-core | Core | Non-core | Core | | |
| Registration of aquifers met in drilling wells | Thin and poor yield aquifers may not be found. After drilling stopped logging is required. | With a shorter penetration distance all aquifers may be recovered with a longer distance thin and poor-yield aquifers may be missed. | All aquifers may be practically found. | | All aquifers may be practically found. | All shallow aquifers may be found with auger drilling. |
| Rough error in establishing boundaries of aquifers | 1.0 m and more; 0.5-1.0 m, with logging. | 0.1 m, with a shorter penetration-distance. | 0.5 m | Up to 0.1 m, with a shorter penetration distance | 0.5-1.0 m | Up to 0.5 m with auger drilling |
| Preliminary estimation of hydrogeological parameters of aquifers in drilling well | Estimation is poor. Aquifer tests are necessary, using formation-testers, well flow-meters etc. | | Good | Good | Good | Fair with auger drilling |
| Estimation of aquifer hydrogeological parameters by means of pumping and injection | As a result of mudding-off of developed aquifers and screens, significant resistances in the section adjacent to the screen and in the screen take place which distorts the natural characteristics of the aquifer and lowers the reliability of the investigations being carried out. Well development, a complex and continuous operation, is required. | | Of high quality | Of high quality | Of high quality | Of high quality |

Table 6. Principal technical-economic characteristics of various drilling methods

| | Drilling methods | | | |
|---|---|---|---|---|
| | Rotary with mud | Rotary with air circulation | Percussion-cable | Combined |
| | 1 | 2 | 3 | 4 |
| Advantages | 1. Possibility of well-drilling to great depths in differently consolidated rocks<br>2. High technical and commercial drilling rates, exceeding 3-5 times percussion-cable drilling rates<br>3. Possibility of using wells of simplified design | 1. High technical and commercial drilling rates exceeding similar indices of drilling with mud<br>2. Provision for water and mud is unnecessary<br>3. Possibility of high-quality testing and capping of aquifers<br>4. Successful drilling in permafrost rocks, under conditions with mud absorption | 1. High quality of hydrogeological information obtained in drilling<br>2. Possibility of high yields in wells as a result of absence of mudding-off in developed aquifers<br>3. Provision for water and mud is unnecessary<br>4. Possibility of successful application in boulder-gravel sediments in drilling wells with large initial diameters (more than 500 mm) | 1. Possibility of using the advantages of various drilling methods, the selection of which depends on geologo-hydrogeological conditions and drilling objectives<br>2. Possibility, if necessary, of obtaining high-quality hydrogeological information in drilling and conducting high quality work on equiping the water-reception portion of the well without mud application |
| Deficiencies | 1. Difficulties in reliable aquifer tests<br>2. Clogging of the developed aquifer with mud resulting in well-yield reduction; necessity to conduct complicated and continuous work on recovery of well-production<br>3. Necessity to provide the rigs with water and high-quality mud<br>4. Difficulties in drilling rocks containing boulder-gravel inclusions<br>5. Difficulties in conducting operations during winter at negative temperatures | 1. Difficulties in drilling with a rate of flow into the well exceeding 2-3 l/sec, and in penetration of often interbedded aquifers and water-saturated sands more than 5 m thick<br>2. Possibility of drilling only in stable rocks | 1. High casing consumption<br>2. Technical and commercial drilling rates are lower than those in rotary drilling | 1. Relatively heavy weight and immovability of equipment |

Table

|  | Drilling methods |  |  |  |
|---|---|---|---|---|
|  | Rotary with mud | Rotary with air circulation | Percussion-cable | Combined |
|  | 1 | 2 | 3 | 4 |
| Recommended conditions of application | 1. In drilling under well-studied geologo-hydro-geological conditions, in the absence of often interlaid aquifers and in capping of artesian aquifers | 1. In drilling in regions without water and frozen rocks | 1. In drilling under poorly studied geologo-hydro-geological conditions, while capping semi-confined aquifers, in case of often interlaid aquifers | 1. In drilling in poorly studied geologo-hydro-geological conditions, in often interlaid aquifers, in capping semi-confined aquifers |
|  | 2. In obligatory application of formation-testers for testing aquifers in drilling and a complex of geophysical studies during and after well penetration | 2. In drilling wells in aquifers with yields of up to 2 litres per second | 2. In drilling wells down 100-150 m deep and drilling in boulder-gravel sediments and wells with large initial diameters | 2. At satisfactory mobility of drilling equipment, in case of drilling a number of wells located in the immediate vicinity, allowing to transport the drilling rig from point to point without having to disassemble it |
|  | 3. In possible application of well-completion methods or screen installation without aquifer mudding-off (drilling with pure water in stable rocks, screen installation by percussion, hydraulic washing and air-lift pumping, drilling with natural solutions etc.) or with reduced aquifer mudding-off (drilling with aerated solutions) | 3. In drilling in stable rocks and in the absence of often interlaid aquifers with large flow rates | 3. In application of vibration devices for installation and recovery of casing tubes |  |
|  | 4. In drilling wells more than 100-150 m deep, provided sufficient delivery of water and high quality mud |  |  |  |

Casing and screen columns are important components and a major cost factor in the construction of drilled wells. In most wells, casings and screens are needed to prevent the walls of the hole from collapsing under the lateral thrust of the aquifer, particularly when pumping takes place. The life of a tube-well is directly related to the capacity of the pipes to resist thrust, corrosion and incrustation. Many types of casings and screens, made of a variety of materials, including metals, alloys, wood and plastics are available.

In the construction of a "driven well", earth materials are not removed from the ground but, rather, are displaced laterally. In soft ground, where the water is at shallow depth, small-diameter wells may be sunk by driving casing or pipe into the ground by means of a sledge- or drop-hammer. The casing must be strong enough for this purpose and should be "pointed", or equipped with a steel point, while the top of the casing is fitted with a driving-head, to prevent its crumpling when hammered. Above the well-point, the tube is perforated to admit water and is usually screened to keep out fine sediment. Generally, driven wells are limited to 10 m or less in depth and to 5 cm or less in diameter; they are used mainly when the water lies within less than 6 m from the surface, so that water can be raised by suction pumps under atmospheric pressure. Where this is not possible, a driven well must be of a diameter large enough to permit a pump cylinder to be set near the water-table. This larger diameter makes it more difficult to drive a well to the required depth.

Wells can be sunk ("sunk wells") in soft, fine-grained materials by "jetting", a process which involves directing a stream of water under considerable pressure through a pipe and a suitable nozzle into the bottom of the hole. Materials so loosened are carried continuously to the surface between the pipe and the casing by the returning stream of water. Under good conditions, the process can be a fast and effective means of developing a water supply. Most individual dug wells, driven wells, and jetted wells have a small yield; but large assemblages of such wells may have a very large output, thus significantly affecting the hydraulic system of a ground-water reservoir. The location and spacing of wells and drains, their depths, diameters, casing and other specifications have to be determined through hydrologic engineering and economic studies, sometimes with the assistance of mathematical or analogue models.

The optimum development of a well-field, especially when the yield is important, is always a delicate operation, because any new producing unit should not cause excessive interference with previous installations.

A well-field has to be conceived in terms of individual yields of each well, the number, spacing and total output of wells; and the nature of the lowering of the water-table for a predetermined pumping pattern. Lastly, the waters which are pumped must be available to the final users at an acceptable cost.

The range of diameters, the depths of wells and the capacity of pumps is quite broad; the capacity of a pumping installation is controlled by the diameter of the pump column and is usually determined by the delivery head, that is, the depth of the water-table during pumping. Some examples of the range of pump capacity are given in the following table:

| | Diameter (inches) | Output (litres per second) | Delivery head (metres) |
|---|---|---|---|
| Test pump | 3 5/8 | 1.0 | 70 |
| | 3 5/8 | 2.5 | 15 |
| | 4 | 1.5 | 45 |
| | 4 | 2.7 | 30 |
| Exploitation pumps | 7 7/8 | 3.5 | 90 |
| | | 7.0 | 45 |
| | | 12.0 | 30 |
| | Fitting a 12-inch casing | 55 | 30 |
| | | 65 | 25 |
| | | 100 | 15 |

Pumps are operated either with petrol, diesel engines or electric motors. When the pumping installations are numerous enough and densely distributed, electric pumps are usually recommended, as they permit a greater flexibility in pumping and reduce maintenance costs.

## D. Operational procedures

In the utilization of ground-water storage, the main problem is to store sufficient surface water in ground storage during periods of great availability to satisfy all water needs with this stored water during periods of low surface-water availability. Generally, a larger quantity of surface water will be stored underground, and through this storage and gradual use, adequate water will be available during both wet and dry seasons. In order to store an increased volume of water underground, two approaches can be envisaged. Firstly, if the outlets of the aquifers are closed for an extended period, an accumulation of ground water may occur. As a matter of fact, such a result is not easy to obtain. In most areas, there are many outlets and their location is not known. However, the construction of (underflow) dams, the setting of grouting systems and the closing of springs may be possible at the main known outlets. Secondly, by extracting ground water the flow issuing from the outlets can be reduced or stopped. Pumping during a dry period may lower the flow that occurs during the following humid season. In other words, the increase in ground-water storage may be in part dependent on the slow drainage that occurs from a heavily pumped recharge aquifer. This delay in ground-water drainage should occur so that the maximum possible quantity of water is available. The design of the system is related to a number of factors, including the dimensions and lithology of the aquifers, hydrological conditions of the aquifers, including natural discharge and their relationship with surface streams.

All ground-water reservoirs are subject to variations in the volume of water stored under natural conditions, as shown by the fluctuations of the piezometric surface. The variations of volume of water in storage can be evaluated when such data as amplitude of fluctuation, storage coefficient and dimensions of the aquifers are known. The fluctuations occur as a result of both recharge and discharge, i.e., the components of the water-balance, the result of which corresponds to the variation of the reserves when the total input and the total output are not balanced. An increase of the volume of water in storage corresponds to a positive balance, a decrease to a negative balance.

Any aquifer system is, in fact, not in balance if a short period of time is considered, but within a span of several years equilibrium is generally obtained. Variations in storage of a ground-water reservoir will, therefore, depend upon the period of time which is considered and upon the natural conditions prevailing during this period. Ground-water reservoirs have this in common with surface-water reservoirs: a better regulating pattern is obtained if a longer period of time is considered.

The fluctuations of a piezometric level in a ground-water reservoir can be defined by both their amplitude and their periods. The amplitude provides an indication of the reserve capacity of the reservoir and of the amount of water which can be extracted through temporary over-exploitation; the period indicates the seasonal character of storage changes and the duration of over-exploitation. Several years are usually required to determine the natural and maximum storage capacity of a reservoir, but this implies that a sufficient and significant capacity for storage is available.

The concept of "regulative reserve" can be defined as the total reserve that is held in an unconfined ground-water reservoir. This reserve can be divided into two parts: the varying "regulative reserve" which may, in some cases, be increased by means of artificial recharge, is the quantity of water which is stored in the aquifer between the highest and the lowest recorded level of the piezometric surface, i.e., the "fluctuation zone"; the "constant reserve", sometimes called the "dead storage" or "geological reserve" can be considered as that portion of the reservoir situated between the bottom of the aquifer and the lowest recorded piezometric surface. The regulating function of the reserve can be used by utilizing that part of the storage in the "fluctuation reserve". It is possible artificially to increase this zone of fluctuation by pumping from the reservoir, and thus increasing the amplitude of the natural fluctuation.

In theory, two situations can be encountered:

(a) The pumpage takes place when the water-table is rising; this is the recharge or replenishment period. This rise, related to an increase of the regulative reserve, is therefore slowed down and sometimes stopped completely. The constant reserve is not affected. During the discharge period which follows, the flow of the outlet is diminished;

(b) The pumpage is carried out when the water-table is lowering (discharging), and this lowering is increased by pumpage: if this pumpage persists so that water levels decline below the natural fluctuation zone the constant reserve begins to be tapped. In the recharge period which follows, the rise of the water-table will be reduced and, therefore, the outflow will be diminished at the following discharge period. The "rate of renewal of the reserve" is the ratio of the annual regulative reserve, $\underline{Q}$, to the total (interannual) regulative reserve $\underline{V}$, i.e., the fraction of the total reserve which is renewed in one year = $\frac{\underline{Q}}{\underline{V}}$.

$$\text{Example: } \underline{Q} = 10^7 \text{ m}^3 \text{ / year}$$

$$\underline{V} = 10^8 \text{ m}^3$$

The rate of renewal is $10^{-1} = 0.1$.

The duration of complete renewal, if no outflow occurs, can be defined as $\frac{V}{Q}$. In this example the duration will be 10 years. The regulating capacity of a ground-water reservoir is greatest if the rate of renewal is small and is less than 1. If the ratio exceeds 1, no regulation is possible; thus small reservoirs, such as narrow alluvial valleys with high tramsmissivity, may be well supplied with water but have no significant storage potential.

Table 7. Regulating potential of aquifers

| Rate of renewal | Amount of water in storage | Regulating potential Annual | Regulating potential Over several years |
|---|---|---|---|
| High (> 1) | Small | None | None |
| Moderate (near 0.5) | Limited | Usable | Limited |
| Small (near 0.1) | Large | Optimal | Optimal |
| Very small ( < 0.1) | Fossil reserves | Very large | Very large |
| Up to 0.0001 | Negligible or none, recharge at present | - | - |

Many ways have been developed to utilize the large volume of stored gound-water and the considerable storage capacity of ground-water systems. In order successfully to utilize these parameters, three conditions must be met:

(1) The natural and human factors influencing the ground-water resource must be known in some detail. However, this does not mean that utilization of ground-water storage must be deferred until lengthy theoretical investigations have been completed. On the contrary, the implementation of small-scale projects can be undertaken even before the properties of the ground-water system are known in full detail. The experience gained during the implementation of these small-scale projects, the hydrological observations, the geological information from bore-holes, etc., can supply most of the information obtained by detailed ground-water investigations. If sufficient judgement is exercised, large-scale schemes can be implemented step by step, each preceding step providing vital information for the following one;

(2) The engineering aims must be clearly formulated and adhered to during the implementation of the project. To cite an example: it has been decided to utilize a ground-water system in an arid region for the purpose of long years of storage in order that the total water supply shall be adequate during excessively dry years. This means that during normal years, a certain exploitable

reserve must be kept in the aquifer. If ground-water pumpage is increased beyond the pre-determined limits, the declared engineering aim will be jeopardized;

(3) Administrative measures must be taken so that the exploitation of ground-water can be supervised and guided in the desired direction.

It is interesting to note that the above conditions are commonly, though not always, met with when large-scale diversion works for river water are planned. Here, they are necessary in order to justify and protect the heavy capital investment, and this provides an early reference point for their introduction. In ground-water projects, the need for clear thinking is just as great, but it is not urgently felt in early stages of the development.

The management of ground-water resources should, therefore, in principle, always operate under "safe-yield" conditions.

The "safe yield" of a ground-water system may be defined as the maximum rate of artificial withdrawal that can be maintained over an indefinite period without adverse effects on the resource. The rate of natural replenishment obviously constitutes the upper limit to the safe yield, as defined above; but apart from that, there is no simple connexion between yield and replenishment. In order to understand the limitations of the safe yield concept, the following points must be considered:

(a) It should be noted that the terms "safe" and "adverse effects" can be defined only in relation to human intervention in the hydraulic system. The terms have no relevance to natural phenomena. Therefore, it is pointless to elaborate rules based on natural criteria only;

(b) Not only pumpage may have adverse effects on the ground-water system; man-made pollution, agricultural practices and other types of human actions also affect the ground-water resources. It is a fallacy to believe that everything will be "safe" as long as pumpage is under control;

(c) If the water resource is already adversely affected, e.g., by the invasion of sea-water, restriction of the exploitation to the assumed "safe yield" may not suffice to remedy the situation. In critical situations, much more radical measures may have to be applied;

(d) In many cases, the determination of safe yield depends strongly on the location and characteristics of bore-holes, their spacing and depth. If a coastal aquifer is penetrated by bore-holes near the sea-shore, the danger of sea-water intrusion will be imminent and the safe yield of these bore-holes will be rather small. Conversely, the safe yield will be much higher if the bore-holes are drilled far away from the shore.

(e) If the term "safe yield" is to be related to "average annual replenishment", the term "average" needs clarification. Averages are defined only in mathematical terms, they do not need to have any physical significance. However, "safe yield" is a quantity of water actually available each year without regard to climatic fluctuations. As a matter of fact, the storage of the aquifer is called upon to "iron-out" seasonal and yearly fluctuations of replenishment, so that a dependable safe yield can be obtained. In this respect the function of ground-water storage is identical to the function of storage reservoirs in supply systems of surface water. Therefore, when the safe yield of an aquifer is determined, it is necessary to take into account its storage, as well as the fluctuations of replenishment which can be expected.

A distinction was previously made between the zone of fluctuating water levels and deeper zones not affected by annual fluctuation. (See chapter I, section G.) For the maximum exploitation of a ground-water system, it is desirable to lower the water-table sufficiently in order to decrease natural ground-water discharge and to rely upon utilization of deeper zones of storage (assuming, of course, that they exist in the particular case). Aquifers that naturally discharge through well-defined springs have been successfully exploited in this way.

In a coastal aquifer, which communicates with the sea by open channels, lowering of the water-table to decrease natural discharge is not feasible. When the water level is lowered by exploitation, the interface of fresh and salt water shifts upwards and inland, replacing fresh water in storage. In such a coastal aquifer, only shallow storage can be effectively utilized.

From an engineering point of view, one may distinguish between "exploitation reserves", which can be utilized without endangering the safe yield of the system, and reserves the exploitation of which will greatly damage the system. The distinction is useful, but not absolute because, frequently, a time factor intervenes. Thus, in a coastal aquifer, huge reserves can sometimes be exploited temporarily, under the condition that they are replaced within a few years, before large-scale sea water intrusion has occurred.

Mining of ground water, i.e., the permanent removal of ground-water from storage, is sometimes practised in order to accomplish well-defined aims. Thus, for example, in a desert region, very brackish ground water is mined and utilized for the extraction of copper from ore. The only objective is to make the supply of ground-water last as long as the supply of copper ore, no other use for this type of water being envisaged.

The exploitable reserves are decreased even by those methods of system-operation that are conducted within the limitations of the safe yield. As previously mentioned, the exploitable reserves then left in the system must suffice, at least, to equalize fluctuations of natural replenishment. In some situations it is possible and advantageous to recover and utilize most of the exploitable reserves instead of causing a permanent decrease in them.

A number of type-schemes have been developed for exploiting ground-water storage. An extreme case is the mining of an aquifer system. For instance, in certain regions of the south-western part of the United States where practically no replenishment takes place, a pattern of ground-water extraction has been developed, by means of an analogue model, for the complete depletion of the aquifers over a period of about 20 years. By the end of that time projects involving the construction of large canals will have been completed and surface water originating from other regions will be brought where needed.

At present, there are few examples of deliberate mining of ground-water on a large scale. Yet, the potential for mining is very large in many areas, such as in the Sahara and in the deserts of Egypt and the Libyan Arab Republic. It has been estimated that in Long Island, New York the aquifers contain enough water to satisfy present pumping rates for at least another thousand years, even if rainfall were to cease and not another drop of water were to be recharged naturally into the formation. It should be mentioned, however, that mining of ground water is, and rightfully so, an unacceptable idea to most hydrologists and conservationists, except in the special cases mentioned above.

A more common approach is the exploitation of seasonal-storage ground water. In the natural state, ground-water can be thought of as a very broad and deep stream which flows very slowly towards its outlet, and with rather small seasonal or yearly fluctuations. Scientific ground-water exploitation makes it possible to utilize a considerable part of the natural yearly flow of this stream within shorter periods of time, in order to supply fluctuating water requirements. Thus, if ground water is used for agricultural irrigation, a large part of the average yearly replenishment will be abstracted by bore-holes during a few months' time. This procedure constitutes, perhaps, the simplest way to utilize ground-water storage.

Modification of spring-flow is also a classical scheme. Perennial springs form a very attractive source of water, especially in arid or semi-arid regions. Unfortunately, water requirements are at their peak during the hot season, when spring flow is usually low; during the cool season, flows are high and requirements are low; as a consequence, much of the previous water is often lost. In many cases it is feasible to drill bore-holes into the ground-water reservoir which feeds the spring and to pump water from them. This lowers the driving head and reduces the flow of the spring. An analysis over time of a hydrograph of spring flow makes it possible to predict the influence of pumpage on the spring flow and to operate the system so that the total amount of water discharged, i.e., residual spring flow and pumpage, is equal in volume each season to the average natural recharge.

In arid regions, springs are often saline owing to intensive evaporation and accumulation of salt near their outlet, or they form so-called sebkhas (saline swamps). Karstic springs near the sea coast are often saline owing to the intrusion of sea water. In both cases it is frequently possible to abstract water of much better quality from bore-holes drilled further up-gradient into the underground reservoir. In this case the ground-water reservoir is utilized for shifting from saline water to fresh water.

More sophisticated schemes are developed for exploiting the regulative reserves. As previously mentioned, after a period of intensive exploitation, a very considerable part of the regulative storage is usually lost during the time it takes for a new hydraulic equilibrium to take place. In some situations it is advantageous to exploit this regulative storage by temporarily increasing the rate of pumping.

The principle of this idea is best illustrated with the aid of the tank model. Assume that, the water level is still high above its eventual equilibrium position and that ground-water abstraction is increased to, say, twice the rate of replenishment. This will reduce the water lost through natural discharge. As soon as the water level reaches an acceptable position, ascertained beforehand, pumpage should be reduced to the safe yield (in the previous example 75 per cent of replenishment), and thus the position of the water level would be stabilized.

During the period of increased pumpage, a considerable part of the stored water is recovered which, otherwise, would have been wasted by discharge through the natural outlet. In actual ground-water systems, even of moderate size, a very large volume of water may thus be recovered over a period of several years.

For the implementation of such a scheme, two prerequisites must be met; (1) Detailed accurate and reliable quantitative information on the ground-water system must be available, (2) There must be a possibility of reducing the abstraction of water to the safe-yield rate at the proper time.

Controlled, temporary over-exploitation of a ground-water system is attractive during the period that is needed for planning and constructing engineering works for the diversion of river water. It is not only the economic value of the water which counts in such a scheme, but the possibility of delaying items of heavy capital expenditure in the river-diversion scheme. The time factor also has an important sociological implication. Potential water-users, for example, farmers in a developing region, may clamour for water, but they do not really know how to utilize efficiently large water supplies when they suddenly become available. Several years may elapse before the water supplied from a new large installation is economically utilized. Utilization of ground water gives the farmers a chance to learn efficient methods of irrigation, accustom themselves to improved agricultural practices, to build up and operate the network of distribution pipes or channels and, last but not least, to develop the requisite organizational infrastructure, such as associations for water users. When the large water-supplies from the river are finally brought to the area, a developed community of users exists, able and eager to obtain the fullest benefit from the new water resource.

Ground-water storage is obviously an essential element of the schemes which aim at a combined and integrated utilization of water resources.

For the full development of a region, the optimum combined utilization of all water resources, both surface and ground water, is necessary. Experience has shown that this is true even in temperate humid climates, as in the Netherlands and the United Kingdom not to speak of dry countries, where each drop of water counts. For the integrated development of all water resources, ground-water storage can be utilized in a variety of ways. The most obvious way is to rely on surface water as much as possible during part of the year and to exploit ground water when surface water is insufficient. This method is, of course, especially important in arid and semi-arid countries, where river-flow fluctuates widely. The water accumulated in surface reservoirs should be utilized as quickly as possible, in order to avoid the very considerable losses by evaporation, and the water-supply should be gradually switched over to ground-water resources during the dry season. This means, in effect, that ground-water storage is utilized as seasonal storage for surface water, without being physically connected to it. The next step consists of establishing a physical connexion between surface and ground water by artificial replenishment and underground storage.

"Induced recharge" can be defined as any increase in the rate of recharge of a aquifer, caused by exploitation. It may be thought of as an intermediate system between natural recharge and artificial recharge. Induced recharge seldom results from an increased infiltration of rainfall water, but is commonly due to an increased rate of infiltration of surface water from rivers, streams and lakes. Two main schemes can be considered. The first is pumping from an alluvial-fill aquifer which is replenished by a nearby permanent stream. Such exploitation permits an extraction of ground water several times larger than the natural ground-water flow in the alluvium. A large percentage of the water which is pumped may originate from the river. This, however, is not an example of exploitation of ground-water storage, because it involves only a short distance and a short transit-period underground for the waters between the surface-water body and the outlet of the pump. The aquifer is used only locally, and more as a conduit or pipeline than for its storage properties.

The second scheme is entirely different, and occurs where the aquifer has a broad areal extent and is naturally replenished by temporary streams, especially flood waters which are available for short periods of time. The greatest ground-water yields are obtained if exploitation of ground water, prior to flooding, has considerably lowered the water-table, thus allowing increased infiltration. Such conditions exist, particularly in some arid and semi-arid areas, where dewatered alluvial beds can be recharged at a very fast rate. In such cases, it is economically advantageous to create an over-draught during the dry season, which yields a maximum amount of water, when the water needs are also maximum, and permits use of the dewatered zone to the maximum of its capacity.

Artificial recharge is the deliberate impounding of water into geological formations under the surface of the soil. Owing to the sophisticated techniques and the importance of works which are involved in such operations, this subject is taken up separately in chapter III.

## E. Storage regions

In order to identify the storage regions of a country, its territory should first be subdivided into hydrogeological units. This has been done for Europe, North America, Australia, Japan and for at least a part of the territory of some developing countries. In the Soviet Union a 50-volume publication, Hydrogeology of the USSR, is about to be completed. The principles of subdividing an area of 22 million km$^2$ into hydrogeological units, as presented in this publication, may be used for other parts of the world. A brief outline of these principles is provided below.

At the first stage of area subdivision, the geostructural principle has been adopted. According to it, the area is divided into different parts: (a) Large artesian basins of the platform type; (b) Folded regions, including intermontane artesian systems; (c) Areas of predominant development of fracture waters, largely in crystalline and metamorphic rocks.

Below, as an example, the first-order hydrogeological regions are distinguished for the western half of the Soviet Union according to the geostructural principle:

(a) Eastern European platform artesian region;

(b) Western Siberian platform artesian region;

(c) Turan (middle Asia) platform artesian region;

(d) Timan-Urals Palaeozoic hydrogeological folded region, with the Pechora artesian basin;

(e) Carpathian - Crimean - Caucasian Mesocenozoic hydrogeological folded region;

(f) Kopetdag Mesocenozoic hydrogeological folded region;

(g) Tien Shan - Dzhyngaria - Pamir Palaeozoic hydrogeological folded region;

(h) Central Kazakhstan Palaeozoic hydrogeological folded region.

Of course, each of these major regions is very complicated and may be further subdivided into major plain artesian basins or intermontane systems. For instance, studies have shown the presence of distinctly expressed lithologic units in the Eastern European platform artesian region. The lower unit primarily comprises Lower Palaeozoic and partially middle Palaeozoic artesian aquifers that can be considered as a single complex basin of almost the entire vast area, with highly mineralized water predominating.

The upper Palaeozoic and Mesocenozoic units contain well-defined artesian aquifers; the latter units may be isolated. Depending upon different conditions of water circulation and recharge, fresh-water aquifers are several tens to several hundreds of metres thick. These artesian basins are regions of the second order, isolated or divided by tectonic sutures either of the first or the second order.

The Eastern European artesian system comprises the following artesian basins: (a) Baltic - Polish; (b) Middle Russian; (c) Eastern Russian; (d) Caspian; (e) Dnieper - Donets; (f) Black Sea ( fracture water-basin ); (g) Baltic; (h) Ukrainian; and (i) Donets (hydrogeological folded zone).

These basins are storage reservoirs of the second order, distinguished according to hydrogeological features in geostructural and tectonic basins, and are units where inflow and outflow, i.e., the water balance, must be studied and estimated as for a single formation. Based on the measured values of the water balance, water chemical and isotope composition, the subdivision of the third order is likely to be made. The regions of the third order should represent separate storage reservoirs for which the possibility of annual withdrawal, recharge and interaction with adjacent storages and surface waters must be appraised.

When such a subdivision of a territory into hydrogeological units is presented, a selection can be made of aquifers having an important storage potential. This potential, when properly utilized, can exert a significant regulative effect on the water flow, thus increasing the availability of water resources. Some examples are listed below (the identification letters refer to the illustrations in figure 7).

A. Unconfined aquifer of substantial dimensions, without constant reserves, but sustained by a permanent draining river.

B. Unconfined aquifer of substantial dimensions, without constant reserves, under the level of the springs flowing along its boundaries. In this case, temporary over-draught is a potential management technique, if the extraction areas are located far enough from the springs, thus not immediately affecting their outflow. Temporary over-draught is especially feasible if the transmissivity coefficient is not very high near the outlets.

In cases A and B, the effect of the pumpings on the outlets is expected to be felt in a period of high waters.

C. Unconfined aquifer, not sustained and holding a constant reserve. This case applies mostly to karstic reservoirs, in which the regulative reserve is sometimes limited, but can be increased artificially and, to a lesser extent, to sands, sandstones, conglomerates and other porous media. Two categories can be distinguished:

$C_1$. Perched, massive aquifers with springs along their boundaries, such as synclines and monoclines bounded by faults.

$C_2$. Aquifers extending in depth beyond the spring areas, i.e. replenishment area of confined aquifers.

As a result of a seasonal over-draught the following has been observed: a decrease in the flow of springs, which may reach the stage of a complete disappearance of the flow; or an increase in the duration of the non-flow period. Pumping can be exerted either in bore-holes or in karstic springs, if an important storage capacity is available at depths under the outlets. This availability is particularly difficult to ascertain in karstic areas because the extent of fissuration and karstification can be quite different from that above the level of the springs.

D. Confined aquifers in the vicinity (from 5 to 10 km) of their direct replenishment areas. In this case the extraction of ground water by the way of pumpings and flowing wells diminishes the outflow of the outlets; the delay which is expected to occur is three to four months. The most favourable case is the one of buried karsts, which are weathered in their upper part and covered with an impervious capping of Miocene clays.

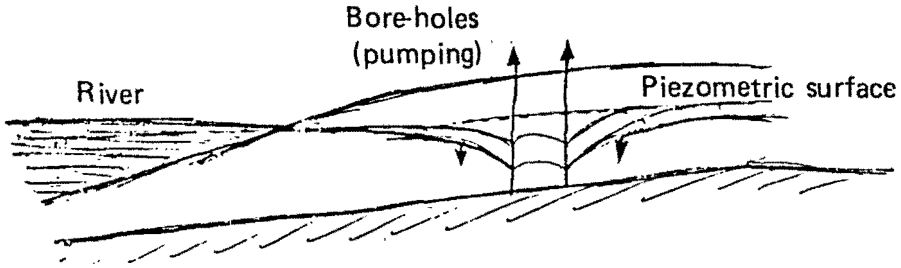
E. Unconfined, vast aquifers in the arid zone discharge large quantities of water into the atmosphere under the effects of evapo-transpiration. In this case, an over-draught is likely to reduce the evapo-transpiration losses and to improve the water balance, if the piezometric surface is sufficiently lowered by the pumpings.

In the above-mentioned types of aquifers and schemes of exploitation, there is a real utilization of ground-water storage through a regulating reserve of water.

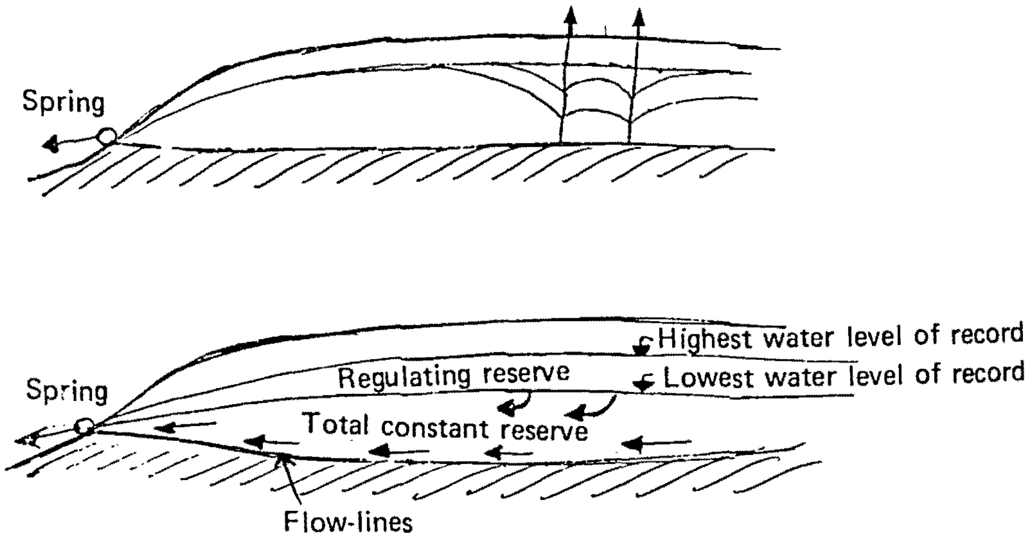
In addition, as mentioned above, the vast confined aquifers, such as those existing in the north of the African continent, hold huge quantities of water which can be tapped with little concern about recharge or a renewal of the regulative reserve, owing to the cost of the deep drilling which is necessary and the relatively small amount of water needed for the satisfaction of the vital needs of the scant populations in these areas. For such aquifers, the regulating reserve is practically negligible and the influence, if any, of such an exploitation upon natural outlets and replenishment areas is very slow.

Figure 7. Examples of aquifers having important storge potential

A Unconfined aquifer without constant reserves but sustained by a river stream

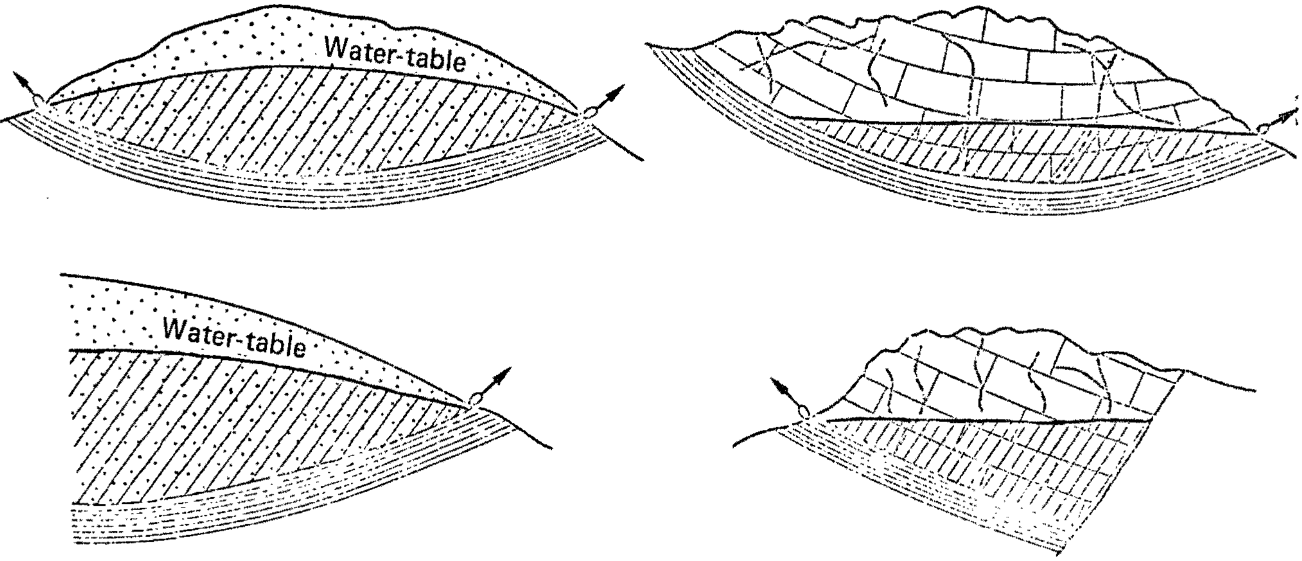


B Unconfined aquifer without constant reserves below the level of the springs



Note continuing discharge of stored water into stream

Figure 7. Examples of aquifers having important storage potential



Porous aquifers

Karstic aquifers

C₁ Various cases of perched aquifers with springs along their boundaries

Figure 7. Examples of aquifers having important storage potential

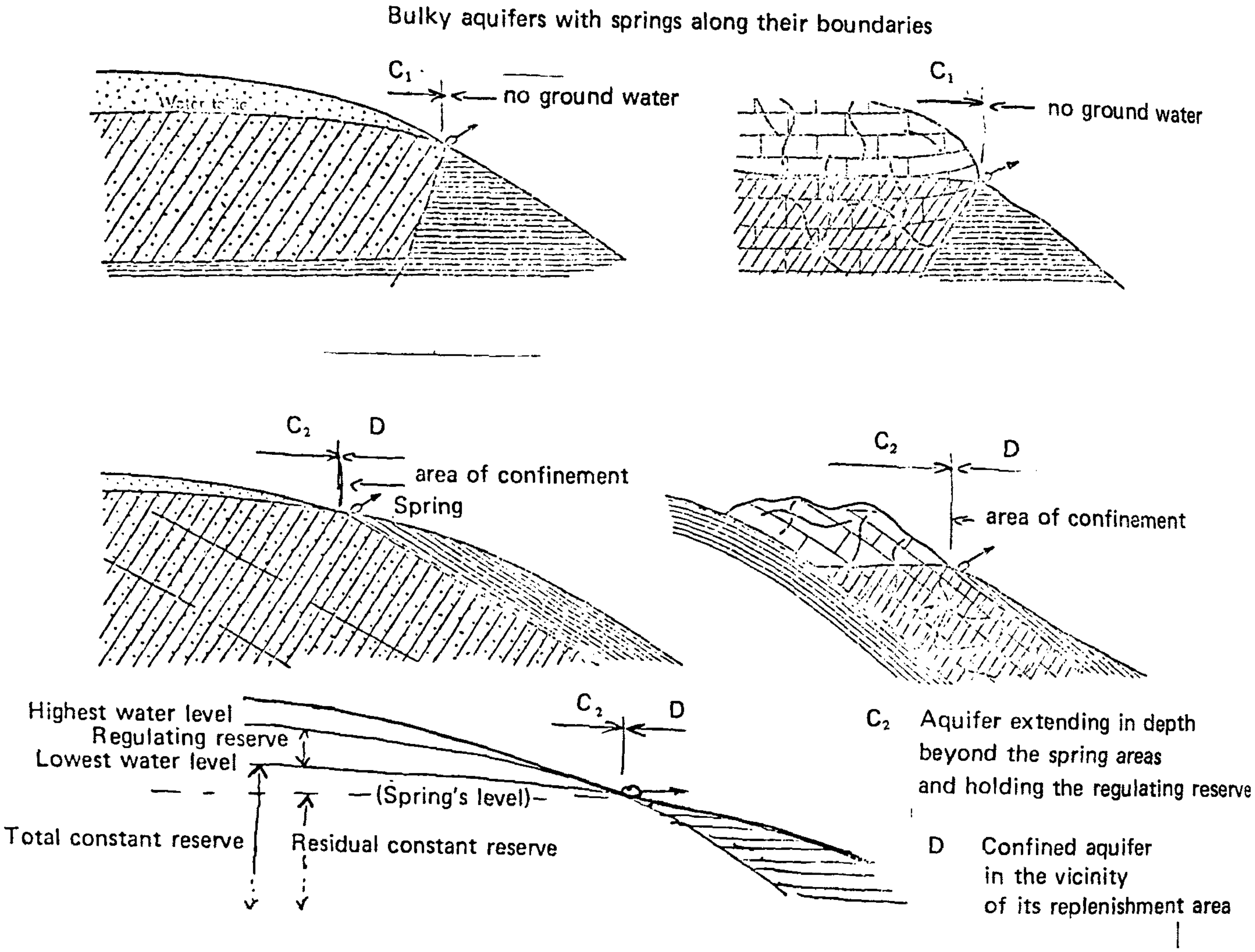
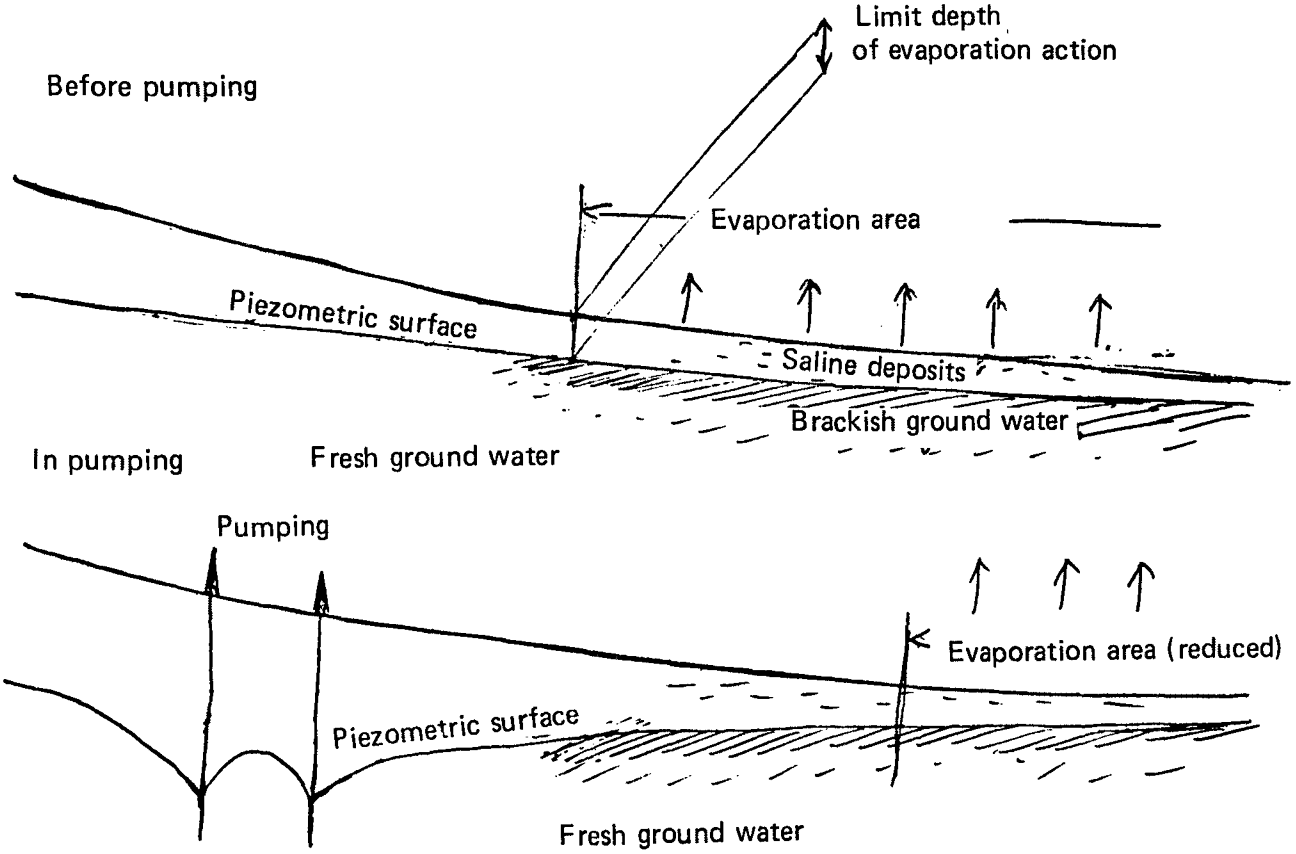


Figure 7. Examples of aquifers having important storage potential



Ground-water storage is not likely to be significant for small aquifers with small storage and a high natural recharge rate, such as alluvial aquifers of narrow valleys and aquifers divided by faults into small isolated compartments. Storage is also likely to be inadequate for:

(a) Unconfined aquifers of vast areal extent which are rather thin, or have a low storage coefficient;

(b) Some unconfined aquifers in the arid zone, in which natural recharge conditions are unsatisfactory;

(c) Unconfined aquifers "sustained" by a surface stream or a lake; in this case, induced replenishment usually occurs shortly after pumping, the aquifer being utilized more for its "filtration effect" than for its "storage effect".

In addition to the basic physical characteristics, previously mentioned, other factors resulting from human intervention play a significant role in ground-water storage regions. For example, in irrigated areas a substantial amount of irrigation waters often infiltrate down to the water-table, thereby recharging the aquifers. In a vast irrigated land, there may be land surfaces at low altitudes beneath which the soil is entirely saturated with water. Drainage through pumping is necessary for rendering these areas suitable for cultivation. The water thus obtained is utilized for irrigation in other sectors. Such a pattern allows maximum utilization of soil and water, and makes possible growth of crop in both areas. This example shows that a combined utilization of surface water and ground-water storage potential may represent, in certain cases, the most efficient approach to water development for irrigation.

In urban and industrialized areas, built-up surfaces, and especially paved or asphalted roads and streets, reduce infiltration and diminish replenishment, and in some of these areas ground water is intensively exploited. The spread of urbanization can thus seriously disturb the exploitation equilibrium of ground-water storage.

A great danger is pollution from urban sewage effluent and industrial wastes. The accumulation of "hard" detergents in ground water and surface water has led some countries to prohibit the use of such products. Examples of industrial wastes are the effluents from oil industries, the accidental spillage of oil from tanks and pipelines and the effluents from chemical factories and medical institutions, which often contain carcinogenic substances, such as phenols or radio-active materials.

Surface resources in a heavily urbanized region are bound to be polluted beyond usability, so that ground-water resources and the storage space afforded by aquifers are of high economical value. In fact, ground-water storage can be used in many areas to store urban and industrial wastes and to purify waste water to various degrees through the process of filtration. Projects of this kind are operating in several industrialized countries, especially in the Federal Republic of Germany and the United States.

## F. Problems

Exploiting ground-water storage is not a simple operation, it cannot be disconnected from the over-all pattern of the water cycle, involving the whole of the water resources of a given area. It requires a good knowledge of the physical data - hydrogeological and hydrometeorological - and also of future demands for water and the distribution of these demands in time and space.

It is obvious that exploitation problems are primarily related to geolithological factors. For instance, poorly compacted geological formations are often more vulnerable to subsidence than compact rocks. Carbonate karstic rocks are highly vulnerable to contamination, but less vulnerable to clogging than are porous rocks.

Exploitation problems are also closely related to hydrometeorological factors and vary widely with climatic conditions. In arid zones, potential evaporation is considerably higher than the average yearly precipitation. However, during a short period of heavy rainstorms, precipitation may exceed the potential evaporation ratio, and infiltration occur, recharging ground-water reservoirs. This phenomenon varies greatly from year to year, and in very arid regions it may happen that no significant rainfall will occur within a span of several years. Salts tend to accumulate on the surface of the soil and even in ground water owing to high potential evaporation and scarcity of surface water.

In view of the above characteristics, the utilization of ground-water storage in arid regions must pursue two objectives: (1) The equalization of the very erratic conditions under which nature provides water; and (2) The preservation and maximum utilization of the limited amounts of fresh water which may be found in a mostly saline or brackish environment. In such regions, it is of primary importance to evaluate correctly the extent of the ground-water storage system and its exploitable capacity. Over-exploitation of ground-water storage usually causes a marked increase in salinity and, therefore, under most practical conditions, the two factors, storage and salinity, must be jointly considered. It is also important to determine the average annual rate of replenishment. However, any calculated value of the replenishment is significant only if the ground-water storage is large enough to satisfy the water requirement, until the underground reservoir is again replenished in periods of abundant rainfall. As a matter of fact, water requirements usually increase during dry years, and some provision should be made for this contingency.

The limitations of ground-water storage are apt to be felt acutely in regions which have been heavily exploited for many years. The depleted ground-water reserves may not suffice to meet the needs in a succession of dry years and, therefore, a critical water shortage may develop, causing a further significant lowering of the water levels and a marked increase in salinity.

Conversely, the conservation of ground-water resources in certain areas of the arid zone will be achieved through pumping that lowers the piezometric surface to a depth at which losses through evapo-transpiration are greatly reduced. In this particular case, the maintenance of satisfactory water quality is achieved by keeping ground water stored below its natural level.

In humid tropical areas, rainfall exceeds evaporation, despite the hot climate. However, very intense rainfall often alternates with dry seasons during which a temporary deficit of water occurs, as small surface streams and shallow aquifers dry out completely. An almost impervious crust of lateritic material forms at the surface owing to the combined influence of heat and humidity, and this reduces infiltration into aquifers. Ground-water reservoirs should be properly utilized to store sufficient water to prevent seasonal deficits. In cold-weather areas, ground-water temperature is higher than surface temperatures during winter and spring. This makes it advantageous to use water from the ground-water storage for the irrigation of crops in order to hasten their growth.

In very cold regions, such as within the Arctic Circle, perennially frozen ground, or permafrost, is widespread. The permafrost may not be continuous, but it profoundly affects the circulation of ground water and, in extreme cases, makes the recovery of ground water virtually impossible. For the utilization of ground water it is necessary to locate thawed zones near large bodies of water and aquifers under the regional body of permafrost. Where permafrost is very thick, wells must penetrate into the bed rock. In Alaska, potable ground water has been pumped at rates as high as 3 l/sec from beneath 180 m of frozen material. However, ground water is generally easiest to develop during late summer and early winter. The quality of water is good, as it is actively recharged from surface streams and lakes generally containing water of high quality.

The main technical problems in ground-water storage are related to the conservation of the resource in quantity and quality and availability. In other words: (a) The storage capacity is to be protected against clogging and subsidence; (b) The aquifer is to be protected against contamination by sea water, inland salt waters and pollutants; and (c) Water in storage should be available when needed.

The essential requirement for securing ground-water storage is to maintain extraction of water within the limits of a safe yield. It must be emphasized that, in addition to the depletion of the resource, over-draught may cause structural damage to the storage system. For instance, excessive rates of pumping may move fine particles toward the wells, resulting in sealing of well-screens or clogging the fine material surrounding the wells and reducing the effective use of storage capacity. Excessive pumping may also cause compaction of aquifers, thus reducing their storage capacity.

In some cases land subsidence may occur. If clayey layers are overlain or underlain by sandy aquifers, de-watering of these aquifers may result in a decrease moisture level in the clayey layer and a resulting decrease in volume. Serious damages are caused by subsidence, including stagnation of surface and ground water inundation by floods and invasion of high tides in coastal areas.

An example of land subsidence was observed in Osaka, Japan, which developed as a consequence of over-draught. Subsidence was first noticed about 1925 and accelerated after 1950, as a result of an increase in ground-water extraction for industrial purposes. The subsidence which reached a maximum of 252 cm for the period 1935-1965 in the area of most severe damage, was clearly related to over-draught. As a preventive measure, appropriate legislation was passed in 1959 to control the volume and rate of extraction. The uppermost position for screens was restricted to 500-600 m, and the sectional area of pipe at the outlet of a pump was restricted to 21 cm$^2$ as a maximum. Pumpage of water for air-conditioning was prohibited and wells not fitted for the above categories were abandoned. With the draught diminishing the lowering of water levels, the subsidence stopped in 1962, for most wells in Osaka. Observation records for one of the wells are shown in chapter IV (see figure 8).

Over-draught may also result in the deterioration of water quality. For example, in coastal areas and islands, which often are densely populated, aquifers are characterized by contact between salty sea-water and fresh water. The major part of ground-water storage-potential exists below sea level in aquifers saturated with water. If the equilibrium of the salty and fresh waters is disturbed by exploitation, sea water will intrude into the aquifer and wedge in below the fresh water. This process usually takes some time and it is, therefore, possible to lower water levels considerably, even below sea level, for limited periods of time, even as long as several months or years, depending upon circumstances, without causing severe sea-water intrusion. Many methods have been suggested for controlling ground-water storage against sea-water intrusion. These include: the reduction and/or rearrangement of patterns of pumping draught; artificial recharge of the aquifer from spreading areas or recharge wells; development of a pumping trough adjacent to the coast; maintenance of a fresh-water ridge above sea level along the coast by injection wells; and construction of artificial subsurface barriers.

In most oceanic islands, ground-water reservoirs are composed of sand, lava, coral or limestone, so that sea water is in contact with ground water on all sides, and a fresh-water lens is formed by the radial movement of fresh water toward the coast. Because fresh ground-water is supplied entirely by rainfall, only a limited amount is available. In order to minimize the danger of the intrusion of sea water, wells should be designed for minimum drawdown, just skimming fresh water from the top of the lens. As water needs of islands are relatively large, the best use has to be made of the ground-water storage which is available. Generally, the only other source of water is demineralized sea-water, a high-cost source to be used only as a last resort. Maintenance of water quality at acceptable levels is always one of the major requirements for successful utilization of ground-water storage.

Many problems of water quality stem from man's activities on lands overlying ground-water reservoirs. The wastes resulting from these activities will impair the water quality if they enter the ground-water reservoirs. Such wastes are numerous; but, in general, can be categorized as sewage, industrial wastes, cooling water, radio-active wastes and solid wastes. The control of these wastes is a requisite for the development of ground-water storage in urbanized and industrialized areas.

Water quality is also subject to deterioration from other sources. Soluble salts on the surface of the watershed and in geological formations (as, for example, occurs with intrusion of sea water) and faulty construction of wells, are among many common causes of degradation of quality. Consideration should be given to all these problems involved in the utilization of ground-water storage.

Clogging of ground-water reservoirs may occur if recharge water contains suspended materials, such as silt and organic matters. (This problem is reviewed in chapter III.) Ultimately, the effective use of ground-water storage capacity will depend upon the effective functioning of wells. The effectiveness of wells can be improved during the "development" phase, which is applied to newly drilled wells immediately after they have been completed. Various procedures of development are commonly used; including pumping, surging, backwashing, injection of compressed air, addition of solid carbon dioxide, chlorhydric acid, or polyphosphates and detonation of explosives. Detonation used in rock wells may also increase and expand the system of fractures and joints of the surrounding rock formation, thus enhancing the storage capacity to a substantial extent. In fact, underground nuclear explosion has been tested in recent years, in an attempt to create large artificial ground-water reservoirs.

## Conclusion

In many areas, utilization of ground-water storage will induce changes in the hydrological system. Such effects may or may not be significant; however, their identification and evaluation should be anticipated, as they may result in serious consequences in the exploitation of ground-water storage. It is obvious that accurate forecasting of the future effects is not an easy matter, because future conditions of the ground-water storage system are highly uncertain, related as they are to numerous factors that change with time. Past experience in ground-water development provides a sound basis for predicting the future effects of utilization. In addition, several methods may be used in such forecasting. For example, the ground-water storage system may be simulated by mathematical models. These models are constructed by using available information on the hydrology of the region, but on a simulated time-scale. By operating the models so as to simulate the passage of several years, it is possible to simulate the future behaviour of the system, provided the models are constructed so that they represent the actual system. The possible damaging effects of improper use of ground-water storage may also be identified by these models, and appropriate measures can be taken to prevent such effects, thus maximizing the over-all beneficial effects of the operation.

# III. ARTIFICIAL RECHARGE

"Artificial recharge" may be defined as a replenishment of ground-water reservoirs brought about as a result of man's activities. It may be planned or deliberate, as in the case of a pit that has been dug for the purpose of putting water into an aquifer; or it may be unplanned or incidental to human activity, as in the case of a buried pipeline that leaks water into the soil.

## A. Purpose and basic principles

There are many reasons why water is deliberately placed into storage in ground-water reservoirs. A large percentage of artificial recharge projects are designed to conserve water for further use. Other such projects recharge water for such objectives as control of salt-water encroachment, filtration of water, control of subsidence, disposal of wastes and to assist in recovering oil from partially depleted oil fields.

From the point of view of artificially storing water for future use, the basic requirement is to be able to obtain water in adequate amounts and at the proper times in order to accomplish this goal. Some schemes involve the impoundment of local storm run-off, which is collected in ditches, basins or behind dams, after which it is placed into the ground. In other localities, water is sometimes brought into the region by pipeline or aqueduct. In the latter case, the water is an import, and represents an addition to whatever natural water-resources occur in the region. A third approach is to treat and reclaim used water being discharged from sewer systems or industrial establishments.

In certain coastal areas of the world, notably in Israel, the Netherlands and the western part of the United States of America (California), artificial recharge systems are in operation in order to block inland encroachment of sea water. Most of these schemes rely on the injection of fresh water through wells in order to build up a pressure barrier that will retard or reverse encroachment of salty water that has resulted from excessive withdrawals from wells. In schemes of this type, most of the injected water is not directly available for reuse, but serves as a hydraulic mechanism to allow a better use of existing ground-water reserves.

In a few places, where heavy withdrawals of ground water has resulted in subsidence of the surface of the land, attempts have been made to overcome the problem by forcing water under pressure into ground-water reservoirs. The success of repressuring to stop subsidence is inconclusive.

Disposal of liquid wastes is another objective of artificial recharge. Sanitary sewage, for example, may be filtered, chlorinated or otherwise treated, and then allowed to filter into the ground through spreading areas or special basins and pits. Sometimes, a scheme of this kind is adopted simply to avoid the cost of constructing long sewer mains. A similar type of operation takes place on many industrial sites, where liquid plant-wastes may be placed into artificial recharge facilities. Storm-water is collected in some places as a means of artificial recharge, and also to reduce the cost that otherwise would be incurred in transporting the wastes to distant areas of disposal.

Another deliberate type of ground-water recharge, which is often overlooked because it is not directly concerned with water-supply, is the injection of waters into wells to speed up extraction of oil. In this approach, which is referred to technically as "secondary oil recovery", oil is forced through the ground toward producing wells by the hydraulic head of water built up around artificial recharge wells. In other words, a recharge cone is created by forcing water into an injection well, and the head of the injected water drives the oil through the geological formation toward an oil production well.

However, as noted above, most artificial recharge projects are planned for the specific purpose of saving or storing fresh water for subsequent use by man. Among these projects some may serve the dual purpose of eliminating objectionable amounts of water at the land surface and, at the same time, putting this water into reserve for eventual extraction.

Two hydraulic effects are generated by artificial recharge, as a result of the head which is applied in the recharge area and the mass of water which is introduced into the aquifer through the recharge area: the piezometric effect and the volumetric effect. The piezometric effect results in a rise of the piezometric surface in the unconfined aquifer(s) and/or a rise of the artesian pressure in the confined aquifer(s). The piezometric effect is related to three main factors. First, it is related to factors which create a damping reaction which can be expressed by a mathematical function. This damping effect is related to the shape of the piezometric surface, to the geological and hydraulic boundaries of the aquifer and to the type and location of the recharging device. Secondly, it is related to the quotient T/C (T = transmissivity coefficient; C = replenishment coefficient - equivalent of storage coefficient). Thirdly, it is related to the artificial recharge yield and the duration of the operation. Other factors such as capillarity forces, water temperature and presence of air bubbles in the aquifer also have an impact on the piezometric effect.

The volumetric effect is related to the specific yield, the replenishment coefficient, the transmissivity coefficient and the boundary coefficient. Model studies that were checked through field experiments have demonstrated that the bulk of the recharge water moves according to two systems of flow. One results in a spreading-out effect, with a speed related to the recharge flow; the other in a sliding effect, with a speed related to the ground-water flow.

A thorough and detailed knowledge of geological and hydrological features of the area is necessary for adequately selecting the site and the type of recharge. In particular, the following features, parameters and data are to be considered: geological boundaries; hydraulic boundaries; inflow and outflow of waters; storage capacity; porosity; hydraulic conductivity; transmissivity; natural discharge of springs; water resources available for recharge; natural recharge; water balance; lithology; depth of the aquifer; and tectonic boundaries.

Aquifers best suited for artificial recharge are those having a flow value of the T/C coefficient; that is aquifers which absorb large quantities of water and do not release them too quickly. Theoretically this will imply that the vertical hydraulic conductivity is high, while the horizontal hydraulic conductivity is moderate. These two conditions are not often encountered in nature. Among the hydrogeological structures that are most frequently utilized for artificial recharge schemes, the following deserve special mention. Carbonate karstic ranges and plateaux can absorb large amounts of water, but often release these waters shortly after their infiltration through large springs fed by fast-flowing underground streams. In some regions wells below the level of the outlets can minimize the volume of discharge after recharge. Examples of such ground-water reservoirs can be found in the Mediterranean region. However, most of the existing recharge areas are located in alluvial plains, as such structures are favourable to ground-water storage both from the point of view of the availability of infiltration waters and from the point of view of the transmissivity of the aquifer. However, adverse conditions are often associated with these structures, namely: limited storage capacity; low amplitude of fluctuations; and lack of storage availability owing to high water-table levels when recharge water is abundant. (It should be noted that the inverse of some of the above factors are, by contrast, favourable to induced recharge schemes.) In fact, in many alluvial valleys, a lowering of the water-table generated by high-yield pumping is often a prerequisite for an artificial recharge operation.

Under temperate-humid climates, the alluvial areas which best lend themselves to artificial recharge schemes are the ancient alluvium, the buried fossil river-beds and the interlinked alluvial fans of main valleys and their tributaries. In the arid zone, recent river alluvium may sometimes be more favourable than in humid zones, because the water-table is subject to pronounced natural fluctuations. Coastal dunes and deltaic areas are often very favourable for artificial recharge schemes. In addition, dense urban and industrial concentrations in such areas may render artificial recharge schemes necessary. Artificial recharge is planned with the double purpose of increasing the availability of water supply and protecting the aquifers against sea-water intrusion. The coastal area of the Netherlands is a classical example of this type of hydrogeological structure.

Large sedimentary hydrogeological basins dominantly contain artesian aquifers which store large volumes of water. Artificial recharge schemes are the exception in such areas. In general, the areas which are first selected for artificial recharge projects are those where water-table levels were substantially lowered as a result of an over-draught or as a result of a deficit in natural recharge.

Any man-made scheme or facility that adds water to an aquifer may be considered to be an artificial recharge system. A list of such facilities includes spreading grounds, pits and basins, ditches and furrows, excavated stream beds and special injection wells.

## B. Spreading-basins

Ground-water recharge by spreading techniques implies the passage of water from the surface of the soil through the non-saturated zone of the soil and geological strata to the saturated part of the aquifer. The term "infiltration" expresses this essentially vertical movement of water through the non-saturated zone. The infiltration rate is conveniently defined and measured as the volume of water which seeps downwards during a unit-time through a unit-area (e.g. if the metric system is used the infiltration rate is expressed in terms of cubic metres/day per square metre). Dimensionally, the infiltration rate is a velocity, metres per day, but this is a mere coincidence, as the physical velocity of ground-water flow is greater by about one order of magnitude than the infiltration rate.

The downward movement of the water is governed by a variety of factors: the vertical permeability of the soil; the presence of soil gases in the non-saturated zone; the presence or absence of limiting layers at depth, that is of layers with small vertical permeability; and the changes which affect soil structure during infiltration, changes which are caused by physical, chemical and bacteriological influences. As a matter of fact, changes take place even if silt-free water is used. When new spreading-grounds are put into operation, rates decrease at the beginning, and then increase during the first hours or the first days of operation. The changes later become less predictable; in most cases a decrease of infiltration rates is observed once again, which may then eventually level out, or seem to continue indefinitely. Sometimes, a second temporary, and smaller, increase of infiltration rates may again be observed. After the spreading-ground drys, the cycle repeats itself, although, generally, at a lower level.

It has been established that such changes are brought about by the following mechanisms. The first, transient decrease of the infiltration rate is caused by the swelling of the particles of the clayey soils. The initial transient increase of the infiltration rate to a temporary maximum is due to the gradual elimination of soil gas from the interstices of the soil. The later changes of the infiltration rate are caused partly by the physico-chemical destruction of the natural soil profile (dispersion), but also mainly by the growth of bacteria and by the accumulation of products of their metabolisms at a shallow depth below the spreading-ground. This last phenomenon is of considerable engineering importance, and it deserves particular attention, as it is sometimes overlooked. As a matter of fact, one would expect that, if no impervious or semi-pervious layers are present between the surface of the ground and the water-table, all the strata located under the spreading-grounds will eventually become saturated with water.

However, in actual fact, saturation very rarely reaches deeper than the uppermost layer of the profile. Bacterial growths clog the pore-space at a shallow depth below the spreading-ground and restrict the passage of water downward. Since the infiltration layer is effectively destroyed by oxidation, spreading-grounds must periodically be dried in order to restore their infiltration capacity. It follows that the areas required for efficient spreading operations are larger than a simple calculation would seem to indicate. The role of bacteria has been ascertained by a variety of methods. Spreading experiments in which chlorinated water was infiltrated through sterile soil did not result in decreased infiltration rates. Thus, clogging which is observed when these conditions are not met, must be ascribed to biological causes.

Clogging and reduction of infiltration rates are also caused by the presence of suspended matter in recharge water. Various methods of treatment may, at least partially, remedy this effect. Very turbid water must be treated by detention in settling ponds and/or by the addition of flocculants. Usually only water which contains less than 1,000 mg/l of suspended solids is accepted for spreading operations.

Several methods are commonly used in measuring infiltration rates. First the entire spreading grounds can be tested in situ. This method gives the most relevant results and should be employed whenever possible. However, if special installations are necessary to bring the water to the grounds, or if the land itself has to be acquired, it is desirable to test the grounds by less than full-scale trials, before a decision is made. In the test-ponds method, a sizable part of the proposed spreading-grounds is subjected to tests of long duration, in order to observe time changes in infiltration capacity, the possible formation of perched saturated zones on buried limiting layers and the influence of ground-water recharge on the water-table. For meaningful investigations on test-ponds, technical information should be available on the geology of the area, and especially the layers between the ground surface and the aquifer; on the area of the ponds· on potential evaporation; on water levels in the saturated aquifer, and in each individual saturated layer, observed in piezometer holes; and also, if possible, on the water-content of the non-saturated part of the aquifers, observed by means of neutron counters. The experiments are conducted by filling the test-pond with a measured volume of water. The drop of the water level is periodically measured with the aid of a staff-gauge, the readings being converted to volumes by the known depth-volume relationship. The volume of water which evaporated from the open water surface is estimated from potential evaporation and subtracted from the volume as previously measured. The volume of water which seeped downward during a specified time interval is thus obtained. If a shallow limiting layer exists, the effective flooded area may be larger than the bottom of the pond. In order to determine infiltration rates which will remain valid when operations are expanded, the extent of the effective flooded area and the average head on this area should be measured in piezometers drilled down to the shallow limiting layer.

In the infiltration method, metal rings measuring from 0.5 to 1 m in diameter are sunk into the ground in order to penetrate below the first saturated layer; they are sealed off by a clay seal from the rest of the soil. A measured volume of water is put into the protruding part of the ring and its downward seepage is observed. This method is especially suitable in regions where the upper layer is less pervious than the lower one. Preferably, concentric double rings are employed in order to minimize boundary effects. The extrapolation of data obtained from infiltrometers requires a great deal of judgement and is not entirely reliable.

The methods based upon the use of undisturbed samples or the results of pumping tests are not very suitable to investigations on spreading-grounds because they pre-suppose saturated conditions and require extensive work under the commonly encountered non-homogeneous field conditions. Undisturbed samples are difficult to take in loose soils with a high content of fines. Infiltration rates over a wide array of rocks are commonly from 0.25 to 1.00 m/day. Clay soils with a fine content of 60 per cent and more may still have infiltration rates of from 0.1 to 0.2 m/day. Only grey-black marsh clays are found to be practically impervious.

Spreading-grounds or spreading-basins must be selected or constructed in order to have an approximately flat bottom which is to be covered evenly by small quantities of water. If the ground selected for spreading operations slopes too much, the amount of earth-moving required for the construction of the basins is, in most cases, the major economic limiting factor. Spreading techniques imply that large surfaces of land are available for the recharge works. Spreading-grounds are arranged in networks, so that excess water from the higher basin escapes into the nearest lower one, this being accomplished by pervious "sausage" dams or by suitable hydraulic arrangements. The silt problem can be alleviated by using part of the basins for settling. Experiments in the area of Los Angeles, California (United States of America) showed that the silt content was reduced from 3,000 parts per million (ppm) to 250 ppm by one settling pond. The rate of settling may be greatly increased by the addition of certain chemicals (flocculants). Another advantage of basins, especially if the water-supply stems from intermittent streams, is the hold-over storage they provide. Depths to water in the basin are usually about from 0.25 to 2.50 m below land surface and only in exceptional cases, where the basin storage itself is utilized, are greater depths of water used. Basins must be operated intermittently in order to allow infiltration capacities to be reconstituted by drying.

The furrow (ditch) technique sometimes requires less soil preparation than the spreading-basin technique. Replenishment by ditches is also less sensitive to silting, because at least part of the suspended matter can be rejected out of the system, together with some residual water. Several layouts are in use. Lateral spreading can be made at right angles to the main diversion canal. In this case the ditches are usually from 4 to 12 ft wide and only as deep as is necessary to carry water over small gullies. At low flow a small meandering channel may be cut by erosion into the bottom of the ditch. Small check-dams are sometimes installed in order to eliminate this effect. In the divided-canals system, the main channel is subdivided into two separate ditches, each of these again into two others etc., the ditches becoming progressively smaller. In the contour-ditch system, the ditch follows approximately the contour of the ground in the fashion of a closely coiled snake. A reception ditch is usually provided at the end of the spreading system and directs surplus water, together with some silt, into the river or main channel. Some data on recharge rates, expressed in litres per second, of the ditch in various geological formations are:

| | |
|---|---|
| Volcanic pumice or porous lava | 1,350 l/s/km |
| Sand dune | 43 l/s/km |
| Sand and gravel beds | 840 l/s/km |

In the flooding system, a thin sheet of water is made to flow over the land surface, provided this surface is smooth enough. For best results, the native condition of the soil should not be disturbed, except for small adjustments carried out by hand during spreading operations.

### C. Pits and injection wells

The principle of recharge through pits is somewhat different. In many pits, most of the infiltration occurs laterally through the walls of the pit; because in most layered, sedimentary or alluvial material the horizontal hydraulic conductivity (or permeability) is considerably larger than the vertical. Old gravel pits or limestone quarries are often used in such projects. Where land is scarce, or where a shallow impervious overburden is found, it is advantageous to construct pits especially for this purpose.

The methods of enhanced stream-bed infiltration aim at enhancing the infiltration from stream-beds during low stages by appropriate structures in the stream-bed itself. If the stream is laterally connected with an aquifer, the direction of flow can actually be reversed in that water flows from the stream into the aquifer, from where it can be exploited, instead of vice versa. The structures employed for this purpose vary widely according to local circumstances. Sometimes low dikes are made in the river bottom, usually with natural material; or the stream may be widened; or drop-structures may be inserted. All these structures aim at reducing the velocities of flow and at spreading the water as widely as possible over the stream-bed. They must be built so that they do not add to flood hazards. Temporary dikes, which high water easily destroys, are an economical and efficient device and are often utilized.

Injection wells are structures which are purposely drilled or excavated below the level of the water-table. Deep injection-pits may also reach the level of the water-table or the water-table may rise above the bottom of the pit during extended operation, but then occurrences of ground water tend to limit the effectiveness of the pit. This feature distinguishes injection bore-holes or wells from pits.

Injection wells are the only feasible method of artificial replenishment in locations where a thick impervious layer exists between the surface of the soil and the aquifer to be replenished. Injection wells also prove advantageous when land is scarce, as in urban areas. On the other hand, the water injected into bore-holes must meet very restrictive quality standards, approaching those of drinking water. Even when these standards are met, trouble-free operations are not guaranteed for long periods of time.

Extraction of ground water from a well and injection of water into it are obviously two diametrically opposite operations. This can be transformed into hydrological terms. When water is extracted it is made to flow from the aquifer into the well by causing a certain drawdown i.e., lowering the water level in the well. The energy which makes the water flow is proportional to the difference between the water level in the well and the undisturbed water level in the aquifer. The drawdown and, therefore, the capacity of the well, are always limited. During injection, the water is made to flow from the well into the aquifer by raising the water level in the well. If the natural water-table level is deep, a very considerable rise of the head can be created and very great injection rates can, theoretically, be obtained. In some cases it is even possible to cap the well and inject the water under external pressure.

In practice however, injection rates are limited by the physical characteristics of the aquifer. In the vicinity of the well, the speed of the ground-water flow may increase to the point that the aquifer is eroded, especially if it is made of non-consolidated or semi-consolidated material. In confined aquifers, confining layers may fail if too great a pressure is created under them. If this occurs, the aquifer will become clogged in the vicinity of the bore-hole and/or may collapse. In one case, injection of water during a long period into cracked crystalline rocks at great pressure, for the purpose of waste disposal, probably triggered earthquakes in the vicinity.

In general, water cannot be recharged by "Free Fall" into the bore-hole because this technique will entrap air bubbles that subsequently become lodged in the pores of the aquifer and effectively clog them. Sometimes air bubbles shake the rock with explosive force, when they escape and destroy the rock. For these reasons, the water should be conducted to an outlet below the water level through a specially inserted column or pipe.

Basically the construction of single-purpose injection wells does not differ from that of a pumping well on the same aquifer. Even single-purpose injection wells require periodical pumping; and therefore the upper part of the casing, down to a few metres below water level, must be wide enough to accommodate a pump. Also, the perforated part of the casing must be wide enough to facilitate cleaning. If the well is drilled into a confined aquifer it is good practice to cement around the casing opposite the aquiclude, in order to avoid erosion in this sensitive area. Injection is accomplished by means of a special pipe that has an outlet below the water-table. As mentioned above, it is absolutely necessary to remove the air contained in the injected water. For this reason, the injection system must be operated in such a way that the pressure, in its entirety, will always exceed atmospheric pressure; in other words, so that suction effects will never develop. Thus, the diameter of the injection pipe must be sufficiently small to restrict the flow of water, or an orifice or valve must be installed at the foot of the injection pipe.

In view of the above limitations, single-purpose injection wells have no intrinsic advantage. Their construction can be justified only by local circumstances, e.g., if the area of injection is far from the area of recovery, in the special case of building up and maintaining a fresh-water barrier against sea-water intrusion and in some other particular situation.

For economical as well as for hydrological reasons it is advantageous to use extraction wells intermittently for recharge purposes. The simplest way is to inject the water through the pump column and the pump, applying some braking device or installing a ratchet in order to keep the pump from turning. In Israel, it has been found that hydraulic resistance in the pump restricts injection rates to about two thirds of the discharge capacity of the pump, and thus practically secures the elimination of suction effects at reasonably high rates of injection. Alternatively, the pump can be drawn and replaced by an injection pipe. In this way, somewhat higher injection rates can be achieved and the rather remote possibility of damaging the pump can be excluded. On the other hand, the procedure is time-consuming, somewhat risky and costly. In arid and semi-arid regions, where the seasons of replenishment and pumping are sharply defined and closely follow each other, the procedure may cause an inordinate amount of work which must be quickly completed; with the related danger of mishaps and excessive payments for the overtime of mechanics and labourers. There is little to recommend this course of action. Another method, being tried in Israel, utilizes the annular space, between the column and the casing, for injection. This is done by means of the installation of a simple by-pass or by replacing the pump-cap by an injection cap. Injection can be carried out simultaneously through the pump and through the annular space, and injection rates can be stepped up to the limits imposed by the properties of the aquifer without pulling out the pump.

## D. Problems and solutions

Problems which arise as a result of recharge projects are mainly related to the quality of raw waters that are available for recharge, and which generally require some sort of treatment before being used in recharge installations. They are also related to the changes in the soil structure and the biological phenomena which take place when infiltration begins, to the changes brought to the environmental conditions and to land-ownership and legal aspects.

A major requirement for waters that are to be used in recharge projects is that they be silt-free. Silt may be defined as the content of undissolved solid matter, usually measured in mg/l, which settles in stagnant water with velocities which do not exceed 0.1 m/hr. This definition comprises a large variety of materials, such as clay particles, organic matter and fine particles of calcite. The silt content of a river depends upon the type of soils in the area of run-off, the vegetative cover of this area, its topographic slopes and the meteorological characteristics prevailing in its catchments and, especially, intensity of rainfall. The silt content of any given river varies very strongly with its regimen. Very high silt contents, up to 25,000 mg/l have been observed in seasonal rivers traversing semi-desertic areas covered by friable loess soils. This means that about 25,000 tons of solid material will eventually settle out, from 1 million $m^3$ of water. Average silt contents of from 3,000 to 8,000 mg/l are not uncommon in rivers during flood periods. As soon as the water becomes stagnant after being collected in a pond; or, if the velocity of flood is much reduced, the silt load gradually settles out. The speed of the settling process is governed by the size and specific weight of the suspended particles and by electro-chemical forces acting between the particles and the water which, in their turn, are strongly influenced by the chemical composition of the water. Therefore, there is no clear correlation between initial turbidity and the speed of the settling process. Experience in Israel and in the United States of America (southern California) has shown that a reduction of turbidity of about from 300 to 1,000 mg/l is achieved by retarding stream inflow for two or three days in shallow retention reservoirs, 5 m or less deep. Retention reservoirs are, in fact, the most common and the cheapest method of reducing the silt load to a level acceptable for spreading operations. Costs of maintenance and operation are determined mainly by the cost of periodically removing the silt collected. Chemical flocculants are sometimes used to speed up the settling process or to obtain a cleaner water. Doses of alum, in the range of 100-150 mg/l, may reduce to only a few hours the time required to obtain a water with only about 300 mg/l suspended matter. Recent experiments have shown that specific polymer compounds, known under various trade names sometimes achieve the same effect with doses of only 0.3-1.5 mg/l. These seem to be highly variable in their effectiveness. To obtain still clearer water, with only 10-20 mg/l suspended solids, further addition of flocculants and, frequently, agitation of the water must be resorted to. In view of the higher cost involved, these methods are rarely employed in recharge operations by spreading.

Suspended matter may clog the soil in two different ways: first, near the surface the interstices of the soil may be filled up and a layer of mud may be deposited on the surface; on the other hand, suspended particles may penetrate deeper into the soil and accumulate there. A layer of mud is formed on the surface by particles, the settling velocity of which exceeds infiltration velocities. Smaller suspended particles are filtered out in the uppermost layer of the soil. The filtration process is governed not only by mechanical factors, but it seems to be strongly influenced by electro-chemical surface forces. Still finer particles, especially very fine grains of montmorillonite clay, are carried further into the soil. Observations in spreading-grounds, composed of medium-grained dune sands, showed that these particles become lodged at from 10 to 20 m below the surface, and some of these particles are carried even deeper. Semi-pervious layers situated deep below the sand, filter out even these particles and become progressively clogged. In the Shigma flood-water recharge project in Israel, it has been calculated that, during five years of operation, about 3 kg of suspended matter were deposited on each square metre of a semi-pervious layer of sand, at a depth of several metres below the surface.

Methods to remedy or minimize the clogging effect by suspended matter can be classified into broad groups:

(a) Periodical removing of the mud-cake and discing or scraping of the surface layer;

(b) Installation of a filter on the surface, the permeability of which is lower than that of the natural strata (the filter must, of course, be removed and renewed periodically);

(c) Addition of organic matter or chemicals to the uppermost layer;

(d) Cultivation of certain plant-covers, notably certain kinds of grass.

Scraping of the surface layer is effective only in rather coarse-grained spreading grounds. In soils composed mainly of sand, repeated compaction by heavy machinery may easily nullify any benefit gained from scraping.

The installation of filter-layers has been used with good results in gravel recharge pits in Peoria, Illinois (United States of America). Layers of sand or pea gravel six inches thick were put on the bottom of the infiltration pits as a filtering medium. In order to reduce the necessity of frequently changing the filter, the mud-layer was removed, while still liquid, with the aid of a vacuum cleaner of the type used for cleaning swimming pools. Superficial raking of the dry pea-gravel also helped in restoring infiltration rates. Various chemicals and organic matter have been used to restore infiltration capacities. These have included gypsum, various organic compounds, cotton-gin trash and alfalfa, the latter grown while the pond was still wet, and then spaded under. The growth of a permanent grass-cover has proved to be an effective method for maintaining infiltration capacities, but it is difficult to select a grass which grows under a given climatic and soil condition and is able to withstand alternate periods of flooding and drying.

Clogging by biological activity depends upon the minerological and organic composition of the water and basin floor and upon the grain-size and permeability of the floor. The only feasible method of treatment developed so far consists in thoroughly drying the ground under the basin. Experiences seem to indicate that short periods of operation (about one month), followed by drying, are more effective than prolonged periods of operation, even if they are followed by a prolonged and most thorough period of drying during the hot summer.

Clogging and destruction of bore-holes may occur as a result of erosion of the aquifer. If velocities of flow are too high, fine sand and particles from local clay layers may be dragged outward into the aquifer and clog it, or even cause collapse of the well. The common-sense precautions against these mishaps in semi-consolidated aquifers are to keep injection rates somewhat below the rate of proved safe continuous pumpings; and to avoid frequent sudden changes of the injection rate, which may cause vibrations. Experience has shown that no deterioration of the aquifer occurs if these reasonable precautions are taken.

Air bubbles, which are sucked into the well through the injection pipe, cause violent vibrations when they finally escape upwards. Cases have been reported where great volumes of air were carried into hard cavernous limestone. When injection was stopped, a geyser of water and trapped air gushed forth, the well collapsed and a crater several metres deep was formed around it. The possibility of air seepage must therefore be completely eliminated. The only certain way to achieve this is to design and operate the installation so that positive pressures (exceeding atmospheric pressure) are maintained everywhere in the injection pipe, even if this entails a regrettable reduction of injection rates.

Bore-holes are much more prone to silting than spreading grounds. No acceptable standard of turbidity can be given. Clarity of the water should conform to the standards of good drinking water. There is a case on record where an attempt was made to inject treated flood water with a residual turbidity of about 50 Jackson turbidity units into a limestone bore-hole. Data are still inconclusive. Most other attempts have been failures. Wherever injection of water has been carried out on a large scale (sandstone and limestone aquifers, in Israel; the lower Lee Valley, in the United Kingdom; and Los Angeles, in the United States of America), the injected water conformed to the standards of potable water.

Clogging of the bore-hole wall by bacterial growths may occur, even if water of potable standard is injected. Experience gained from large-scale injection works in Israel can be summarized as follows:

(a) In one installation, where the water supply stems from ground water and is injected into another aquifer for operational purposes, no biological clogging occurred during 10 years of operation;

(b) Water from the Lake Kinneret, although it is treated and brought up to drinking-water standards, causes considerable clogging after comparatively short periods of injection. The phenomenon is tentatively ascribed to the higher temperature of the water, to the relative abundance of nutrients in it and to the remnants of algae bloom which are perhaps not completely destroyed by chlorination;

(c) Clogging occurs in both limestone and sandstone aquifers but it is more prevalent in the latter;

(d) In most cases, short periods of pumping quickly clean the incrustations and restore the capacity of wells;

(e) The best method of operation seems to consist of short periods of injection (about one month), alternating with one to two hours of pumpage;

(f) The water pumped during redevelopment must be rejected, but it is only an insignificant percentage of the injected water.

Chlorination at the well-head is practised in the Los Angeles installations, but does not seem to eliminate entirely the need for redevelopment by mechanical means and pumping.

Environmental problems may stem from artificial recharge projects. Such projects usually have to be carried out in the vicinity of densely populated and industrial areas, where large quantities of water are needed. The close vicinity of spreading-grounds to population centres often creates various kinds of problems. In particular, it is well known that stagnant water serves as a breeding ground for mosquitoes, flies and a variety of other biological nuisances. The best remedy is to operate parts of spreading-grounds in sequence, so that water remains in each part for a shorter period than the larvae-stage of the insect's life-cycle. This remedy may, however, lead to unrealistically large land requirements. Another method is to apply insecticides, making certain beforehand that they decompose quickly and have no toxic effect on the water. In addition, the installations may become an eyesore unless properly tended, surrounded by trees and more or less concealed. They also may become an accident-hazard, as any body of open water results in trespassing by children and is a target for acts of vandalism. The need for fencing spreading-grounds and for providing proper guards may become an important item in the operational expenses, unless proper legislative measures are taken which make recharge areas available as property of the State.

Pressures due to the high value of land may prevent the execution of projects. To the layman and the developer, spreading-grounds may appear to be waste land which could be better used for building purposes. In the Los Angeles area there are proposals to erect buildings on stilts over some spreading-grounds. Such construction would be certain to exclude light from the ground and to restrict the passage of air over it. As a consequence, the growth of plants would probably be stopped, infiltration capacities would decline and a nuisance would be created by the decay of organic matter. Such proposals, attractive though they may seem, need very careful investigation before being acted upon. In Long Island, New York, all housing projects include provisions for pits and ponds, which are designed to collect run-off water and infiltrate it underground.

Other types of damage can also be generated by such projects. Artificial recharge is a procedure designed to raise ground-water levels, which, under certain circumstances, can cause substantial damage. If, for example, the water-table in a particular locality has been depressed for many years as a result of heavy pumping, and if, during that time basements, undergrounds, and similar structures have been built below the land surface, there is a distinct possibility that an artificial rise of the water-table would cause economic harm. Damages may also be claimed if the recharged water is of inferior quality to that previously enjoyed by nearby well-owners. Such might be the case where saline water, originating from treated sewerage effluent, is recharged into a fresh-water aquifer. The mixing of the two water bodies cannot be controlled directly, but the entire aquifer can be handled in such a way so that extraction bore-holes temporarily draw either the injected water only or the fresh native water only. Experiments to this effect have been conducted, with some success. However, although artificial recharge is usually thought of as a beneficial approach for the conservation of water, it should be pointed out that some such schemes may have a partly negative effect. In some places, for example, water of poor chemical quality may be imported into an area for the purpose of recharging aquifers whose storage of high-quality water is being depleted. In such instances, more water is made available, say, for irrigation, but the practice may simultaneously create a deterioration of water used for drinking purposes.

There is no general solution for such problems. Each case has to be studied independently, taking into account the physical, economic, human and legal aspects. There is no doubt, however, that in most cases the over-all benefits of such projects in water-short areas largely transcend the drawbacks.

## E. Unplanned ground-water recharge

Whereas planned artificial recharge has the specific objective of replenishing ground-water resources, unplanned artificial recharge occurs with no such objective or purpose and is incidental to some other human activity, such as irrigation. The amount of water recharged in an unplanned way is vastly greater than the amount deliberately recharged. Irrigation, for example, plays a very significant role in the recharge of ground water in many parts of the world. Cesspools, septic tanks, leaky water mains and sewers, industrial waste-disposal pits and similar facilities also recharge large amounts of fluids into the underground environment. Some of these operations significantly affect the composition of ground water and pose important problems related to pollution of water in industrialized countries. These problems will become increasingly important. Problems related to incidental recharge attracted the attention of scientists and engineers only recently, and are not well known as yet.

Incidental recharge of ground water from cesspools and septic tanks has always been a problem from the most ancient times. The oldest system of disposing of human excrement was either to dig cesspools or to discharge the wastes into rivers. Present systems employ much the same principles. In other words, household wastes are deposited in cesspools, released to sewers or treated in septic tanks before discharge into rivers or into the ground. The over-all amount of disposal in cities is said to be from 1 to 1.3 litres per person per day. The amount differs between rural and urban areas and varies with seasons, but the 1 litre per person per day would be appropriate as an over-all average. A simple calculation based on the above figure would show that the total urine disposed of by the population of Tokyo (10 million people), for example, would amount to 10,000 tons per day. Since the populated area of the city is approximately 400 $km^2$, the annual amount of excrement of 3.6 million tons is equivalent to only 10 mm of precipitation, which is negligible compared with the average annual rainfall of 1,600 mm. Even if the total excrement is recharged underground, it is very minor in amount.

Cesspools have been used since historic times, but the basic principle and the method of constructing the system have remained essentially the same. Currently, most of the homes in large cities, and a substantial percentage of the homes in smaller cities, use septic tanks. They are less prevalent in rural areas, where many homes are still equipped with cesspools.

The incidental recharge from cesspools is very difficult to measure. Evidence of the recharging can be ascertained by testing and analysing the water from shallow wells. The effect of incidental recharge is seen in the Cl and $NH_4$ content, and the presence of the Cl ion is clearly indicated by the specific resistivity. The resistivity of ground water in areas some distance away from cesspools is commonly about 10,000 $\Omega$ cm, while in villages or small towns resistivity commonly ranges from 4,000 to 5,000 $\Omega$ cm. This is due to incidental recharge taking place over a fairly long period of time.

Dams designed for storing substantial or large amounts of surface water can have a considerable recharge effect in their vicinity. For example, although the rocks near the dams are naturally hard and have a low permeability, the amount of water recharge to these units can be significant. Usually water stored behind dams is discharged after storms and, during such periods, the water will recharge the ground water of the estuary.

The incidental recharge of ground water by the return of irrigation water will be interpreted herein as those waters taken from rivers and returned to rivers after use as irrigation waters. In Asia and the Far East, rice paddies require the largest quantity of irrigation waters. Most of the flat land is used for rice cultivation. The paddy fields in Japan occupy a total of 3.35 million ha. The demand for water for these rice paddies is 20 mm on the average, which amounts to 5,300 m3/sec of irrigation water (458 million $m^3$/day). Because the area of the rice paddies is so large, the recharge of ground water from these fields is extremely large, and they are of great importance, especially in areas upstream of plains and alluvial fans. For instance, in Japan, on the alluvial fan of the Tedori River, which is covered by alluvial sediments from 40 to 100 m thick, the recharge by the return of irrigation water was found to exceed 6.3 $m^3$/sec. In the Kimgawa alluvial fan, in the area of the Tone River, incidental recharge in sand and gravel sediments, underlying 126 ha of irrigated paddies, was evaluated through sophisticated methods and was found to amount to 600 $m^3$/day per ha.

The incidental recharge from irrigation channels shows the same rate of infiltration as in the case of rice fields. Where the main channels lead water from the upper parts of the rivers, the recharge is more active near the crest of the fans. In most areas dirt or rock-laid channels are common. In recent years there has been a growing tendency to have irrigation channels lined with concrete, in order to prevent water leaks. However, leaks cannot be completely avoided.

Buried water pipes, even those that have been most carefully installed under engineering supervision, also leak to some extent, thereby causing incidental recharge. It has been estimated that there is an average of 25 per cent leakage in waterworks. Sewers, and other types of buried waste-disposal systems, leak in a similar manner. The incidental recharge of shallow ground water, and its pollution by leakage from sewers, in particular, are becoming matters of growing concern in many localities. In some cities, sanitary sewage and drainage water may flow through separate sewer systems. However, in cities with incomplete or no sewerage system, the waste cannot be differentiated. Waste water from homes, rain water, factory waste-waters and all other waste waters flow into rivers, including man-made channels of all sizes which run through these cities. The amount of incidental recharge that takes place is greatest, not from sewers, but from rivers of this kind that flow through the cities and act as sewers.

Sewers are constructed in accordance with regulations and laws governing their structure and construction, and if any incidental recharge occurs, it might be presumed that it would be from cracks or joints or from other openings formed by careless construction. If the construction is adequate, there should be no incidental recharge from new sewers. Sewers, however, are buried underground and are constantly under pressure and strain, especially in areas having soft or unstable soil conditions. Through movement of land and settling, the sewers may break, in spite of careful and sturdy construction. Recently, pollution of ground water from sewage that contained alkyl benzene sulphonate (ABS) in detergents caused widespread concern. This is frequently the result of incidental recharge through the processes described above. In the case of the Kagoshima Prefecture, in Japan, ABS in shallow wells was detected in approximately 30 per cent of the samples. The limit of detection in this case was 0.05 parts per million (ppm).

It is difficult to determine the effect on cities of incidental recharge of ground water by factory waste-waters, because central water-supply systems take care of the water needs, and there is very little direct information concerning the ground water, except where a large amount of ground water is heavily polluted and the water is mobile. However, the pollution of ground water beneath cities by recharge of house and factory waste-waters has been going on for a long time, with the result that the free ground water under whole city areas may be polluted.

There is a good example of incidental recharge by factory sewer-waters at Kawasaki, Japan. There, an electric-cable manufacturer had used a sewer to dispose of waste sulphuric acid, after using it to clean cables. The sewer system was incomplete and the acid waters had infiltrated into the ground over a long period of time. In May 1963, Kawasaki laid 200 mm steel water-pipe along the road around the factory. This pipe burst in October 1965 and in January 1968, and an investigation showed that the breaks were caused by corrosion of pipe resulting from incidental recharge of the acidic waters from the factory sewer. The acidic waste was first stored in a trap and then released to the sewer. The leak occurred near the trap and the sewer. Ground water was sampled every 3-5 m along the fence of the factory by drilling to depths of 1.5 m. The analysed elements were pH and three ionic constituents: sulphates, copper and total iron; since these were the factors affecting the corrosion of the pipe. The area is reclaimed land consisting mainly of sand and silt, mixed with coal cinders and rocks. The extremely high concentration of sulphate ions and copper ions were detected around the sewer trap and the old sewer, in an area having a 10 m radius. Lower concentrations of these elements were detected in an area having a 30 m radius.

Waste-waters disposal on land or underground is related to ground-water recharge. In land disposal, the method is the same as in artificial recharge, beginning with a presumption that the waste material will not exert any harmful changes in land covering the recharge area and that the water will be thoroughly filtered when percolating through various formations, and thus be harmless by the time it reaches the saturated zone of the ground-water reservoir.

However, some industrial-waste waters cannot be cleaned by the filter action of the geological formations and, where disposal is by infiltration, the result is ground-water pollution by incidental recharge. A similar method, frequently used for disposal of mine water utilizes shallow-dug pits which penetrate to the free ground-water surface. Waste waters are disposed of directly into these pits.

Another increasingly popular scheme for waste disposal is injection of liquid waste into deep wells. In utilizing this method, it is necessary to take adequate precautions to prevent pollution of the good ground-water now in use, or those waters that might have a possible value in future. In other words, the aquifer into which the waste is injected must be one which will not be used; and adequate tests must be made, prior to injection, to assure that the waste water cannot move from the aquifer system. If it is possible that significant quantities of waste might be injected, a complete determination of the hydrological system must be made, including, particularly, an analysis of the existing ground-water flow system and natural boundaries of fresh and salt water. Injection of waste will necessarily alter the flow system and positions of boundaries. Where large injections of wastes are probable, the effect on the natural system may result in disastrous changes in availability of water and water quality in areas remote from the injection site. Unlike surface waters, which move and mix rapidly, polluted ground waters travel very slowly and may not affect other wells for a long period of time. An aquifer which has been polluted is quite difficult, if not impossible, to clean out.

Many problems can arise in disposal of wastes into wells. Suspended material in the water, for example, can plug the sand around the injection well and decrease the injection rate. Then, pressure must be applied in order to continue disposal. In principle, the waste waters used for injection should not include suspended material, should not react with the terrains and should not be corrosive. Waste water may also contain such troublesome micro-organisms as reducing bacteria, iron bacteria and algae, all of which are capable of propagating at a fast rate; various precipitates formed by these organisms plug the pores. In order to eliminate these micro-organisms, chlorine, formaldehyde, phenol and other chemicals are added, but adequate treatment must be designed specifically for each installation. Corrosion of steel pipes may plug the pores of the aquifers; and, in order to avoid this, cement-lined or fibre-glass casings are sometimes used.

The geology and the hydraulic properties of the formations have a great influence on the incidental recharge by waste disposal. In order to guarantee the confinement of the waste material in a certain layer for long periods, the geology of the area must be thoroughly considered. For instance, fissures and caves in limestone formations are quite suitable for the disposal of waste, but it first must be ascertained that the limestone forms an isolated ground-water unit and that the waste will not pollute the circulating ground water. Acidic waters dissolve limestone and the effect of the two increased open areas may be to diffuse the pollution. Similarly, fissures related to faults must be avoided, as the waste water may rise to the surface along the faults. Incidental recharge may occur at any horizon through damaged, leaky or flowing wells.

In places where wells have been drilled into multiple aquifers, it is common to find significant differences in piezometric levels. In other words, the water levels in two adjacent wells may be quite different if each is terminated at a different depth. An outcome of this condition is that water can be transferred vertically through a well from one layer to another if a leak develops in the well casing or if the casing becomes broken accidentally. Leaks tend to occur as wells become older, and are especially common in abandoned wells and old test-holes. Where vertical flows of this kind take place, one aquifer is, in effect, being pumped while another is being recharged. Sometimes the contributing aquifer contains water of inferior quality, so that the unplanned recharging causes a deterioration of water-quality in the receiving aquifer. Rather serious problems of this kind are known in several areas where abandoned oil-test wells have leaked brines into fresh-water aquifers.

Another similar type of unplanned recharge occurs where naturally flowing wells are allowed to spill over onto the ground. In such places, the water may originate in a deep aquifer and be recharged, as from a spreading basin into the shallowest aquifer, thus causing a rise of the water-table. In some areas, uncontrolled flowing wells have raised the water-table high enough to harm the root systems of crops and to cause drainage problems.

## Conclusion

From the description of recharge installations outlined above and from the case studies presented in part two, it is apparent that artificial recharge is not a widespread technique. A world-wide survey conducted by the International Association of Scientific Hydrology in 1968 found a total of 107 cases in 16 countries - mainly industrial countries. In fact, most of the recharge installations listed in the survey were located in central, northern and western Europe; Israel; Japan; and the United States of America. Less than half a dozen case studies were located in developing countries of Africa, Asia and Latin America, the reason being that artificial recharge usually is utilized only when a high price can be paid for water which is in great demand. Most installations are in industrialized areas, and, to a less extent, in arid areas.

However, it would be erroneous to think that artificial recharge has no future in developing countries; urban concentration coupled with industrialization is increasing and accelerating in these countries. In many semi-arid and arid countries, conventional sources of water-supply are now being used nearly at their total capacity (from 80 to 90 per cent in North Africa) and artificial recharge will soon represent the only hope for tapping additional water resources. Among these possibilities are water which is presently lost to the sea by surface run-off or to the air by evaporation. The last resort, sea-water desalination, is far more costly than artificial recharge and requires the use of energy in large quantities.

However it is likely that the transfer of the technologies of artificial recharge to developing countries will not be easy, considering the cost and complexity of the technique, and the bioclimatic conditions that exist in tropical areas. An interesting new field for engineering research is, therefore, open; and which should command the attention of water agencies and international associations and organizations.

# IV. MANAGEMENT CONSIDERATIONS

Man's history has been filled with projects to manage surface-water resources, largely by dams, reservoirs and diversion works. However, his history of "managing" ground-water resources is marked principally by lack of real management. Instead, when an exploitable ground-water reservoir has been found, it has frequently been developed without proper planning, and numerous problems have resulted. Lowering of water levels in wells is the most common problem, resulting in increased pumping costs; and in economic losses to those whose pumping equipment would not operate at the increased lifts required or whose wells were not drilled sufficiently deep. Poor placement of wells resulting in mutual interference has often been a problem. Coalescing cones of depression of the water-table and over-draught of the ground-water reservoir has frequently occurred, with resultant reduction of ground-water supplies or deterioration of quality. Therefore, whenever a ground-water reservoir is to be exploited at its full capacity, or at an increased capacity resulting from an artificial recharge scheme, it is essential that the policy-makers be made aware of the limiting condition of the use of ground-water storage under varying conditions.

Technical aspects, however, which were heretofore examined at length, are far from being the only ones which ought to be considered in a ground-water storage/recharge project. Economic, legal, environmental and institutional aspects are also of paramount importance. They are reviewed briefly in the following sections.

## A. Economic aspects

Ground-water storage and artificial recharge are economical as long as they are less costly than any alternate solution for making water resources available for use. As an area develops, first it normally utilizes surface-water supplies, if available and if adequate in quality. When surface water proves to be deficient in quantity or quality, ground-water is usually the next source to be developed, again, if available and if adequate in quality. If this, too, proves to be deficient, then water-conservation or water-treatment measures can enhance an area's water assets. Often, water conservation can be accomplished through the water-pricing structure; the more expensive, the more care taken in water usage. Water conservation can also be made the corollary of flood control, by preventing the loss of storm run-off, either by storage in surface reservoirs or by implementing means of artificial recharge into ground-water reservoirs. Generally, the flood-control facilities are quite compatible with water conservation programmes, and often serve both purposes. Occasionally, a facility justified only as a flood-control facility will also provide a major water-conservation benefit. An example is a flood-control reservoir located upstream from an area amenable to infiltration from surface spreading; whenever waters are stored in the reservoir, infiltration to the ground-water basin occurs. In areas suitable for infiltration, it is well to consider developing flood-control channels with unlined inverts, in order to enhance ground-water replenishment. In some areas, it has been found to be most economical to drain storm run-off into sumps (infiltration basins), rather than to develop a complex drainage system. Development of areas suitable for ground-water replenishment is the next logical step in water conservation; this can involve both spreading and injection facilities. In some arid and semi-arid areas, springs and streams have been dried up as a result of ground-water extraction, thus avoiding the loss of water to the ocean or inland seas and through evapo-transpiration. In other areas, plant growth along streams has been removed, thus eliminating transpiration losses. The reclamation of waste water often is an attractive water-conservation programme. If a treatment is needed for disposal of sewage effluent into streams and oceans, that same treatment may be adequate for permitting the use of the effluent for ground-water replenishment by infiltration through spreading-grounds. In most cases, tertiary treatment of the effluent will be required before it is suitable for injection through wells into the ground-water body.

Other alternatives for a water-supply are importation of water from an area of surplus or the conversion of sea-water or brackish water. Importation, conversion and reclamation of water are generally very expensive, and water-conservation programmes should first be examined to enhance the water assets of an area. The prevention of salt-water encroachment is also a method of water conservation, although it may have other benefits, too. For example, in Los Angeles County, California sea-water intrusion is prevented principally for the purpose of protecting the ground-water reservoirs, so that they may continue to be used to store the maximum quantity of imported water. The Los Angeles area imports about two thirds of its water supply. Because it is prudent to plan facilities capable of delivering future water needs, because it is more economical to operate aqueduct facilities at optimum levels (more or less maximum) and because surface storage facilities are not available, considerable quantities of imported water are stored in the ground-water reservoirs. The objectives of management are to accomodate peaking demands by pumping ground-water rather than by taking imported water. In justifying the protection of the ground-water reservoirs, benefit-cost ratio studies were made by comparing the annual cost of producing the present quantity of water pumped from the ground-water, including the cost of operating the barrier projects, with the cost of supplying an equivalent quantity of imported water and constructing sufficient surface storage facilities to provide for peak demands, without the benefit of using ground-water as regulatory storage. The economic ratio derived showed that the average annual cost of developing, operating and maintaining surface-storage facilities for imported water to be 2.4 times as great as the average annual cost of providing barriers to prevent sea-water intrusion and continuing to pump from the ground-water basin. The comparison was based solely on annual cost and did not consider the value of having a ground-water supply in case a major catastrophe, such as an earthquake, disrupted the imported supply of water for an extended period.

Water quality should also be considered. This becomes more critical if water reclamation is a part of the water-management scheme. In California, it has been found that water gains from 100 to 300 mg/l in total dissolved solids (salts) each time it is used. Therefore, reclamation of waste water can only occur a few times before the water is marginal in quality. One approach to determining the value of water quality is to "treat" an inferior water with a superior one; and then, through a proration of costs, determine how much it costs to upgrade the inferior water to a usable standard, and thereby determine the value of water quality. As an example, assume a superior water has a total dissolved solids (TDS) content of 400 mg/l and costs \$50.00/1,000 $m^3$ (perhaps the cost of pumping it out of the ground). If the "treatment" simply consists of blending the waters by discharging to a common reservoir, and the goal is 800 mg/l TDS water, then:

1,000 $m^3$ of 400 TDS water at $50.00 added to

1,000 $m^3$ of 1,200 TDS water at $10.00, result in

2,000 $m^3$ of 800 TDS water at $60.00.

Therefore, it costs $50.00 for a "treatment" to reduce the TDS 400 mg/l (from 1,200 to 800), but the "treatment" results in twice the original quantity of water, or it costs $25.00 to reduce the TDS by 400 mg/l, or $6.25/100 mg/l.

Usually artificial recharge is utilized only in an already exploited ground-water basin. It is often quite expensive and generally can be justified only in an area of advanced development. In most areas, it is possible to extract ground water for a number of years so that advanced development may have taken place and the financial base is adequate to justify artificial recharge.

The above discussion presents the usual course of events as an area develops its water programme. Economics should be carefully considered in selecting the best alternative, as the best scheme for one area is not necessarily the best for another.

There are many intangible benefits associated with artificial recharge and the use of ground-water reservoir storage.

(a) If an area must import its water supplies, or at least a portion of them, it is necessary that storage reservoirs be a part of the system;

(b) In nearly all areas the ground-water reservoirs provide for greater capacity for storage and at a lower cost than would be considered necessary for surface storage;

(c) If it is economical and feasible to use the ground-water reservoirs, there is great value in having the water available locally, in case a catastrophe, such as an earthquake, cuts off the imported supply;

(d) The ground-water reservoirs also eliminate evaporation losses, perhaps not an intangible benefit, as this can be closely measured if desired;

(e) Algae growth and growth of similar nuisance plants in surface-water reservoirs may impose an undesirable taste to a water supply. Water stored in ground-water reservoirs is, of course, not affected by plant growth, and generally retains a high quality during storage. Pollution problems are minimized in ground-water reservoir storage and less care need be taken to prevent contamination, as compared with surface storage;

(f) Rarely is a surface-water system free of leakage, and normally this leakage replenishes the ground water. The exploitation of the ground water provides a means of recouping a portion, and perhaps all, of this loss through leakage;

(g) As ground water is withdrawn and an aquifer de-watered, subsidence will often occur, especially in unconsolidated formations. Artificial recharge, if practised on a more-or-less safe-yield basis will minimize subsidence problems. Subsidence over a large area, especially in areas with minimum-surface slopes, can be a very expensive problem. Gravity drains, such as sewers and storm drains, may have gradients altered so that they no longer flow, or may be broken. Differential subsidence can have very adverse effects upon structures. The subsidence problem should be carefully considered before an exploitation plan of ground-water mining is adopted;

(h) Artificial recharge provides a treatment and generally improves the quality of the water so recharged, as it moves through the rock formations. This improvement, too, may not necessarily be intangible, as a value may be established for the improvement in water quality. Other intangible benefits, unique to a particular area, frequently are found while planning or executing a recharge project.

Any proposed planned artificial recharge scheme should first be evaluated to determine its financial feasibility and economic justification. Financial feasibility refers to the ability of the project beneficiaries to repay the cost of the project. Economic justification, expressed in terms of a cost-benefit ratio, permits comparison of alternative projects to select the most economical project.

Expenditures for land and casements, engineering and construction of facilities, water or rights to water and operation and maintenance generally make up the total cost of a project. An examination of the cost of existing projects has shown that these costs vary greatly with:

(a) Purpose;

(b) Method of recharging;

(c) Quantity and quality of water available for recharge, and regimen of flow;

(d) Surface and subsurface conditions;

(e) Location of the artificial recharge project; and

(f) Standards and requirements of the agencies involved in recharging operations.

The cost of land and casements usually forms a large proportion of the total cost of a project. It includes the cost of surveys, maps and acquisitions. In some cases, legal and court fees are involved when public agencies must utilize condemnation procedures. Also, in urban areas, additional expense is often involved in rezoning a recharge site.

The cost of the land varies with location and the time at which the land is purchased. As a result of the present trend of urbanization and inflation, cost of land increases with time. As an example, the land at many existing projects located in the populated areas of southern California (United States of America) is currently worth over $50,000/ha, compared with the original cost of about $500/ha in 1930. Any natural resources found on lands purchased for artificial recharge projects can, of course, be used to reduce the apparent total cost of the project. This is particularly evident when the sand and gravel, found on many project sites in and near populated areas, is sold to companies dealing in building materials.

The largest portion of the total cost of a spreading-grounds project is generally to:

(a) Divert water from streams;

(b) Convey water to and from the recharging area;

(c) Measure the amount of flow;

(d) Contain water within, and control flow through, the recharging area; and

(e) Operate and maintain the facilities efficiently and safely.

In the case of recharge through injection wells, the largest portion of the total cost is expended on:

(a) The supply facilities;

(b) The injection wells;

(c) The regulating equipment; and

(d) Operations and maintenance. The redevelopment of injection wells is particularly costly.

Costs of engineering include expenditures for preliminary studies, field surveys and maps, laboratory tests, designs, plans and specifications and construction inspection and control. These costs are greatly affected by the standards and requirements generally dictated by the type of development in and around the project area. In urban areas, the need for fencing and other protective measures, as well as aesthetic treatment, may add significantly to the total investment in spreading facilities. The total cost of a spreading project is also affected by the type and size of such appurtenances as structures for diversion, equipment for treatment of water and measurement of flow and conduits for conveying the water from a source to the spreading project and for returning unused water to the main stream. When costs of these appurtenances are large, in proportion to the facilities in the spreading area, the cost per unit-area is considerably higher tha for projects in which cost of appurtenances is not a major item.

In southern California, the costs of rights of way for the sea-water barrier projects are relatively low, as most of the facilities are located in public streets, where additional rights of way are not required. However, this means that engineering, construction and operation and maintenance costs are considerably higher. The regulatory facilities must be hidden from the public eye. This is do by placing them in vaults below the street surface. The public also demands quiet, which means that sounds from equipment must be muffled, and most equipment cannot operated at night. This is a burden, particularly for operating a drill rig. Generally, it is best to operate around-the-clock, until drilling is completed, in order to minimize the risk of losing a hole. Most often this cannot be done in southern California, and costs go up accordingly.

Operation and maintenance costs include such items as rent, utilities, taxes, insurance and legal fees. Variable operation and maintenance costs include cost o operating personnel, patrolling, cleaning and repair of facilities. Costs of operation and maintenance are frequently related to the amount of water spread or injected during the operation period. As the amount of water recharged increases, the cost per unit-volume of water recharged usually decreases. Thus, the cost for spreading a unit-volume of water is expected to be less during wet periods than during dry periods. However, variable costs may be great, even though a large amount of water is spread, owing to inefficient use of personnel and spreading-grounds. In general, high efficiency of operation is reached when the spreading project is operated at design capacity for a long period of time.

The following check-list should be considered when planning artificial recharge projects:

### Planning

1. Source of water and pricing policy
2. Water rights
3. Potential liability (inverse condemnation problems - flood-out gravel-mining operations, building fresh-water mound too close to ground surface, thus jeopardizing surface improvements)
4. Effects on ground-water basin management
5. Effects on ground-water quality
6. Investigations (generally involving an exploration of the geological and hydrological conditions) to prove feasibility of scheme
7. Finances
    - (a) Capital improvements
    - (b) Water
    - (c) Operation and maintenance

### Rights of Way

1. Surveys
2. Maps
3. Title search
4. Acquisition
5. Condemnation
    - (a) Legal fees
    - (b) Court fees
6. Rezoning

### Engineering

1. Surveys
2. Mapping
3. Design
4. Contract administration
    - (a) Inspection
    - (b) Testing

# Construction

1. Spreading facilities
    - (a) Grounds or basins
        - (1) Levees or dikes
        - (2) Inlet structure
        - (3) Waste-way structure
    - (b) Recording equipment
    - (c) Diversion facilities
    - (d) Control facilities
    - (e) Access facilities
    - (f) Fences
    - (g) Shelter house
    - (h) Treatment equipment

2. Injection facilities
    - (a) Injection-well construction
        - (1) Casing material
        - (2) Gravel packing
        - (3) Grouting
        - (4) Packers
        - (5) Method of drilling
            - (a) Reverse-rotary
            - (b) Standard-rotary
            - (c) Cable tool
            - (d) Other
        - (6) Perforations
    - (b) Observation wells
        - (1) Casing material
        - (2) Gravel packing
        - (3) Grouting
        - (4) Method of drilling
            - (a) Reverse-rotary
            - (b) Standard-rotary
            - (c) Cable tool
            - (d) Other
        - (5) Method of completion
            - (a) Perforations
            - (b) Capped for geophysical well-logging
        - (6) Monitoring facilities
    - (c) Extraction wells - same as for observation wells, plus
        - (1) Pumping equipment
        - (2) Energy
            - (a) Electricity
            - (b) Internal combustion
    - (d) Control facilities
        - (1) Pressure-regulation station
        - (2) Meters
        - (3) Valves
            - (a) Shut-off
            - (b) Control
            - (c) Pressure-relief
            - (d) Blow-off
            - (e) Vacuum
    - (e) Treatment facilities
        - (1) Chlorination equipment
        - (2) Acid equipment
        - (3) Other
    - (f) Pipelines
        - (1) Materials
            - (a) Concrete cylinder
            - (b) Steel: mortar-lined and coated
            - (c) Asbestos cement
            - (d) Plastic
    - (g) Buildings
    - (h) Monitoring equipment
        - (1) Recorders
        - (2) Sounders
        - (3) Samplers
            - (a) Submersible pump
            - (b) Thief sampler
            - (c) Air-lift pump
            - (d) Electrical conductivity

## Operation and Maintenance

1. Spreading facilities
    - (a) Grading
    - (b) Storm-protection
    - (c) Structure repair and replacement
    - (d) Equipment maintenance
    - (e) Fuel for equipment
    - (f) Equipment rental
    - (g) Disking or silt-removal
    - (h) Insect-control
    - (i) Weed-control
    - (j) Aesthetic treatment (such as screen planting with adequate watering systems)
    - (k) Rodent-control
    - (l) Patrolling
    - (m) Treatment (flocculents)
    - (n) Slope maintenance
    - (o) Vandalism
2. Injection facilities.
    - (a) Observation of monitoring devices
    - (b) Measuring water levels
    - (c) Sampling water
    - (d) Redevelopment of wells and disposal of wastes
    - (e) Treatment
        - (1) Chlorine
        - (2) Acid
        - (3) Other
    - (f) Maintenance of equipment
    - (g) Structure repair
    - (h) Fuel
    - (i) Equipment rental
    - (j) Patrol
    - (k) Water analyses
    - (l) Vandalism
3. Office
    - (a) Supervision
    - (b) Administration
    - (c) Wages
    - (d) Office (and field) overhead
        - (1) Rent and utilities
        - (2) Telephone
        - (3) Supplies
        - (4) Maintenance of office equipment
    - (e) Salaries
    - (f) Liability (insurance)
    - (g) Taxes
    - (h) Interest

It is recommended that particular emphasis be placed upon the items in the above list which have the highest costs.

In planning, careful consideration should be given to pricing policy if water must be purchased. If possible, the long-term pricing schedule should be known, as a project could be developed on a sound economic basis and then, if the price of water rose in an adverse and unforeseen manner, the project would no longer be sound. This would be especially critical if the calculated benefits had not yet accrued to the project.

Potential liability should also be carefully considered. Rising water levels may be detrimental to some land-use programme; for example, gravel-quarrying operations, and a court injunction stopping a project is far from desirable. A proper investigation cannot be over-emphasized. Generally, it will be expensive, but it is very desirable in order that the best scheme may be adopted. Normally, this investigation will (and should) include a geological and hydrological exploration of the ground-water reservoir.

During the design stages, the long-term economics of the project should be carefully analysed. This may be emphasized when considering injection facilities. Clogging of injection wells is a serious problem. In the United States of America, the Los Angeles County Flood Control District has found that clogging of wells is caused by one or more of the following factors:

(a) Deposition of corrosion products;

(b) Bacterial growth;

(c) Chemical precipitation;

(d) Physical deposition of water-borne materials;

(e) Rearrangement of the gravel pack and surrounding materials, owing to pressure fluctuations.

From 1964 through 1966, 20 wells required redevelopment and the costs averaged $3,800 for the wells serving one aquifer and $5,200 for the deeper wells that served two aquifers.

It is far better to design for minimizing clogging than it is to be forever handicapped with it as a maintenance problem. It would be well to consider, first, the drilling method. Thus, the cleanest method (perhaps reverse-rotary) may initially cost more, but may, in the end, be far less costly owing to lower maintenance costs. Next, consider the desirability of a gravel pack, the shape, location and density of perforations, the material to be used in the casing, water-delivery facilities and the need for chemical treatment of the water. The Los Angeles County Flood Control District concluded that non-corrosive materials should be used in the pipelines and well-casings and that treatment with chlorine is necessary.

If the water-supply is received at fluctuating pressures, consideration should also be given to the need for a pressure-regulation station. In addition to eliminating undesirable pressure fluctuations, it may result in considerable savings in pipeline costs if the source-water is received at various pressures, as is the case in southern California, where the source-water is also used to supply domestic and industrial needs and the pressure fluctuates considerably owing to change in demands. With a pressure-regulation station at the up-stream end of the system, the pipeline could be designed to withstand the lowest source-delivery pressure (which was the only pressure guaranteed by the supplier), rather than the highest pressure. Enough savings were realized to pay for the cost of the pressure regulation station.

In the case of spreading-grounds, thought should be given to the surrounding neighbourhood. If operations are sustained, insect problems will undoubtedly occur. If they are serious enough, then the public will apply pressures to the extent that operations be changed to minimize the problem. If the grounds are large enough to permit considerable latitude in operations, this may not be serious; if not, then unit costs of water-spreading will undoubtedly rise. In addition, it may be necessary to make the facility aesthetically pleasing to the neighbourhood. This may involve screen planting. Initial costs may be high, as water supply facilities, as well as plants, are required. Maintenance costs are likely to be high, too.

Another area which cannot be overlooked is the cost of a highly trained technical staff. High costs demand that operations be efficient. To make them efficient requires that good records be kept, and proper reporting and careful analysis of the system be made periodically.

## B. Legal aspects

Although one would assume it to be accepted without question that a resource as valuable as ground water should be controlled and managed in accordance with modern concepts of resource development, the fact is that ground water in most parts of the world is still subject to little or no control of this kind. The explanation lies mainly in the widespread ignorance of how, where and why ground water occurs. Even in very recent times, for example, it was commonly believed that ground water flowed mysteriously in underground rivers and that the sources of these rivers were in remote regions. Few people had any notion of the science of hydrogeology and, under those circumstances, it is easy to understand why Governments and legislators could not devise rational control measures.

A second complicating factor is that ground water has been thought of as a property or mineral right, so that the landowner believed that he owned the ground water and could do with it as he pleased. Thus, if one man pumped large amounts of ground water from his own wells, and if this, in turn, caused a depletion of ground water on neighbouring tracts of land, little or nothing could legally be done about it. However, as the science of ground water has developed in recent decades, it has become apparent that many of the old views of this resource are incorrect. More and more, Governments are coming to realize that the waters beneath the surface of the land constitute a common resource, to be utilized by a number of users for the benefit of all. Ground water cannot be apportioned on the basis of artificial property boundaries, because a withdrawal of water by any individual user quite clearly affects the ground water beneath adjacent tracts of land. With this growing understanding of the science, has come a greater appreciation of the need for control and management by public regulatory authorities. The systems of acquisition of ground-water rights, which are the rights granted or recognized by law or custom to take possession of water occurring in a natural source of water-supply, and generally to put it to beneficial use, vary widely from one country to another, mainly according to a climatic pattern. Thus, in areas where there is a water surplus, the "private ownership" doctrine is generally accepted; whereas, in areas

Table 8. Costs of artificial recharge
(1971 dollar per 1,000 $m^3$)

| Area and description | Capital costs | Operation and maintenance costs | Total | Type | Remarks |
|---|---|---|---|---|---|
| France | | | | | |
| Croissy area; chalk reservoir; annual spreading, 11,000,000 $m^3$ | | | 60.00 | Spreading | |
| Federal Republic of Germany | | | | | |
| 1. Dortmund area; alluvium reservoir; annual spreading, 5,000,000 $m^3$ | | | 30.00-40.00 | Spreading | |
| 2. Dusseldorf area; alluvium reservoirs; annual spreading, 60-70,000,000 m3 | | | 120.00 | Spreading | High cost attributed mainly to treatment |
| 3. Frankfort; alluvium reservoir | | | 10.00 | Injection | A lateral leaching line from the river |
| Israel | | | | | |
| 1. Sandstone and limestone formations 80,000,000 $m^3$ annually injected | | 14.30 | 14.30 | Injection | Multipurpose wells; capital costs justified for extraction purposes, therefore only operation costs attributed to injection |
| 2. 20,000,000 m3 maximum; local water spread annually into sand dunes then into sandstone | | | 50.00 | Spreading | All costs included; costs vary widely, depending upon abundance of water |
| Japan | | | | | |
| Unconsolidated formation; injection test, fixed-assets cost $97,353; represents first year's operation, injection of 1,947,175 $m^3$ from November 1961 to September 1962 | | 19.00 | | Injection | |

Table 8. (continued)

| Area and description | Capital costs | Operation and maintenance costs | Total | Type | Remarks |
|---|---|---|---|---|---|
| Switzerland | | | | | |
| Basel area; alluvium formation | | | 25.00 | Spreading | |
| United States of America | | | | | |
| Los Angeles area; spreading in unconsolidated formation; injection into confined but unconsolidated formation | | | | | |
| 1. Local storm run-off; costs based on seven spreading grounds, and 683,492,000 $m^3$ total spread | 4.16 | 6.25 | 10.41 | Spreading | |
| 2. and five spreading basins; costs based on 98,796,508 $m^3$ total spread | 7.52 | 7.18 | 14.70 | Spreading | |
| 3. Imported, untreated Colorado River water, costs based on 1,472,101,000 $m^3$ total spread | | 0.78 | 0.78 | Spreading | Utilizing existing facilities which were justified for spreading local storm run-off, therefore, only operations and maintenance costs are attributed to spreading, not including cost of water, which at 1969 prices is \$16.21 per 1,000 $m^3$ |

Table 8. (continued)

| Area and description | Capital costs | Operation and maintenance costs | Total | Type | Remarks |
|---|---|---|---|---|---|
| **United States of America** (continued) | | | | | |
| 4. Reclaimed waste water, costs based on 65,080,000 m$^3$ total spread | 1.64 | 1.64 | | Spreading | Utilizing existing facilities, which were justified for spreading local storm run-off; therefore, only operations and maintenance costs are attributed to spreading, not including cost of water, which at 1969 prices is \$14.59 per 1,000 m$^3$ |
| 5. West Coast Basin Barrier Project; about 55,000,000 m$^3$ injected annually; total fixed assets costs about \$7,000,000 (all construction not yet complete) | 5.87 | 7.49 | 13.36 | Injection | Not including cost of water, which at 1969 prices is \$20.26 per 1,000 m$^3$ |
| 6. Alamitos Barrier Project; about 5,550,000 m$^3$ injected annually; total fixed assets costs about \$2,500,000 (all construction not yet complete) | 20.96 | 35.95 | 56.92 | Injection | Not including cost of water, which at 1969 prices is \$20.26 per 1,000 m$^3$, not including operation and maintenance for extraction wells |

The table presents actual costs of artificial recharge now being carried out in various parts of the world. Where known, costs have been broken down to show both capital expenditures and operation and maintenance expenditures. If the operation and maintenance cost is considered to be the only cost, it is shown in both the "Operation and maintenance" column and in the "Total" column. In the case for Japan, only the operation and maintenance cost was known; no figure was included in the "Total" column.

where there is a water deficiency, especially those located in arid or semi-arid zones, ground waters are generally considered to be public property and, therefore, part of the public domain. A number of other situations related to the main concepts of private ownership and public property are summarized below.

The common-law rule of absolute ownership recognizes ownership of ground water by the owner of overlying land and places no restriction upon the owner's right of use of the water on his overlying land, or elsewhere. This doctrine considers the owner of the land to be the owner of all the water in the underlying aquifer, and not merely to have the right to the use of this water; in England it is also known as the rule of "unlimited use"; and in the United States of America as the doctrine of "land-ownership". It is a common legal concept in Canada, most of Europe, part of Latin America and in the eastern portion of the United States.

The rule of "reasonable use" recognizes ownership of ground water by the owner of overlying land, but limits the right of use of the water to such use on, or in connexion with, his overlying land, as is reasonable with regard to the similar rights of all other owners of lands which overlie the same source of water supply. A variation of this rule is the doctrine of "correlative rights", which stipulates not only that the use should be reasonably beneficial to the owner's land, but that the owner is entitled only to his reasonable share, if there is not enough water to supply the needs of all. These doctrines are mostly in force in certain states of the United States in order to attenuate the rule of absolute ownership. Similar doctrines are found in southern Europe and in some countries of Latin America.

According to other doctrines, the owner of the overlying land is entitled to use the ground waters under it only if he complies with certain legal provisions which put his activities under government control. Usually, he merely has to notify the administrative authority concerned. Sometimes, however, the stipulations go so far as to require prior authorization from the administrative authority in the form of a permit or a concession. In most cases, such notification or authorization is not necessary when the water is used only for domestic purposes and the watering of animals.

Under doctrines somewhat similar to the one just mentioned, private ownership with appropriate administrative control is still the rule, but there are areas of a country, sometimes known as "restrictive areas", where more rigorous administrative regulations are applied. In some cases, for example, a permit may be required for the drilling of a well, but there are special areas where it is further stipulated that drilling must be carried out according to very strict administrative specifications.

According to the concept of public property, ground waters are part of the public domain and belong to the public. Consequently, the Government has a duty to ensure that ground waters are used in the best interest of all concerned and that ground-water rights are under administrative control. Where ground waters are held at law to be public property, their use by private individuals must be reported to the appropriate administrative authority and may require official sanction.

In some countries any individual may, with administrative authorization, obtain a concession for water rights on or under any person's land without having to pay an indemnity to the landowner. However, where the concept of public property prevails, there are usually restrictions on the free use of ground water by any individual or corporation.

In certain countries of North Africa and the Middle East, ground water brought to the surface by human effort can be used freely only by the person or persons who have done this work. However, when the extraction of water is made for the purpose of investigating natural subsoil resources other than water, the water can be used by those engaged in these investigations only to the extent necessary for such work. Any surplus water goes back to the public domain.

Elsewhere, anyone who has beneficially used ground water from a natural source on or under any land, for a certain period of time, is the rightful user of this water. This is the doctrine of "prior appropriation", which is prevalent in most of the western states of the United States and in several countries of Africa and the Middle East. The time element alone, the fact of being the first to use the water, confers preferential rights. Logically, misuse of the water should result in loss of these water rights, and from this stems the doctrine of "prescriptive rights". Such prescription of rights is sometimes applied to owners of overlying land who have not been using their ground waters for a certain period of time.

A summary of the variety of legislations and customs presently existing in the world for ground water is presented in a recent United Nations publication on water legislation. 4/ The need for legislation for water resources as a whole; which would take into account the close links which often exist between water in surface streams and ground water stored under riverbeds in banks, or up-stream of springs, is now acknowledged in a number of countries.

In several industrial countries, legislation has been established to protect ground water in storage against pollution and over-draught. However, it should be noted that very often these measures have been taken under emergency situations, such as when pollution and over-draught had already significantly endangered the resource. Such examples should serve as a warning for areas where ground-water development is expanding and where new industrial and housing projects are being implemented. For too long ground water has been considered as a kind of self-renewing mineral which could be indefinitely extracted by anyone on his own piece of land or under concession by the landowner, without any further restrictions. The lack of a sound legal basis often has made it very difficult to introduce efficient administrative control-measures.

A workable legal basis for ground-water administration must take cognizance of the following points:

(a) Ground water occurs in natural hydrogeological units which have to be defined by experts. These boundaries commonly do not coincide with political or administrative boundaries;

(b) Ground water should not be regarded as property of any particular user or landowner; but rather as a natural asset of the whole community; and

(c) Ground-water exploitation should proceed under license and in a controlled fashion, keeping in mind previous customary rights, as well as the need to maintain the natural asset for the benefit of the whole community.

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4/ Abstraction and Use of Water: A Comparison of Legal Régimes (United Nations publication, Sales No. E.72.II.A.10). See, in particular, chapter II.

Even if the legal basis of ground water is adequate, there arise a number of administrative questions. For instance, owners of private wells have little inclination to measure accurately the quantities of ground water which they pump. Quite mistakenly, owners of private wells feel inclined to conceal the truth, if asked questions by inquisitive government officials about pumpage. Conceivably, they do not themselves know how much water they actually extract. In order to obtain reliable information on the degree of exploitation and to apply control measures, water meters must be installed, maintained and periodically read by the competent authority. All other methods, such as estimates based on irrigated areas and hours of operation of the pumps, are only makeshift measures. Controls should also be extended to the construction and modification of bore-holes, which should proceed only under licence from the competent authority. It is advantageous to make the driller legally responsible for holding a licence for each bore-hole he drills. If the driller contravenes the law, his rig may be temporarily impounded on the spot and the illegal work may be stopped at once. If the law holds the client legally responsible for obtaining the licence, it may be difficult to actually locate the client, as the driller need not have to know the client, in the legal sense of the term, and the work may proceed practically unchecked.

Owners of private wells usually do not have the feeling of sharing an asset with their neighbours, although they may only be a short distance away. This peculiarity stems from the rather mysterious attributes with which ground water is bestowed in the eyes of most people. A patient effort of education is, therefore, necessary. Water users have to be informed of the characteristics of the reservoir they are tapping. The periodic publication of maps showing ground-water level, salinity and other data, would help make them aware of the realities involved.

Ground-water legislation has proved to be ineffective in a number of cases for three reasons: first, the landowners often consider that ground water underlying their property is equally their private property, and that dumping on their property is their right; secondly, it is difficult to check the quantity of water which is extracted from hundreds or thousands of wells in an area, even the use of metres has often proved to be ineffective for this purpose; thirdly, the laws and usages of many countries do not permit easy access into private property by the personnel who normally would be in charge of enforcement. A special effort should therefore be made to make the users of ground water aware of their common interest in obeying the regulations and accepting the controls. The need for making land available as public property, or for reserving space in development projects for recharging ground-water reservoirs should also be mentioned. Certain aspects of this problem were mentioned in chapter III and are illustrated in part two (case studies No. 17, Long Island Recharge Schemes and No. 18, Los Angeles County.)

## C. Environmental aspects

One of the main purposes of ground-water storage and artificial recharge schemes is to conserve, if not to increase, availability of water resources, both in quantity and quality. This aim in itself could be considered an important element in the improvement of environmental conditions. However, it should not be forgotten that some storage and recharge programmes involve the construction of a considerable amount of public works for the purpose of spreading water over vast areas. The operation of these facilities may be detrimental to previously existing environmental conditions. Further, the increase in availability of water resources will generate new environmental problems, such as the disposal of additional waste water and the drainage of excess irrigation water.

From the point of view of the conservation of water resources in quantity it should be pointed out that ground-water storage and artificial recharge programmes, by overcoming the disastrous effects of ground-water over-draught, such as the rapid fall of ground-water levels, maintain a certain amount of moisture in the subsoil, thus allowing vegetation and related animal life to subsist. Substantial savings of energy consumption are to be expected if pumping heads are reduced as a result of the rise of ground-water levels generated by such schemes. The conservation in quantity of water stored underground implies, in particular, that any adverse effects of leakage be adequately overcome, either by additional recharge, or through an appropriate device which will obstruct the outlets through which the leakage occurs. In the arid zone, ground water is conserved through pumping that lowers the piezometric surface to a depth at which substantial losses through evapo-transpiration do not occur. In this particular case, water is conserved by keeping the water level artificially below its natural level; this policy may have adverse effects upon the environment.

It should also be remembered that bringing additional water into an area for impoundment may have a disastrous impact upon the environment. If the amounts of water involved are excessive, rich agricultural regions can be turned into swamps, and deep saline ground water may be brought to the land surface, thus destroying the crops and the soils. In the elaboration of such schemes, careful attention should be given to the ecological effects of the changes which will occur in the distribution of water resources in space and in time. It is also essential that the hydraulic structures - canals, dams, pits and spreading-grounds - be incorporated harmoniously into the natural and human environment. A good example of what can be achieved in this field is represented by the 2,000 recharge basins, or "sumps", collecting run-off waters in Long Island, New York (see part two, case study No. 17). These sumps are fenced, thus protected against dumping and pollution, and hidden from the public view by means of appropriate location and by screens of densely planted trees.

Improper management of ground-water reservoirs may have disastrous effects upon the environment, especially if the pumping rate greatly exceeds the recharge potential. Sea-water intrusion, underground clogging of existing wells and subsidence were mentioned in chapter II, section F. An example of the disastrous effects of subsidence, and of successful remedial measures which can control it, are provided in the following example of the Osaka city area (Japan).

In this area subsidence occurred because of removal of water from sandy aquifers and resultant shrinkage of adjacent clay layers. Serious damage resulted, including stagnation of surface and ground water, inundation by floods and, especially in the coastal area, invasion of high tides. Subsidence had been observed in the area since the early 1920s, and it accelerated abruptly after the Second World War. Since 1950, subsidence had increased more rapidly because of the need for water by industrial plants. The subsidence continued until 1964 in most of the area. The maximum record of subsidence was observed in the most severely damaged centre, and reached 251.7 cm during the 30 years from 1935 to 1965. It was ascertained that ground-water over-draught was the cause of this disaster and, as a result, a law established severe control on draught and pumping devices installed after 1959. The uppermost position permitted for a screen setting was below 500-600 m and the maximum cross-sectional area of the pipe at the outlet of a pump was limited to 21 $cm^2$. Pumpage for the above-mentioned categories were abandoned. Supplemental waterworks designed to supply industrial water from surface-water sources were begun.

As a result of these changes, the draft diminished and the decline of the ground-water level stopped in 1962. The rate of subsidence decreased and finally resulted in rebound of the land in 1964 for most wells in Osaka. Observation records for one of many wells are shown on the diagram in figure 8.

Maintenance of water quality at acceptable levels is one of the major requirements for successful utilization of ground-water storage. Major factors in considering the suitability of a water-supply are water-quality requirements and limitations associated with its contemplated use. Various standards have been established covering all aspects of water quality, including bacteria content, physical properties and chemical constituents. Generally, water-quality problems with respect to the first two aspects can be readily and economically resolved. However, the presence of undesirable chemical constituents is frequently a major problem in the utilization of ground-water storage.

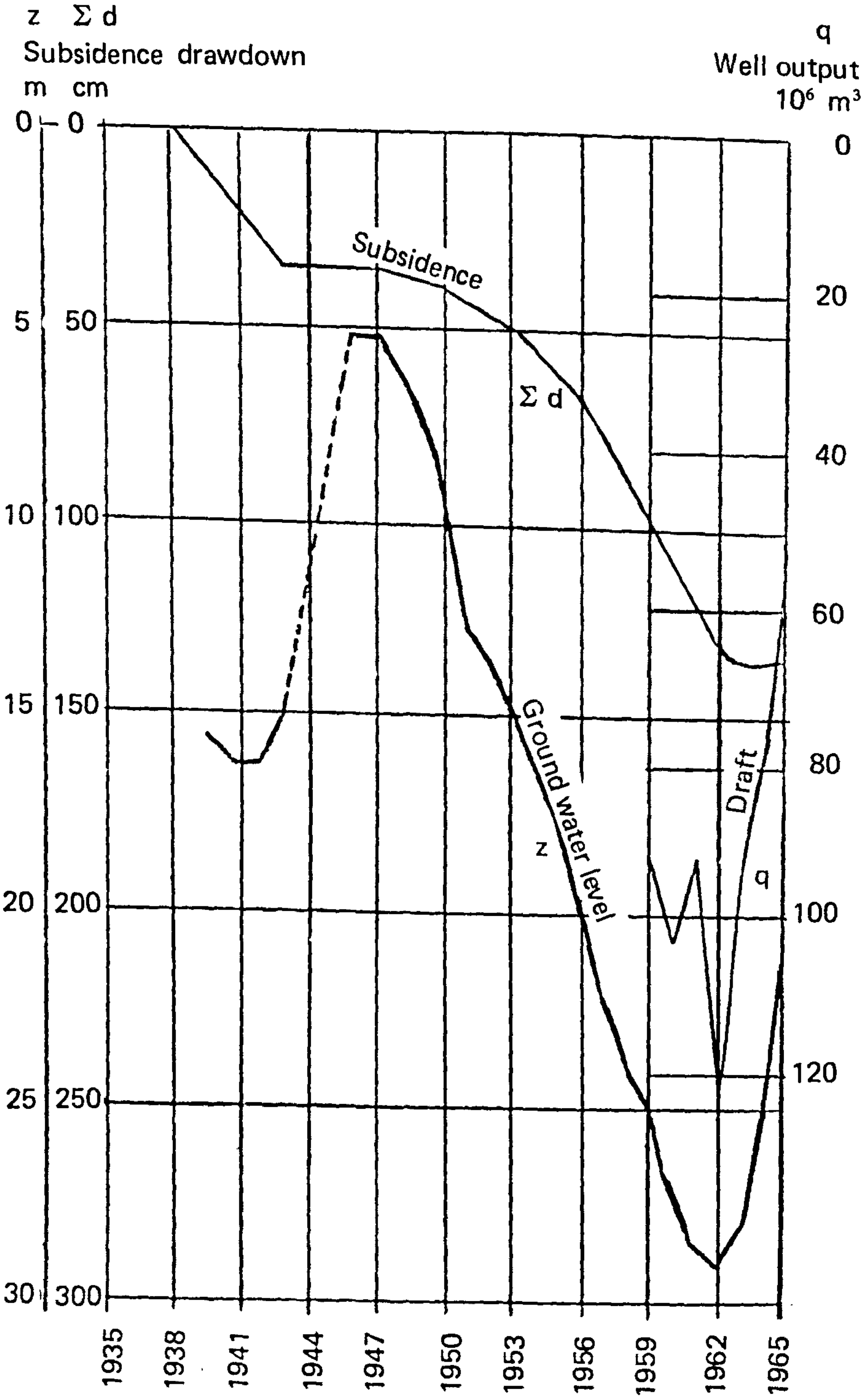
Many water-quality problems stem from man's activities on lands overlying ground-water reservoirs. Certain of the wastes resulting from these activities, such as sewages, industrial wastes and radio-active wastes will impair water quality if they enter the ground-water reservoirs without prior adequate treatment.

The control of these wastes, especially in urbanized and industrial areas, is a prerequisite for the development of ground-water storage. Deterioration in quality may also originate from other sources, such as the presence of salts in the watershed surface, in geological strata or in a nearby sea or salt lake.

From the above remarks it can easily be assumed that any substantial ground-water storage or artificial recharge project will effect changes in the environment. Such effects may or may not be significant, but their identification and evaluation should be anticipated to the greatest possible extent. It is understood that accurate forecasting of such effects is not an easy matter, because the future condition of the ground-water storage system may be highly uncertain, depending upon a large number of interdependent factors which change with time.

Past experience in ground-water exploitation serves as the best basis for predicting the future effects of utilization. Numerous case histories could be quoted, some are presented in part two of this study.

Figure 8. Land subsidence at Kujo, Osaka, Japan
(Observation records for number 3 well)



In addition to past experience, several analytical techniques may be used in such forecasting. For example, the ground-water storage system may be simulated by mathematical models or analogue models, as mentioned in chapter II, section B.

From the anticipated changes in water resources with respect to location, amount, distribution in time and quality, environmental changes may be forecast through the use of proper computer programmes using water data as the main input.

## D. Institutional aspects

The nature and the size of storage/recharge projects will, in most cases, require government action. At the outset, it is the duty of the Government to evolve a policy clearly defining the aims of the State regarding ground-water investigation, development and use within the broader framework of water-resources development. Whatever these purposes may be, this policy must be supported by a corresponding programme of action and by provisions for setting up an organizational framework.

In addition to the legislative and rule-making prerogatives, the ground-water policy of the Government may be, for example, to limit its activities merely to one stage of development, such as investigation; or to cover the whole range of activities from the preliminary survey to financing construction, operation and maintenance. It may happen that the programme is a long-term one, proceeding in planned stages; or the programme may be a short-term one, or even an emergency project designed primarily to provide quick relief in selected areas suffering from a particularly acute water shortage. Whatever the magnitude and urgency of the projects, government policy and control co-ordinate them and link them together in a master plan. Short-term and long-term programmes may thus mutually support each other, and so may the various stages involved. In a long-term programme, the major development of ground-water resources ideally should await completion of long-term investigation; in practice, however, investigation and development are often carried out together, providing, as they progress, better and more reliable data for planning the next stage of work. Government policy obviously determines the type and nature of organization required. Thus, a long-term programme necessitates the establishment of a permanent organization within the country, while a short-term, or an emergency programme, may be entrusted to a greater extent to outside technical assistance and execution by contractors. However, in this last case, it is also preferable to have the programme supervised and checked by a competent government service. As a matter of fact, the effective implementation of any ground-water policy requires a competent and efficient organization, which, in turn, presupposes the existence of a legal framework. The latter may be established in a unified water code or in provisions of various separate laws, and in special decrees and regulations issued by the responsible agencies.

As mentioned above in section B of this chapter, water codes and similar laws vary greatly from one country to another. They usually deal with granting of water rights, fees to be exacted, public registers, inspection and control of water exploration, drilling, supply, sanitation, conservation and related matters. As the importance of ground water increases and Government becomes more active in this field, more comprehensive enactments are needed to provide for the creation, organization, functions and powers of water departments or agencies, and for budgetary appropriations and other financial arrangements.

The form of organization is closely related to the structure of the central Government and to local conditions. Variations can therefore be as wide as the limits of these two controlling factors.

For instance, if the purpose of the project is to increase the quantity of water to be piped into the water-supply system of a major city, it is likely that the city government will be responsible for the execution of the project through its technical services, especially if the funds come from, or are related to, the municipal budget.

If ground-water specialists are not attached to these services, they may be assigned to the city by the central Government. A similar situation exists in the United States of America between the state government and the Federal Government. In many states, ground-water specialists from the United States Geological Survey are assigned to participate in co-operatively financed projects with the state government.

In an increasing number of countries, such as Argentina, Ethiopia and Tunisia, all water problems are dealt with by a single ministry, organized as a public corporation, regardless of the use or the origin of the water supplies to be utilized. In other countries, a central water commission is established to co-ordinate water activities which are handled by several government agencies.

A summary of the organization of water supply in the world is provided in a recent United Nations publication. 5/ In general, ground-water investigations, development and control are handled by a specialized service or branch within a geological department, a water-resource department of a water-supply corporation or a public works department. Drilling operations are carried out by a Government or a private contractor, under the supervision of the ground-water service, while the related public works component (earth-moving, spreading-grounds canal-construction, engineering works) is handled by contractors, also under the supervision of the ground-water service.

A number of conditions are essential for the proper functioning and effectiveness of the ground-water service, regardless of its ministerial framework. First, the ground-water responsibilities should be self-contained in a given unit, section, branch, office or other component headed by a competent ground-water specialist. Secondly, the ground-water service should have close ties with the other water services and the geological services. Thirdly, the ground-water service should have supervisory, if not managerial, responsibilities concerning drilling and construction operations.

It happens, indeed, too often, that large-scale water projects are designed by waterworks engineers who disregard the possibilities offered by ground-water reservoirs as a large water storage facility. In many cases, ground-water storage potential would represent an economic alternate (or complementary) solution to projects involving the construction of dams. It is, therefore, essential that ground-water specialists participate in the design of water development projects, and the consideration of possibilities offered by ground-water reservoirs be secured on an institutional basis. It is also necessary that the ground-water

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5/ Abstraction and Use of Water ... See, in particular, chapter IV.

service be involved, on an institutional basis, in project implementation, especially with respect to the drilling and public works component, not only in an advisory capacity, but in a managerial capacity.

Other institutional aspects to be considered include the creation of associations of water users, the education of the public with respect to water use and the granting of concessions to firms or corporations for the operation of water systems. These aspects are not basically different from those related to surface-water projects and will not, therefore, be discussed in the present study.

## E. Managing ground-water storage

In general, water management can be defined as comprehensive planning for beneficial use, plus operation for optimum economic and social benefits, of total water resources. Although the subject of this report is ground-water storage and recharge, it is well to recall the interdependence of surface and ground water. Thus, it is essential that any plan for the management of ground-water resources be co-ordinated with plans for proper management of surface-water resources. Ultimately, this approach should lead to an integrated utilization of water resources which will make an optimal use of the storage potential available aboveground and underground.

Water resources management is a vast subject in itself and it cannot be dealt with extensively within the scope of the present study. The following brief remarks are presented as a summary of all aspects involved in the management of ground-water reservoirs, most of which were previously reviewed in this report.

The first step to be taken in the management of ground-water resources is the assessment of the size and hydraulic parameters of the ground-water reservoir(s) involved. Methods and techniques to be used were previously mentioned. In general, they include a hydrogeological investigation, supplemented by geophysical studies, drilling and test pumping. Main hydraulic parameters determined will be the storage capacity of the reservoirs concerned.

The magnitude of the storage capacity available underground has frequently not been recognized by engineers and water planners and, therefore, has not been properly utilized. As an example, the gross storage capacity of the ground-water basins of California is estimated at more than 1,000 x $10^6$ acre-feet ($1.2 \times 10^{12}$ $m^3$), whereas the gross storage capacity of surface reservoirs in the state, according to the state's plan for ultimate development, will be only 77 x $10^6$ acre-feet (95 x $10^9$ $m^3$). All of the gross ground-water storage capacity may not be economically usable but, with reasonable assumptions, well over 250 x $10^6$ acre-feet (310 x $10^9$ $m^3$) of ground-water storage capacity is clearly usable on a cyclical basis. This compares with a total of only 50 x $10^6$ acre-feet (62 x $10^9$ $m^3$) of available active storage, when all the surface reservoirs of California have been constructed.

After the storage capacity and other characteristics of the ground-water reservoir have been determined, a feasibility study should be undertaken. This study can be expected to lead to recommendations regarding storage and utilization of surface and/or underground water. Underground storage, because of its large size, is particularly valuable for the regulation of water supplies where carry-over storage from wet periods to dry periods is necessary. These periods may be simply the wet and dry seasons of a single year, or they may be the wet and dry years of a cycle. Where carry-over storage is planned for a period of several years, the change in water level in the ground-water reservoir may be very great, and deep wells will be required to abstract water during periods of drought.

Before operational procedures to manage ground-water storage can be put into effect, problems must be solved in the political, social, and legal realms. Existing water rights are often a major legal problem, and it may be necessary to modify these rights for management procedures to be put into effect.

Recognition and protection of existing installations for development of ground water, whether or not according to a formal right, is sometimes essential in the development of a water-management scheme. A problem along this line presently exists, as an example, in ground-water storage reservoirs near the city of Madras, India. Present ground-water development in this basin has been on an unmanaged basis. As the ground-water level has been quite shallow, many farmers have installed centrifugal pumps on their individual wells. Such pumps are ideal for short lifts, but are dependent upon natural air pressure; under field conditions, the pumps can lift water no more than 6 m, if that. Under a United Nations Development Programme (UNDP) ground-water project, executed by the United Nations, consideration was being given to intensive development of the ground-water storage reservoirs near Madras to supply water to the city itself. If this procedure is put into effect by the installation of wells of heavy draught, water levels in that portion of the basin can be expected to fall below the pumping limit of the centrifugal pumps. Under proper management procedures, some type of compensation or water-substitution for those suffering economic loss may thus be called for.

A social custom in a great many countries, which may or may not be supported by law, is that an owner may drill a well whenever he desires, and may extract as much water as he wishes. In some countries this custom has been a factor of development. It caused little damage where wells were hand-dug and could yield only small quantities of water, extracted by hand or animal traction. However, where ground-water development is to be managed, it is locally necessary to modify and limit this custom or right, especially where bore-holes are driven through thick aquifers and are equipped with powerful pumps that yield large quantitites of water. Public education regarding ground-water conditions and the advantages of ground-water management are necessary. However, for the landowner to support the management scheme, he must continue to receive adequate water supplies, and must be compensated for any economic losses he suffers with respect to existing wells, pumps etc.

It is essential that the quality of ground water in storage be protected by legal means. Under many geological conditions, usable water occurs in reservoirs overlain, underlain or laterally bounded by water of poor quality. The condition is quite common where the usable reservoir is capped by an impervious zone, above which is a shallow aquifer containing water of poor quality. In such a situation laws must provide that wells to the lower, good aquifer must not be open in the upper aquifer, nor can gravel-packed wells be permitted. The alternative is movement of the upper, poor quality water downward, degrading the quality of the water in the good aquifer. Proper construction of wells must be required by law, and must be performed under close supervision of qualified inspectors.

Proper management includes regulation of disposal of wastes, human and industrial, into ground-water storage. It is almost universally desirable to prohibit contamination of usable aquifers by injection, through wells, of either sewage or industrial wastes. In this connexion, it must be observed that radioactive wastes injected into an aquifer may remain a health hazard for many years.

Regulation of pumping is normally part of ground-water management. The location of wells that comprise an approved pumping pattern is necessary, after which the rates of pumping and amounts of water pumped are regulated.

After the investigational procedures have been completed, and a planned programme for ground-water storage management has been drawn up, operational procedures should then be put into effect. These procedures can be expected to include items mentioned in preceding sections and the enactment of all legal measures necessary to implement them.

Among the main administrative problems to be solved is the selection of the organization, government agency or corporation which will manage the ground-water reservoirs. Most efficient management can generally be carried out by a single organization. However, if one such organization is not selected a co-operative arrangement between two or more agencies may be satisfactory, if worked out properly within a broader framework involving a national or regional commission and/or agency for water resources development.

Operation of ground-water storage reservoirs should, of course, be integrated with the operation of available surface-water supplies, where usable surface supplies exist. This conjunctive operation can be expected to involve cyclical storage in ground-water reservoirs. Introduction by man of water into underground storage takes place through artificial recharge schemes. A great many methods of artificial recharge exist, principally surface spreading, and injection by recharge wells, as described in the previous chapter.

Partial management of ground-water storage reservoirs has begun in many areas. Limitation of number of wells drilled, control of amounts of pumpage and careful monitoring of ground-water levels have been in effect in many parts of the world for some years. In some areas, mainly in industrial countries, artificial recharge to replenish ground-water storage or to create a ground-water mound to repel sea-water intrusion is practised on a large scale.

Operation of ground-water reservoirs lends itself well to simulation by models. Electric analogues have been used with some success, but the more sophisticated mathematical models are perhaps the most effective and adaptable simulators of physical conditions. Present, past and future conditions of storage, water-level change, accretion and depletion can be effectively reproduced. The digital computer has already been used in several countries for predicting the future under various possible operating conditions, for large ground-water reservoirs. An example is California, in the United States. Moreover, computer programmes for water-resources management tend to become increasingly sophisticated, and to incorporate a large number of parameters with the purpose of forecasting not only the evolution of water resources, in time and space, but economic, social and environmental factors that may affect all categories of water users.

## Conclusion

The past has shown that in many developing regions the exploitation of ground water in storage grows by slow stages, from a few isolated wells yielding comparatively small supplies for local purposes, to extensive well-fields that provide a considerable part of the region's water supplies. A major advantage of ground water is that this resource can be developed in stages, in keeping with growing demand and without the need for heavy initial investment of capital. However, this advantage also harbours the danger of over-exploiting and damaging the resource if the utilization of ground-water storage is not properly carried out.

A number of conditions must therefore be satisfied as a prerequisite of any major decision with respect to the utilization of a ground-water reservoir, including especially the following:

(a) The natural and environmental conditions influencing the utilization of ground-water storage must be known in some detail. However, this does not mean that the utilization of ground-water storage must be deferred in all cases until lengthy theoretical investigations have been completed. On the contrary, the implementation of small-scale projects can be undertaken, even before the properties of the ground-water storage system are known in all detail. The experience gained during the implementation of these small-scale projects from hydrological observations, geological investigations by bore-holes etc. will provide a sound basis for later detailed investigations. If sufficient judgement is exercised, and transferred into a reasonable development pattern, large-scale schemes can be implemented step by step, each preceding step providing vital information to the subsequent step;

(b) The engineering aims must be clearly formulated and decisions be made by considering future possibilities during the implementation of the project. For example, assume it has been decided to utilize a ground-water system in an arid region for the purpose of long-term storage, in order to safeguard the water supply over several years, including excessively dry years. This means that, during normal years, a certain exploitable reserve must be kept in the aquifer. If, at the same time, ground-water storage is exploited beyond the predetermined limits, the declared engineering aim, and the integrity of the economy, will be imperilled;

(c) Administrative measures must be taken so that the ground-water storage/recharge project(s) can be implemented, supervised and guided in the desired direction. An adequate agency or organization should be entrusted with the technical capability, the financial means and the powers of decision which are necessary for managing projects of such complexity; in addition, as mentioned above in this chapter (section C) proper legislation and regulations should be enacted with a view to ensuring that necessary raw-water resources and land property will be made available to these projects, taking into account the interest of the water users and of the public;

(d) Short-term and long-term socio-economic benefits expected from the scheme should be assessed carefully and compared with those expected from alternative projects.

It is interesting to note that the above conditions are usually, though not always, satisfied when large-scale surface water projects, such as diversion works for river water, are planned. For these projects, the conditions must be satisfied in order to justify and protect the heavy capital investment, thus providing sound guidelines in the early stages of planning. In ground-water development, the need for such conditions is equally important, but it is generally not as urgently felt in the early stages of planning.

Until recent times ground-water storage and recharge projects have been implemented only in industrialized countries. It now appears that such projects could be the most immediate answer to water shortages in developing countries, not only in industrial areas of these countries, but in densely populated areas of the arid and semi-arid zone, in coastal areas, in islands, and other areas of water shortages. The experience already gained in such projects, of which a broad sampling is provided in part two of this study, would certainly lead to the identification of a number of first-priority projects and of their main components.

From the perspective which has been given in this study for ground-water storage and recharge, it may be inferred that such projects are complex and relatively costly and that, in all their aspects and all stages of their implementation, they require a full commitment from the government.

It is likely that projects will often require an input of technology, equipment, specific managerial guidance and funds which cannot entirely be found in the developing countries concerned. In the years ahead the international community, through its institutions, should therefore be prepared to respond to requests for assistance in this field. It should, also, whenever justified and feasible, propose such projects as a preferable alternative to costlier projects, considering that ground-water storage management and artificial recharge schemes have, in many cases, proved to be a fast, economical, and successful way of increasing the availability of water resources in areas of water shortages.

## Selected references

Most of the published material on the subject of artificial recharge of ground water is listed in the three following publications:

Bize, S., L. Bourguet et J. Lemoine. L'Alimentation artificielle des nappes souterraines. Paris. Masson et Cie. 1972. 199 p.

Signor, D. C., D. C. Growitz and W. Kam. Annotated bibliography on artificial recharge of ground water, 1955-1967. Washington. United States Geological Survey, Water Supply Paper 1990. 1970. 114 p.

Todd, D. K. Annotated bibliography on artificial recharge of ground water, through 1954. Washington. United States Geological Survey, Water Supply Paper 1477. 1959. 115 p.

In addition, it is worth mentioning the papers presented at the Artificial Groundwater Recharge Conference, held at the University of Reading, 21-24 September 1970. These papers were published by the Water Research Association, Medmenhaus, Marlow, Buckinghamshire, England.

With respect to the Union of Soviet Socialist Republics, the main source is Hydrogeology of the USSR, in 50 volumes, published by Nedra, Moscow.

# PART TWO

# CASE STUDIES OF GROUND-WATER AND ARTIFICIAL RECHARGE

# INTRODUCTION

As an illustration of the preceding developments and at the suggestion of the panelists 34 case studies are presented in this part. Many originate from unpublished notes and reports, from publications which are not readily available and from documents in French, Hebrew, Russian and Japanese.

## Location and natural conditions

The case studies refer to 20 countries throughout the world. All climates are represented: from the desert or hyperarid type (rainfall negligible or less than 100 mm in three cases, 4, 14 and 16; to the tropical-humid (rainfall exceeding 2 m) cases 13 and 28. Between these extremes the following climatic environments are represented:

(a) Arid/semi-arid (cases 10, 18, 25 and 31);

(b) Cold or temperate humid, 8 cases: (1, 9, 12, 15, 17, 20, 21 and 29);

(c) Temperate, oceanic and Mediterranean climates, 15 cases: (2, 3, 5, 6, 7, 8, 11, 19, 23, 24, 26, 27, 32, 33 and 34);

(d) Continental climates, 2 cases: (22 and 30).

The following types of geographical units are represented:

(a) Alluvial valleys, 16 cases (1, 4, 7, 8, 9, 11, 14, 15, 18, 19, 22, 23, 24, 26, 30 and 32);

(b) Coastal plains, 10 cases (2, 6, 12, 20, 21, 25, 27, 28, 29 and 34);

(c) Inland plains and deserts, 3 cases (3, 10 and 16);

(d) Islands, 2 cases (13 and 17);

(e) Mountains, 2 cases (31 and 33);

(f) Delta, case 5.

## Geology

The ground-water reservoirs are located in unconsolidated clastic sediments: alluvium, diluvium, glacial drifts of Pleistocene-Quarternary age in most cases (with the exception of cases 6, 13, 16, 27, 28 and 33). Carbonate rock aquifers (dolomite, limestone chalk) are present in cases 3, 6, 25, 26, 27, 31 and 33. Sandstone aquifers are present in cases 3, 16, 25, 27 and 28. Volcanic rock aquifers are found in case 13.

## Reservoir capacity and hydrogeological conditions

The area extent of the ground-water reservoirs described here is quite diverse.

From less than 100 $km^2$ (cases 14, 29, 30, 32 and 34) to hundreds of thousands $km^2$. The thicknesses of the water-bearing layers are, on average 5-50 m or more in the alluvium, and sometimes much more in large sedimentary basins. The amount of water in storage is most often 100 to 1,000 million $m^3$.

The effective porosity of the aquifers is in most cases (and especially in alluvium) 5 to 10 per cent. Aquifers are mainly unconfined except in cases 13 and 16. Values of hydraulic conductivity are most often in the range of 10 to 100 m/day, to 500-1,000 m/day and above for highly transmissive, coarse alluvium and fractured limestones.

## Recharge and discharge of reservoirs

For nine cases (2, 5, 6, 8, 10, 11, 12, 18 and 31) the yearly replenishment is assessed at values exceeding 100 million $m^3$; and for four cases 1,000 million $m^3$ (cases 7, 13, 21 and 24). The discharge values are of the same order of magnitude. Discharge exceeds natural recharge in 18 cases (1, 2, 3, 5, 6, 10, 11, 12, 16, 18, 20, 21, 23, 24, 26, 27, 29 and 33); artificial or induced recharge is applied in all but seven cases (2, 7, 10, 13, 16, 28 and 33); that is, in 27 cases. These recharge projects or group of projects which are described, are located in industrialized countries with the exception of three cases (4, 25 and 27).

The integrated utilization of all water resources of the area is envisaged in case No. 2 while induced recharge is envisaged in cases 10 and 28. Ground-water reservoirs are irreversibly "mined" in case 16.

In addition to over-draught, one of the main problems is salt-water intrusion, encountered in eight cases (5, 13, 17, 25, 27, 28, 29 and 34).

## Utilization of water resources

The various types of users are as follows:

(a) Mainly city water supply and industrial needs (industrial users are underlined) 22 cases (1, 2, 3, 9, 11, 12, 15, 17, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 31, 32, 33 and 34);

(b) Mainly agriculture (irrigation, rural water supply, livestock), eight cases (4, 5, 7, 8, 10, 14, 16 and 19);

(c) Multipurpose (agriculture and human consumption) three cases (6, 13 and 18);

(d) Experimental, case 30.

## Conclusion

This over-all look at the 34 case studies presented here shows that ground-water reservoirs are widely distributed, varying in their characteristics and dimensions, but often of a great capacity. It also shows that in a number of cases, whatever the natural or human factors might be, they are being developed intensively to the best of their storage capacity through the utilization of artificial recharge or induced recharge schemes. It must, however, be kept in mind that these case studies are the result of a sampling and do not reflect the over-all situation in the world; the case studies apply to areas which have been carefully investigated owing to a shortage of water resources or to especially high demand. There are still large numbers of ground-water reservoirs in the world, especially in developing countries, which are still under-developed and/or not even investigated.

# BALTEZERS WATERWORKS, LATVIAN SOVIET SOCIALIST REPUBLIC*

The background information on the Baltezers Waterworks is as follows:

(a) Region: the Baltezers Waterworks supply water to the city of Riga, a major port on the Baltic Sea;

(b) Geography: glacial plains; the waterworks are located 18 km to the north-east of the city.

(c) Climate: temperate, humid, with relatively mild winters and cool and rainy summers. Average annual temperatures are -5°C. in January and +17°C. in June. Average yearly rainfall is 566 mm. The land is covered with snow from mid-December to mid-March.

(d) Reservoir type: Alluvium and moraine deposits.

## Ground-water reservoirs and utilization

Geological conditions in the region of the waterworks are characterized by alluvium deposits of fine and medium sands from 30 to 40 m thick, capping a low permeability horizon of loam moraine. Pine forests cover most of the area. The water-table is at a depth of from 6 to 8 m from the surface of the ground. Average values for hydraulic conductivity range from 30 to 50 m/day.

Since 1904, the natural ground-water flow has been utilized in the central water-supply system for the city of Riga. The ground-water flow is tapped by means of a battery-line of bore-holes connected to a siphon pipeline. The growing requirements for the rapidly expanding city have resulted in over-draught, with a discharge greatly exceeding natural replenishment. A deep and expanding cone of depression developed in the piezometric surface, threatening to put the siphon pipeline out of action.

## Artificial recharge

In order to restore the ground-water level in the area of the cone of depression, and to increase the output of the waterworks, an artificial replenishment scheme using recharge basins was begun in 1952. Seventeen infiltration basins with a total area of 120,000 $m^2$ were constructed in the vicinity of the waterworks. The dimensions of the basins are: length, 200-400 m; width at the bottom, 15-25 m; depth 1.5-2.5 m. The basins are located about 180-200 m from the line of tube-wells.

Up to 90,000 $m^3$ of water from Little Baltezers Lake are daily pumped into the spreading basins. A system of canals connects the lakes and the rivers. River water is brought to Lake Baltezers, which acts as a natural sedimentation basin. The

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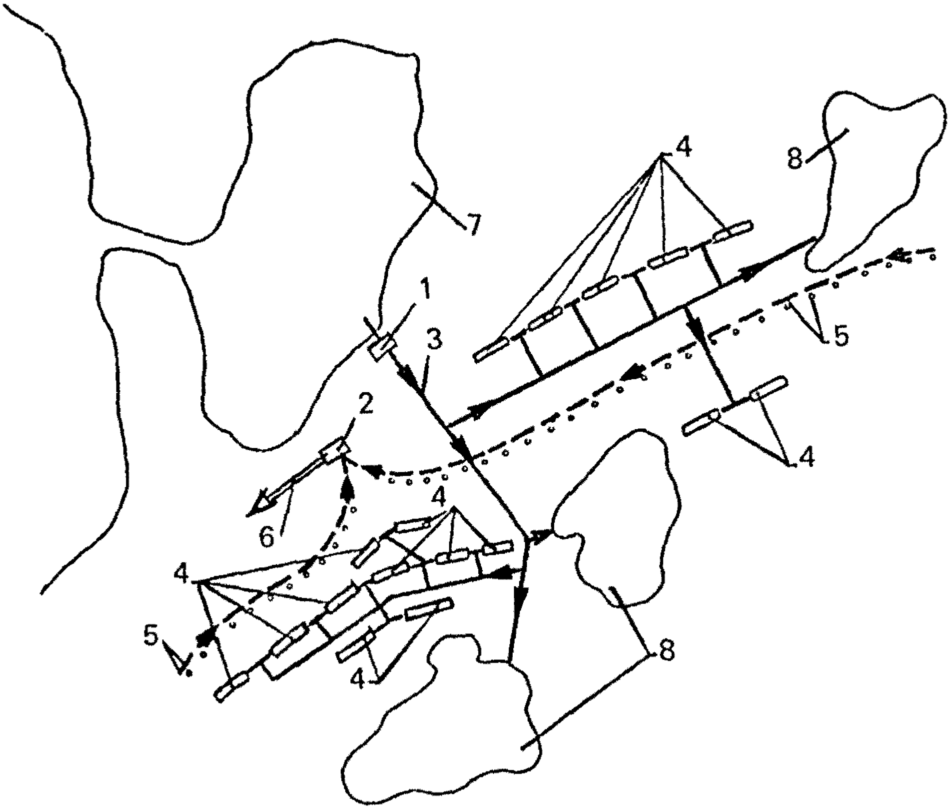
* Case study No. 1 prepared by V. Kunin (Union of Soviet Socialist Republics).

Figure 9. Plan of the Baltezers waterworks, Latvian Soviet Socialist Republic



Legend

1. Pumping station for lake water
2. Pumping station for ground water
3. Pipelines for lake water
4. Infiltration basins
5. Bore-holes and siphon pipeline
6. Pressure water-pipe for ground water
7. Source of raw water
8. Small lakes

artificial replenishment is done throughout most of the year. There is a cyclical exploitation of the basins. Once or twice a year a caterpillar tractor is used to clean the basins. The average infiltration rate is 0.7-1.0 m/day. The basins are filled gradually for an entire cycle.

Over the years, artificial replenishment restored water levels to original altitudes in the area of the cone of depression, and higher in the region of replenishment. The output of the tube-wells increased and reached 80,000 $m^3$ per day.

Lake waters, as compared with natural ground water, have greater colouring (40°); oxidation by permanganate is eight parts per million (ppm); turbidity, 3-8 mg (average indexes). Ionic content in the lake water is similar to that found in natural ground water, except for chlorides. Water quality is improved as it flows from the spreading basins to the bore-holes. The following changes take place in the water as this flow occurs:

(a) Nearly complete retention of suspended matter;

(b) Disinfection of the water;

(c) Decrease in colour;

(d) Diminishing of oxidation by 3-4 times;

(e) Equalizing of concentration of chlorides and temperature.

The infiltration installations have operated excellently for the past 20 years. No lowering of water quality has been observed, except for increasing oxidation by permanganate from 1.5 to 4.0 mg/l during the first four years of the exploitation of the installations. Water quality data are shown in table 9.

Table 9. Water quality data

| Indexes | Unit of measure | Little Baltezers Lake | Ground water | |
|---|---|---|---|---|
| | | | Artificial | Natural |
| Colour | Cobalt scale° | 40 | 15 | 9 |
| Turbidity | mg/l | 3-8 | - | - |
| Odour | 0 | 0 | 0 | 0 |
| Oxidation $O_2$ ($KMnO_4$) | mg/l | 7.83 | 3.44 | 1.37 |
| Hardness - total | $\frac{\text{mg-equ}}{l}$ | 4.88 | 4.70 | 2.23 |
| pH | - | 7.84 | 7.51 | 7.79 |
| Cl | ppm | 90 | 82 | 6-7 |

# BARCELONA AREA, SPAIN*

The background information on the Barcelona area project is as follows:

(a) Region: Mediterranean;

(b) Geography: coastal plain dominated by the Pyrenees on the north and highlands of the Mediterranean coastal system to the west;

(c) Climate: Mediterranean; mild in the coastal region, cold in the mountains. The average rainfall on the over-all drainage basin is 750 mm, varying geographically from 400 to 2,000 mm. Rainy seasons are spring and autumn. Average annual temperature is 16°C in the coastal region, 9°C in the high mountains;

(d) Reservoir type: deltaic sediments of the Besos and Llobregat rivers, underlain by older sediments of the coastal platform;

(e) Methods of investigation: geological mapping and investigation; electrical resistivity inventory of wells (250 soundings); drilling (70 bore-holes totalling 12,200 m); installation of 110 piezometers; water sampling for chemical analysis; tritium dating; observation of water levels and pumping tests.

## Ground-water reservoirs

The coastal platform is formed by upper Tertiary sediments covered by deltaic sediments.

The principal aquifers are Quaternary gravel and sand. The main aquifers are unconfined but, locally, towards the sea, impermeable interbeds confine ground water. In the Barcelona area two aquifers are found: the upper one is unconfined and the lower confined. A sandstone aquifer in the Tertiary is of lesser importance.

The Llobregat delta is about 10 x 20 km = 200 $km^2$. Aquifer thickness is about 20 m. With respect to the deep aquifer of the Llobregat delta, hydraulic conductivity ($\underline{K}$) varies from 25 to 250 m/day; the transmissivity coefficient ($\underline{T}$) varies from 500 to 5,000+ $m^2$/day, being highest in the central part. The average specific yield of the upper aquifer is form 20 to 30 per cent. Water-quality has deteriorated in past decades and the quality of river water is also deteriorating. Sea-water intrusion is a problem.

Natural recharge is from the rivers and from precipitation. Recharge during floods of 1 million $m^3$/day has been estimated. Total recharge to the Llobregat delta ground-water reservoir varies from 60 to 250 x $10^6$ $m^3$/year. Water moves from the upper to the lower aquifer at a rate of from 30 x $10^6$ to 60 x $10^6$ $m^3$/year. In 1958 total discharge through wells was about 30 x $10^6$, but by 1967 it had increased to 50 x $10^6$ $m^3$/year. Estimated natural discharge to the sea is 5 x $10^6$ $m^3$/year. Water balance for both ground water and surface water has been achieved for the period 1958-1967.

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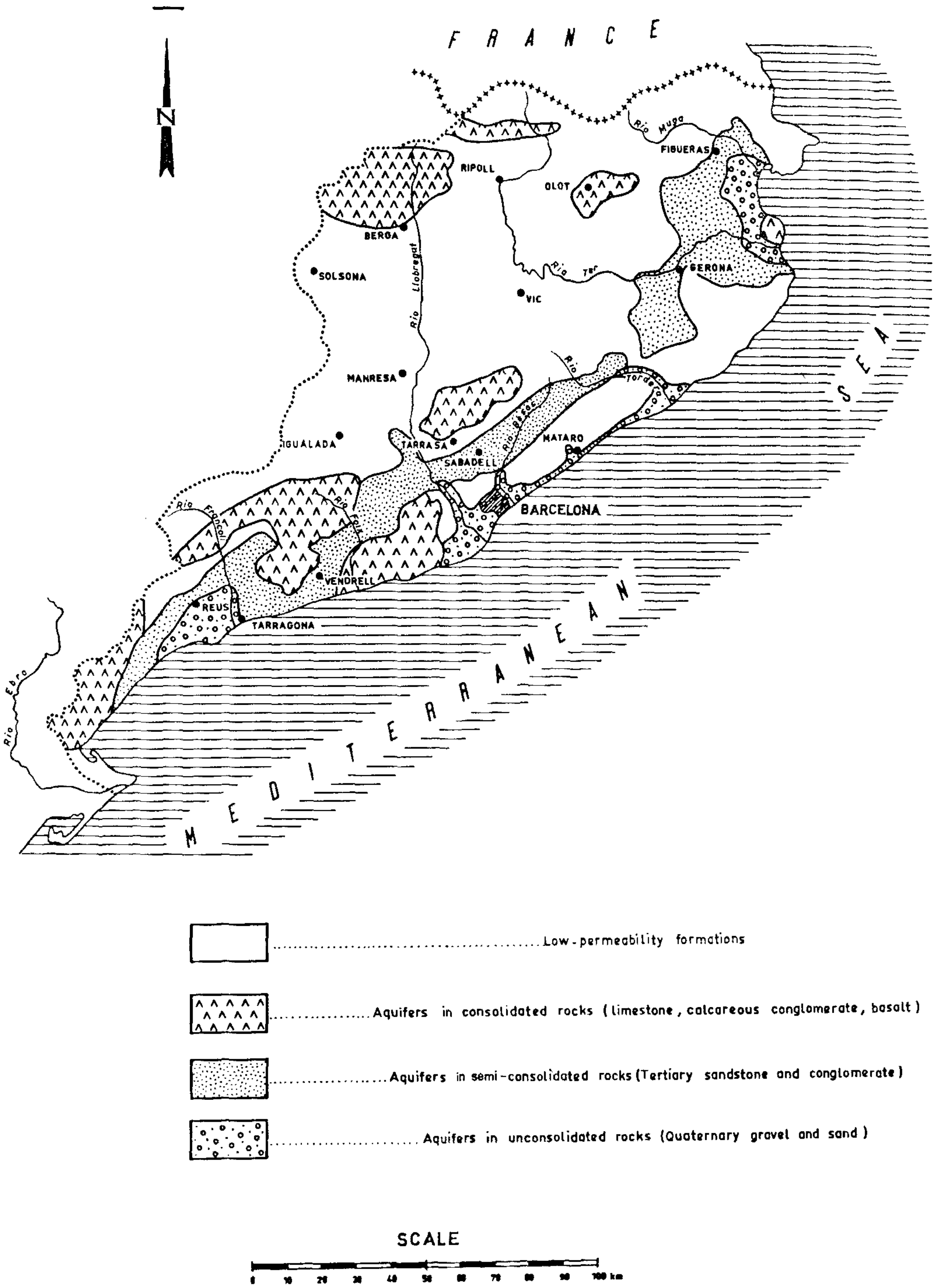
* Case study No. 2 prepared by R. De Wiest (United States of America).

## BARCELONA AREA, SPAIN

FIGURE 10



CASE STUDY Nº 2

## Utilization of ground water

As previously mentioned, utilization of ground water for Barcelona is continually increasing. Ground water is used for both human and irrigation purposes. Surface water is also utilized for the city.

The major problems are:

(a) Water levels in the deep aquifers have lowered from 7 m above sea level in 1900 to 20 m below sea level in 1958;

(b) It is presently estimated that the water demand of the Barcelona region will exceed the supply in 1985;

(c) Water quality is deteriorating;

(d) Spanish water law, making ground water a private asset belonging to the landowner, is a serious problem with respect to operation and management;

(e) Knowledge of hydrogeological conditions is insufficient.

It is proposed to use surface reservoirs to retain floods and conserve run-off, which now unnecessarily wastes into the sea. Ground-water reservoirs would be utilized to receive and store excess surface water, utilizing artificial recharge, if necessary. It is proposed that the ground-water reservoirs situated close to the centres of demand would be used for annual control, covering low seasonal flows and the consumption peaks. Detailed studies by means of mathematical or/and analogue models are recommended.

References:

Llamas and Molist, Hydrology of the deltas of the rivers Besos and Llobregat. *Agua*, 1967.

Vilaro and Martin, Hydrologic balance of the Llobregat basin. Madrid, 1968.

# BASEL RECHARGE SCHEME, SWITZERLAND*

The background information on the Basel recharge scheme is as follows:

(a) Region: Birsfelden, near Basel;

(b) Geography: plain of fluvio-glacial alluvium, crossed by the Rhine River, upstream from the urban area of Basel;

(c) Climate: temperate, humid;

(d) Reservoir type: glacial gravel and sands.

## Ground-water reservoirs

The geological cross section is characterized by a layer of fluvio-glacial gravel carried by the Rhine River and deposited in a vast alluvial plain; and by a substratum composed of limestones and fissured Middle Triasic sandstones.

The aquifer is 50 m thick with an average horizontal permeability coefficient of 340 m/day. Ground-water flow (before artificial recharge) is 100 l/sec.

The waters utilized for artificial replenishment originate from the Rhine. They are pumped by the Steinholzli station, up-stream from Basel. Water characteristics are given in the following table:

| | |
|---|---|
| pH | 7.85 |
| Nitrates, ppm | 3 |
| Chlorides, ppm | 10.5 |
| Sulphates, ppm | 48 |
| Total hardness | 17.75 (French degrees) |
| Oxygen saturation | 95 per cent |
| Suspended matter | Less than 20 ppm in general;<br>Almost always less than 100 ppm |

Precipitation takes place in the watershed; replenishment is by the waters of the Rhine during flood periods. The ground water moves towards the river which, in general, acts as a drainage system. The flow of discharge is towards the Rhine River; exploitation is accomplished through pumping. Due to over-draught, a deficit of ground water has appeared. The resources of the aquifers are estimated at 2 x $10^6$ $m^3$/year.

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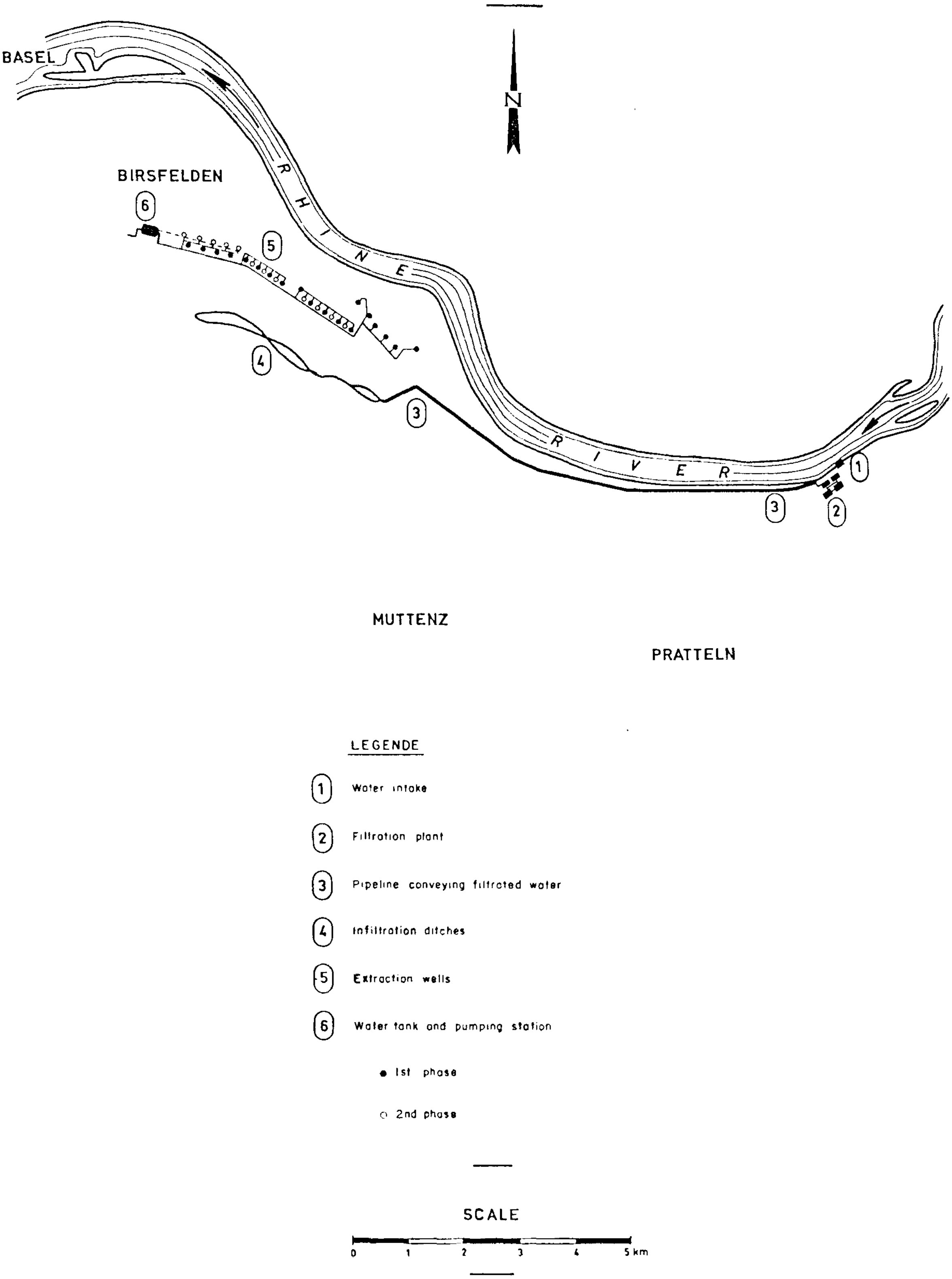
* Case study No. 3 prepared by G. Castany (France).

FIGURE 11

# BASEL RECHARGE SCHEME, SWITZERLAND



CASE STUDY Nº 3

## Artificial recharge

The principal use of ground water is as a municipal supply for Basel. The resources of the alluvial aquifer of the Wiese River, which, until 1956, supplied the city of Basel, were insufficient during drought periods. It was therefore decided to exploit the Hard aquifer by increasing its resources by an artificial recharge scheme, utilizing the waters of the Rhine. The recharge site was created in 1955, and has been in use since 1957.

The waters of the Rhine pass over fast filters which reduce the suspended solid contents to 0.3 ppm. It then flows into infiltration ditches located on the right bank of the river at approximately 2 km distance. The water is pumped into wells located between the injection ditches and the river, approximately 500 m distant from the ditches. It is distributed without treatment.

The first phase of the construction permits infiltration of $45 \times 10^6$ $m^3$/year, or 1.5 $m^3$/sec. A second phase, now under construction, will increase infiltration to $65 \times 10^6$ $m^3$/year.

In fact, the actual output during pumping is from 30 to 40 per cent of the total, the difference being reserved to maintain the piezometric level above the level of the waters of the Rhine, to prevent the infiltration of poor-quality water from the river. The intake is located up-stream of Basel, where the water is relatively good; but the pumping installations down-stream, are in a zone where the waters of the river are highly polluted.

In 1965, of $30 \times 10^6$ $m^3$ injected, $16 \times 10^6$ $m^3$ could be recovered ($18 \times 10^6$ in 1967). The installation functions as a continuous process. However, if the pollution of the raw water exceeds established limits, it would be possible to stop the infiltration temporarily, with the ground-water reserve acting as a regulating system.

The water of the Rhine is raised 18 m in the filtering station, which has two systems of fast filters, each including 10 basins of 50 $m^2$. Water is brought into the infiltration basins by means of a pipeline 3.5 km long, with a diameter of 1.25 m. The infiltration basins, which will reach a length of 5 km over a width of 2 km, are covered by a layer of sand on the bottom. To protect the site, all 26 pumping stations are buried.

The cost of installation and equipment, as of 31 December 1965, was $US 4.4 million; the cost of 1 $m^3$ of pumped water (everything included) is $US 0.024; the average sale price to private users is $US 0.05/$m^3$ (taking into account the maintenance and operation costs of the distribution system).

### References:

Bize, J. et L. Bourguet, Le prix de revient de l'eau dans trois aménagements d'alimentation artificielle. Techniques et sciences municipales (Paris), 3:115-117, 1968.

Casati, A. Les ouvrages de réalimentation de la nappe souterraine de la Hard. Techniques et sciences municipales (Paris), dec. 1961.

# BISKRA ALLUVIAL VALLEY, ALGERIA*

The background information for the Biskra alluvial valley is as follows:

(a) Region: Algeria, edges of the Sahara;

(b) Geography: alluvial valley;

(c) Climate: semi-arid; rainfall, 250-400 mm. Most of the rain occurs during autumn and winter;

(d) Reservoir type: alluvial fill;

(e) Methods of investigation: electric analogue - model study.

## Ground-water reservoirs and utilization

The valley is filled by alluvial deposits of a seasonal ephemeral stream. The material is generally coarse. The principal aquifer is an unconfined alluvial deposit. The boundaries of the aquifer are well-defined. Its surface area is 5 km$^2$ and its thickness ranges from 30 to 40 m. Recharge proceeds through direct infiltration of flood waters, which occurs just a few days each year. The conditions of stream-flow in the valley are variable; the river-bed is dry during the hot seasons.

The depth of the aquifer to the water-table is 4-10 m; transmissivity coefficient (T) is 1,700 m$^2$/day; hydraulic conductivity coefficient (K) is 40 m/day; effective porosity is 20-30 per cent; total storage availability is 20-30 million m$^3$. Yearly discharge in the form of pumping and underflow is approximately 11 million m$^3$.

The pattern of pumping has increased annual recharge by 5 million m$^3$. This pattern has regularized the flow that is available for exploitation. The effect is the same as having a surface reservoir for water supply. The problem of further inducement of recharge remains.

The optimum exploitation of the aquifer has been determined through an electric analogue - model study which matches the fluctuation of the piezometric surface with the regimen of the floods. It has been shown that the daily rate of infiltration fluctuates from 3 to 5 cm, depending upon the period of the year and the amount of flood waters. The rate represents the effective infiltration ratio recharging the aquifer, and incorporated into the zone of saturation.

References:

Tixeront, J. et J. M. Daniel. Alimentation et suralimentation des nappes souterraines. Observations d'un cas de suralimentation par pompage; l'oued Biskra (Algerie), Haifa, International Association of Scientific Hydrology, 72:177-178, 1967.

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* Case study No. 4 prepared by G. Castany (France).

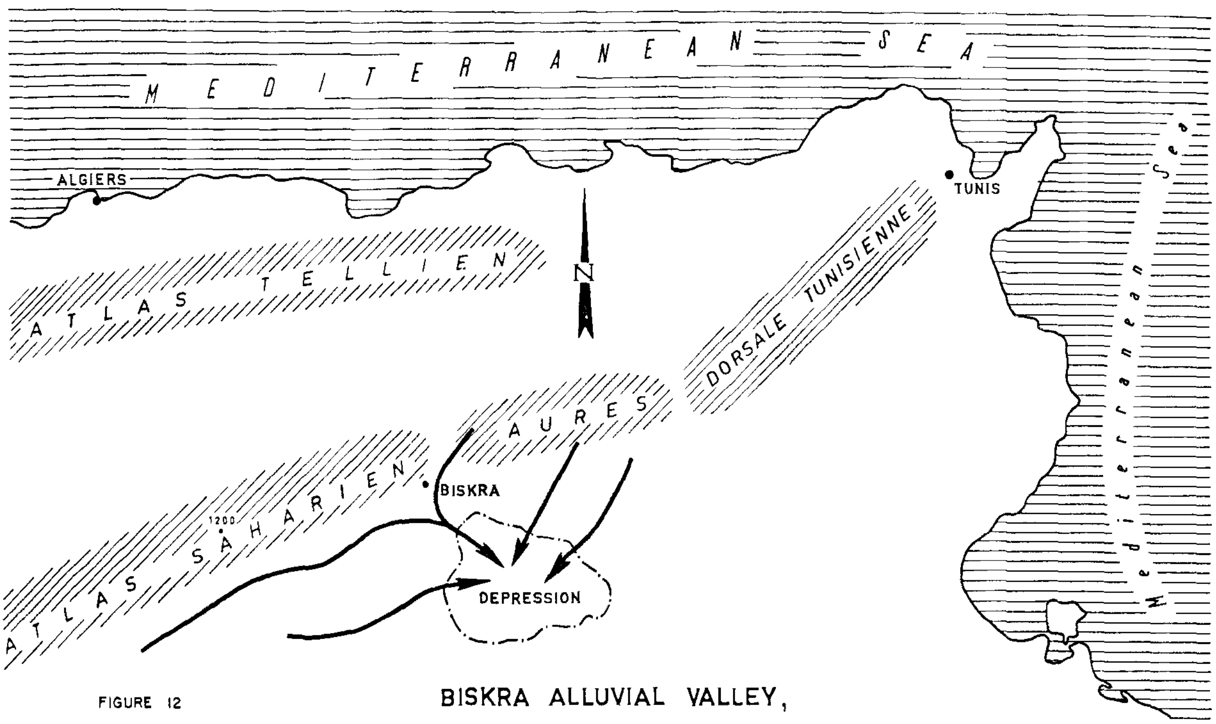
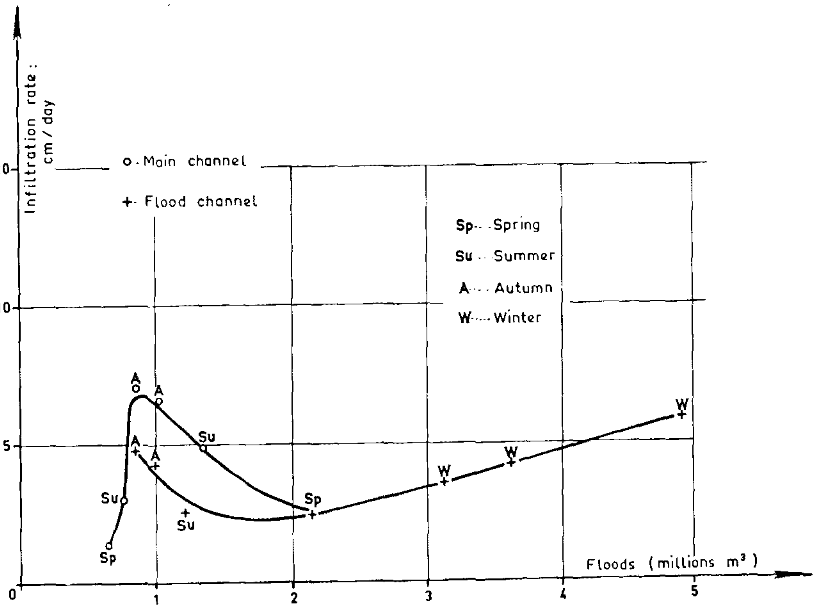


FIGURE 12

BISKRA ALLUVIAL VALLEY, ALGERIA

SCALE



CASE STUDY No 4

# BURDEKIN DELTA, AUSTRALIA*

The background information for the Burdekin delta is as follows:

(a) Region: eastern coast of Queensland;

(b) Geography: delta with many river channels;

(c) Climate: temperature ranges are 21°-32°C in summer; 12°-27°C in winter; rains occur mainly in summer with a 76-year rainfall average of 1,070 mm (930 mm for December-April). The average maximum is 2,450 mm; the average minimum is 100 mm;

(d) Reservoir type: alluvial deposits;

(e) Methods of investigation: 150 bore-holes, totalling 4,000 m, have been drilled since 1959; bi-monthly measurements of water levels; geophysical survey.

## Ground-water reservoirs

Geological conditions are characterized by deltaic sediments resting on an old granitic surface. The aquifer is of coarse sands (one third of total alluvium thickness 15 to 45 m above bed-rock) with lenticular clayey horizons. Average hydraulic conductivity is 300 m/day; storage coefficient rises to 0.21, with an average of 0.16. With respect to water quality, electric conductivity does not exceed 1,000 micromhos/cm at 25°C. Sea-water intrusion occurs near the coast and tidal reaches.

Annual river flow at Home Hill station is $10^6$ $m^3$. The maximum flow is $28 \times 10^3$ and the minimum is $0.15 \times 10^3$. The mean flow is $9 \times 10^3$ and the median is $7.5 \times 10^3$. The average recharge is expressed by a rise of the water levels of approximately 1.50 m.

Artificial recharge has been planned and experiments have been conducted. Absorption rates were tested and a rate of 100 l/sec/km was adopted for natural channels with a view of achieving a 3-m head of water above standing water-level. The same rate was adopted for artificial channels 7 m wide. The rate would be 350 l/s/km for sand-filled trenches.

In 1963, $250 \times 10^6$ $m^3$ were extracted, exceeding the long-term safe yields of $175 \times 10^6$ $m^3$ for an 8-year period and $210 \times 10^6$ $m^3$ for a 32-year period. The fresh-water flow along 40 km of coast, which is necessary to maintain the salt-water wedge in equilibrium, is about 140 l/sec, or 4.5 million $m^3$/year. Average annual deficiencies of the ground-water balence range from $100 \times 10^6$ (long-term) to $150 \times 10^6$ $m^3$ (short-term).

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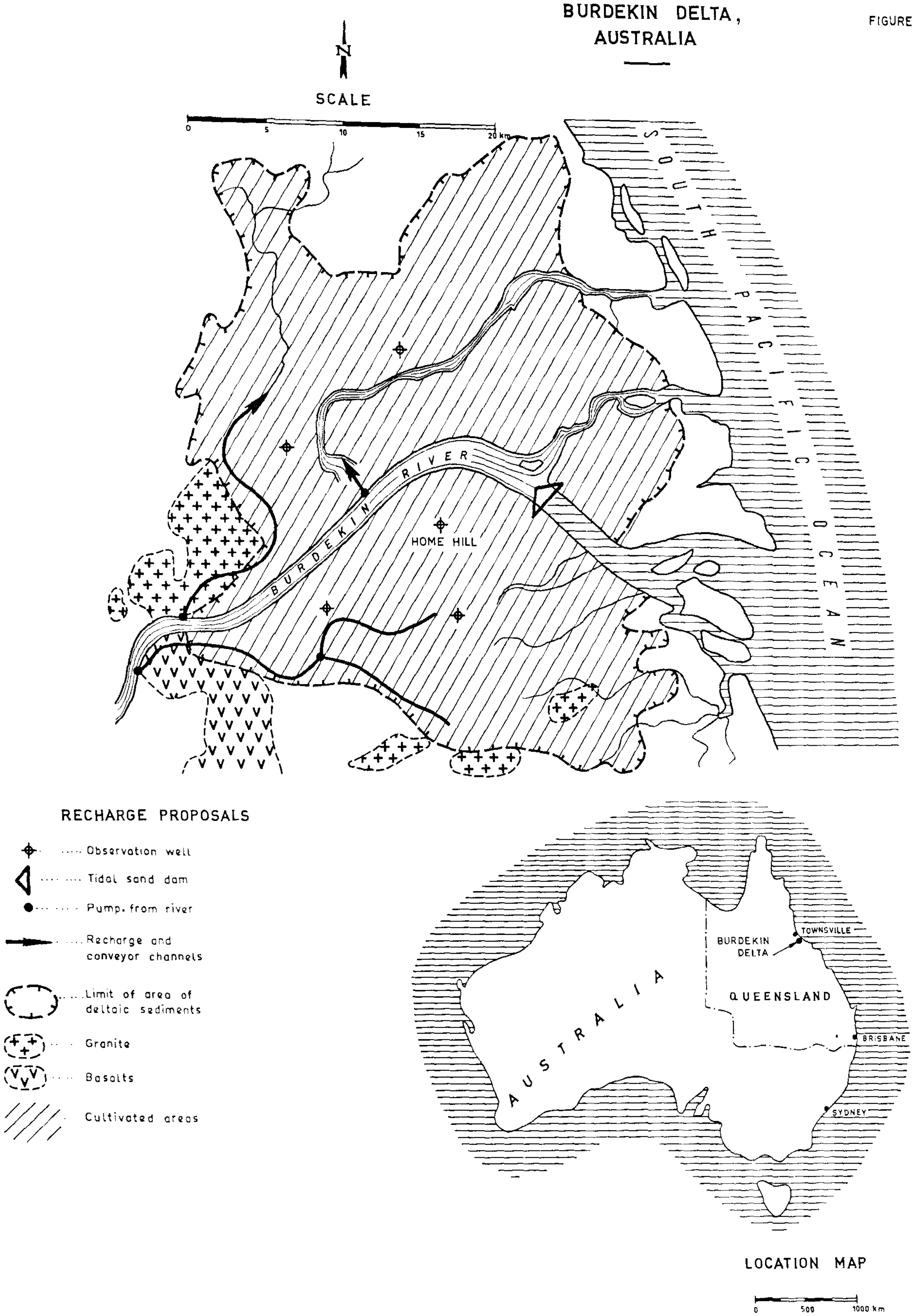
* Case study No. 5 prepared by R. De Wiest (United States of America).

FIGURE 13

# BURDEKIN DELTA, AUSTRALIA



CASE STUDY Nº 5

## Utilization of ground water

Shallow ground water is pumped for sugar-cane irrigation, with 17,500 ha irrigated in 1955, and 21,500 in 1964. Recharge is operated by three pumping units, each of 800 l/sec capacity.

Sea-water intrusion and overdraught have occurred as have low water-levels in the south-west. The solutions proposed are: diversion of run-off from catchments adjacent to the delta; recharge mound to exclude salt water; pumped diversion of the flow of the Burdekin River into natural and artificial channels; and construction of weirs on the tidal inlets. The results of the first recharge operations are not yet known. The methods used to determine the mound of artificial replenishment required will be applied to other coastal aquifer systems.

## References:

O'Shea, J. A. The water resources of the Burdekin delta. Washington Water for Peace Conference, 1967.

# COASTAL PLAIN AQUIFER, ISRAEL*

The background information for the coastal plain aquifer is as follows:

(a) Region: eastern shore of the Mediterranean Sea;

(b) Geography: the coastal plain is a gently inclined, undulating area which rises from the shores of the Mediterranean to maximum elevations of about 80 m above sea level at a distance of 15-20 km from the coast, and is bounded on the east by the foot-hills of the mountains of Judea and Samaria. The northern boundary of the coastal plain is formed by a promontory of the Carmel Mountain in the south. The Shiqma River may be taken as the southern boundary because from here southward climatic and hydrological conditions become semi-desertic. A number of rivers with very erratic, short periods of flow cross the plain from east to west. The only perennial river, the Yarkon near Tel Aviv, divides the coastal plain into northern and southern parts;

(c) Climate: semi-arid, Mediterranean type. Rainfall occurs only during the winter (October-April) and averages about 550 mm/year in the northern part and from 400 to 500 mm/year in the southern part;

(d) Reservoir type: sedimentary; calcareous sand and sandstone and intercalated marly strata deposited in a littoral environment;

(e) Methods of investigation: the geology is known in great detail from hundreds of exploitation and observation bore-holes. Water levels and the salt-fresh-water contact are monitored by means of an extensive network of observation bore-holes. Quantitative investigations were carried out with the aid of mathematical techniques and analogue models.

## Ground-water reservoirs

The aquifer is composed of littoral-marine calcareous sands, calcareous sandstones and intercalated layers and lenses of marly loams, all of Pleistocene age. It has a maximum thickness of 130 m at the sea shore and wedges out at the foot-hills in the east.

The aquifer is underlain by a layer of blue-black shales several hundred metres thick, probably of Neogene age. Near the eastern part of the aquifer boundary, the shales are replaced by chalky-marly formations of Senonian-Eocene age. The aquifer and the underlying shales present no recognizable tectonic features.

The thickness of the aquifer near the coast is about 130 m. At a distance of about 10 km from the shore it is 80-100 m thick and further east it rapidly wedges out. The effective thickness of the aquifers is about 25 per cent less than the above geometric thickness, owing to the intercalated semi-pervious to impervious marly strata.

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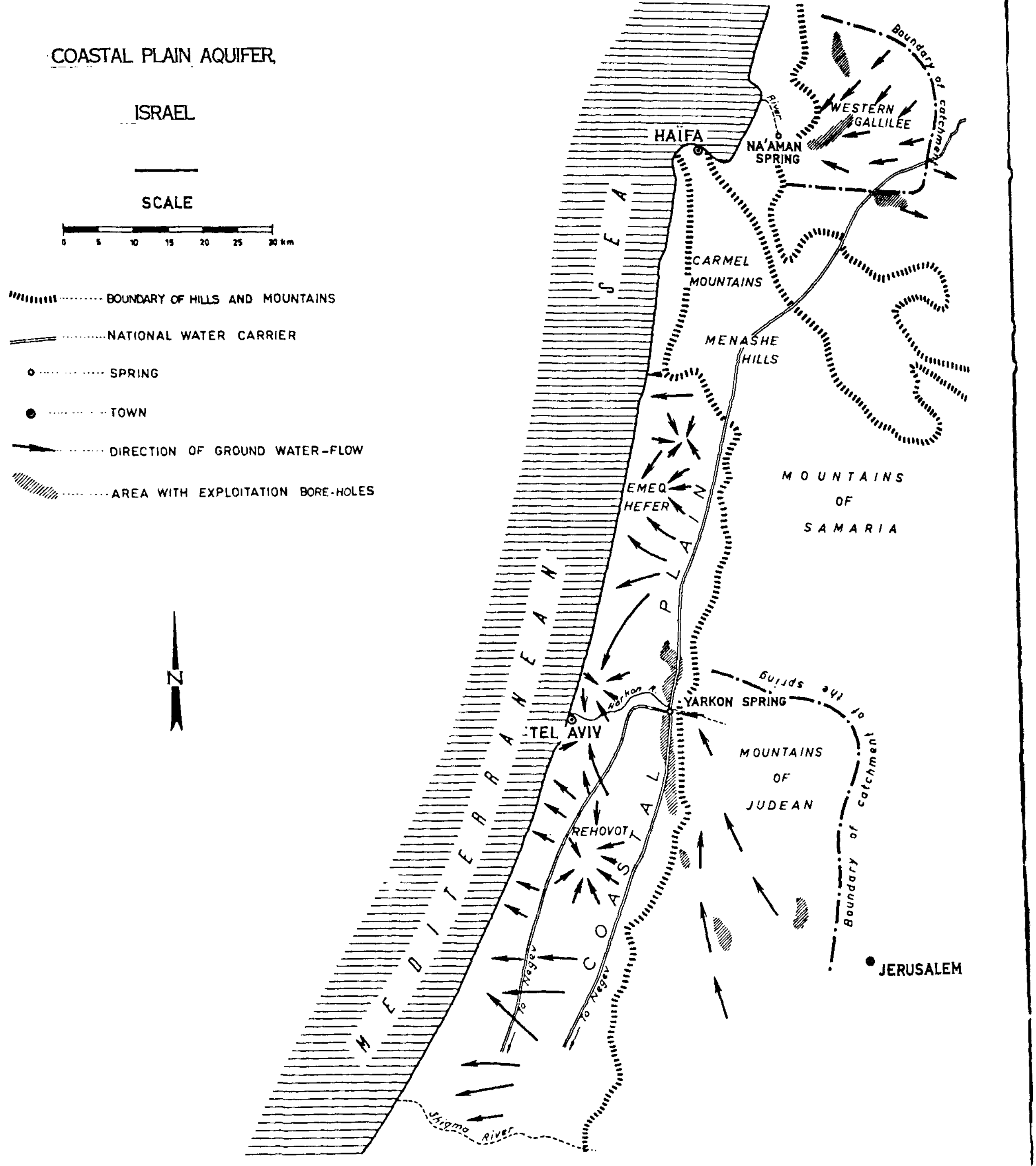
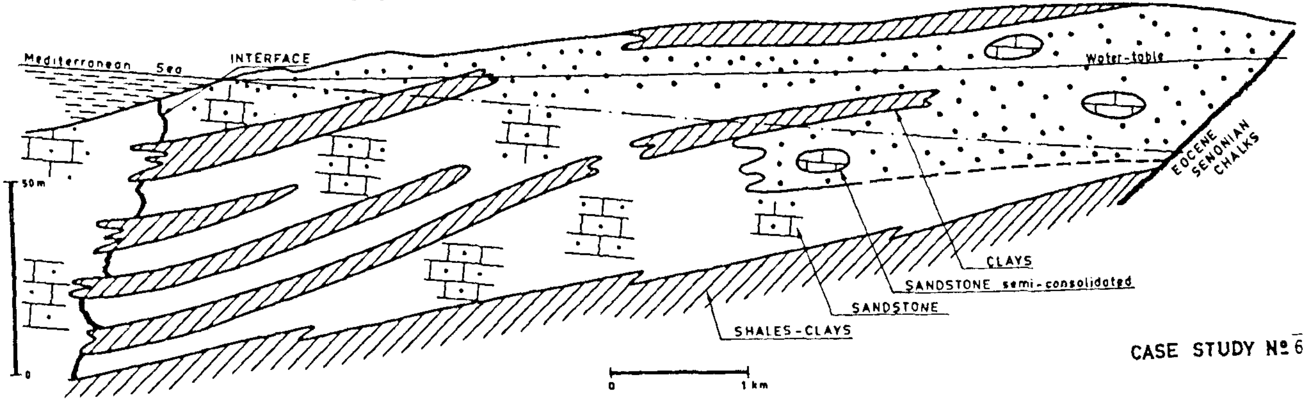
* Case study No. 6 prepared by S. Mandel (Israel).

FIGURE 14

## COASTAL PLAIN AQUIFER, ISRAEL



## COASTAL PLAIN OF ISRAEL - SCHEMATIC CROSS-SECTION



CASE STUDY No 6

Transmissivity of the aquifer is 1,000-4,000 $m^2$/day near the coast and only 100-500 $m^2$/day at the eastern edge. Its specific yield is 15-20 per cent. The aquifer stores 20 x $10^6$ $m^3$/sq km near the coast; 10 x $10^6$ $m^3$/sq km at 10 km inland. Water quality is mainly in the range between 120 and 300 ppm. Total dissolved solids (TDS) is 50-130 ppm Chlor-Ion.

The aquifer is replenished by rainfall over the coastal plain and, to a small extent, by seepage from the seasonal rivers traversing the plain.

The aquifer discharges into the Mediterranean Sea in the west; only a few very minor springs and swamps near the coast indicate ground-water drainage to the surface. In the natural state, ground-water level contour lines ran parallel to the coast; i.e., natural flow-lines were perpendicular to the sea coast. Natural replenishment has been determined to be about 230 x $10^6$ $m^3$/year, on the average. In the natural state, about 2 x $10^6$ $m^3$/year of water discharge into the sea through each kilometre of coastline.

The aquifer underlies one of the most fertile and most densely settled regions of Israel. Its exploitation amounted to only about 60 x $10^6$ $m^3$/year in 1948, but increased by leaps and bounds in the succeeding years, and reached 480 x $10^6$ $m^3$/year in 1962. This represents about 45 per cent of the total amount of water used throughout the country in that year, and exceeds the estimated safe yield, about 190 x $10^6$ $m^3$/year, by a factor of 2.5. Over-exploitation caused a very marked lowering of the water levels, which were depressed below sea level in some areas. From 1963 onwards, water from the Jordan River was imported into the region and the hydrological situation has now stabilized at a safe level.

## Utilization of ground water

The aquifer is exploited by several hundred bore-holes with average yields of 250-350 $m^3$/h. The bore-holes operate from 2,500 to 3,500 h/year, mainly during the summer months (June-September).

The impervious bottom of the aquifer, which ascends towards the east, is relied upon to control sea-water intrusion. It is intended to keep the ground-water levels sufficiently high at a distance of 2-3 km from the coast, so that sea water cannot intrude above the impervious bottom further inland. Between this line and the coast, withdrawals by means of shallow bore-holes are rigidly controlled. A scheme to this effect, the "coastal collector", is in the pilot-plant stage.

Apart from its function as a source of water, the aquifer is also used as a storage reservoir for flood water from rivers, and as a storage reservoir for water from the Jordan River conduit. Management of the aquifer is greatly aided by the network of observation bore-holes. Furthermore, pumpage is gauged and strictly supervised by law.

Most of the bore-holes are owned and operated by Mekoroth Water Co. Ltd., which supplies water for farm irrigation at about $0.04 per $m^3$ (calculated at the 1971 rate of exchange). The price of urban water supply is determined by the municipalities and varies considerably from place to place.

In towns, water rates follow a sliding scale. The quantity which is considered basic is supplied to each household at a low rate, while consumption in excess of this quantity obliges the user to pay much more.

The high cost of water, the sliding rate scale in towns and a vigorous campaign of educating the public has led to a remarkable reduction of water-demand per unit of irrigated area and per capita, without adverse effects of productivity or the standard of living.

## Artificial recharge schemes

The purposes of the replenishment of the aquifer by water from the Jordan River are as follows:

(a) Restoration of safe ground-water levels in the coastal aquifer;

(b) Long years of storage of water from the Jordan River, the yield of which changes very erratically from year to year. The storage capacity of Lake Tiberias is insufficient to regulate these fluctuations and, therefore, underground storage must be utilized;

(c) Seasonal storage. During winter, in addition to the natural replenishment, the aquifer is artificially replenished with water from Lake Tiberias so that it can be more heavily exploited during summer.

The operation of the system is described below.

Water from Lake Tiberias is conveyed to the central and southern parts of the country by the National Water Carrier. This pipeline is connected with most of the bore-holes by means of a network of subsidiary lines. All the water in the National Carrier is pre-treated and is of potable quality.

The extraction wells are also used during winter for recharging. The wells are 80-120 m deep; their specific discharge is about 50 $m^3/h/m$ of drawdown. For extraction purposes, they are operated with yields of 200-300 $m^3/h$. The lower parts of the wells consist only of slotted pipes, which are put opposite the more consolidated parts of the aquifer. No gravel packs or other special filter elements are installed. A small part of artificial replenishment is carried out through improvised spreading-grounds. During winter and spring, 1968/69, 31 bore-holes and three spreading-grounds were used for artificial replenishment of water from the Jordan; 62 x $10^6$ $m^3$ were recharged through bore-holes, and 5 x $10^6$ $m^3$ through spreading-grounds.

A bacterial slime forms on the well face and greatly impairs the efficiency of operations after about one month of uninterrupted injection. It was found that a few hours of pumping cleans the well-face and restores the capacity of the bore-hole. The water which is pumped during these short cleaning periods is dark and smelly, and must be discarded.

The estimated cost of injecting Jordan River water into bore-holes is $0.015/m^3 (at the 1971 rate of exchange). This estimate mainly reflects the cost of energy and manpower for supervision, since only small items of installation were constructed specifically for injection purposes.

Operations are carried out by Mekoroth Water Co. Ltd., within the framework of the water laws of Israel.

Because this is one of the major tools for the management of the water resources of Israel, operations will be continued and expanded. Additional chlorination may be required to combat clogging.

## Artificial replenishment in the area of Emeq Hefer

Emeq Hefer (Hefer Valley) is situated about 40 km north of Tel Aviv and covers an area of about 110 sq km. The permissible annual yield of ground water from the aquifer of the coastal plain in this region is about 15 x $10^6$ $m^3$/year. The area is intensively cultivated and its water requirements greatly exceed this quantity. During the late 1950s about 40 x $10^6$ $m^3$ of ground water were pumped annually from the aquifer. As a consequence, the water levels declined sharply and sea-water intrusion became critical. A pipeline was constructed conveying additional water supplies from an aquifer of Cretaceous limestone situated 15 km to the east of Emeq Hefer. This water is used partly for irrigation and, during the winter, partly for artificial replenishment.

The purpose of artificial replenishment was:

(a) To restore acceptable hydrological conditions in the aquifer; (b) to utilize the coastal aquifer as a seasonal storage reservoir, so that larger quantities can be pumped from it during summer; (c) to optimize operation of the regional water-supply system.

At first, existing exploitation bore-holes were used for injection. Later on, owing to legal difficulties with the private well-owners, several special injection bore-holes were added. Currently, recharge is carried out in nine bore-holes operating at an approximate recharge rate of 220 $m^3$/h/bore-hole. In 1965/66, recharge operations reached a peak of almost 10 x $10^6$ $m^3$, and they have been continued on a reduced scale since then.

The scheme works satisfactorily, as long as clean ground water from the Cretaceous aquifer is used for injection. Trial runs with water from the Jordan River produced clogging effects by bacterial growths on the face of the well. The cost of injecting water amounts to about $US 0.02/$m^3$. Operations are carried out by Mekoroth Water Co. Ltd. Private well-owners, who benefit from the operations, are billed for injected water. The scheme will be continued.

## Elimination of sea-water intrusion in the Tel Aviv area

Greater Tel Aviv is a densely populated area extending over about 100 sq km. Until 1958, its water supply depended solely on local wells exploiting the Pleistocene aquifer. The permissible yield, about 17 x $10^6$ $m^3$/year, was exceeded in the early 1950s and withdrawals reached more than 80 x $10^6$ $m^3$ in 1957/58. A deep cone of depression formed and sea water intruded to a distance of 2.4 km from the sea coast, putting many wells out of action. From 1959 to 1964, exploitation was reduced and water was imported to satisfy the requirements of the area. While the cone of depression created by the excessive pumpage slowly filled up, sea water continued to move inland.

The purpose of the project was to build a temporary fresh-water barrier to check the advance of sea water until the water levels further inland recover sufficiently. Water from the line of the Jordan River was injected into 22 city wells parallel to the shore line and at distances of 1.5-3 km east of it. Later on, additional wells were drilled, especially for recharge to the bottom of the aquifer. About 140 x $10^6$ $m^3$ were recharged in this way during the years 1964-1966. Observations showed that the advance of the zone of diffusion was checked during the winter, while during the summer a slow eastward movement was still recognizable. The scale of operations was then reduced and they will be discontinued in the near future, because, in the former cones of depression, water levels have now approached the calculated safe conditions.

Work in a densely built-up area presented the usual engineering problems. It was difficult to maintain the required rates of injection in each bore-hole and, simultaneously, to maintain the regular urban water supply from the same network. The water of the Jordan River used for injection caused clogging by bacterial growths and the capacity of the wells had to be reconstituted by short pumping periods.

## Artificial replenishment by surface water from the Shiqma River

The Shiqma River forms the southern boundary of the coastal plain. It drains an area of 734 sq km with an average annual rainfall of about 350 mm/year. The river is in flood only during a few days each winter and dry the rest of the time. Several completely dry years are on record. An average flow of 7 x $10^6$ $m^3$/year may be taken as an indicative value of the river flow.

Good sites for surface storage cannot be found on the river and evaporation losses from an open water-surface would, in any case, greatly impair their efficiency. Ground-water storage is the only way to utilize the flash floods. A storage reservoir with a capacity of 2.8 x $10^6$ $m^3$ holds the flood and also serves as settling pond.

A pumping station with a capacity of 10,000 $m^3$/h conveys the water through a 48-inch pipeline and conveyance channel over a distance of 3,000 m to spreading-grounds covering an area of about 40 ha, situated on sand dunes at an elevation of about 10 m above the reservoir. The spreading-grounds have a capacity of about 800,000 $m^3$ of water. Infiltration rates are about 1,000 mm/day at the start of each season, decline to about 250 mm/day after 20 days of operation and remain at that level until the end of the short season. The water is recovered by bore-holes, which had been in operation prior to the construction of the dam. However, artificial replenishment makes it possible to maintain a high rate of ground-water abstraction.

The turbidity of raw water is around 10,000 ppm suspended solids, but it varies widely from flood to flood; in one exceptional flood-wave of 12.5 x $10^6$ $m^3$ volume, turbidities of 50,000 ppm were reached. As a rule, water with a turbidity of only 500 ppm or less is spread on the grounds. For this purpose, detention periods of 5-7 days in the reservoir are necessary.

The following figures, which are expressed in millions of cubic metres, summarize operational records. In view of the very large variability of climatic conditions in this area, it is misleading to calculate averages from the short record.

| Totals for period | Total flow in river | Diverted into spreading-grounds | Lost over spillway | Losses from reservoir | Accumulated silt in reservoir |
|---|---|---|---|---|---|
| 1960/61-1967/68 | 67.3 | 28.6 | 35.2 | 3.5 | 1.1 |

Settling of silt in the hold-over reservoir is too slow. If, in a wet year, floods occur at intervals of less than 10 days, they meet a full reservoir and are lost over the spillway. The addition of coagulants and/or heightening of the dam are under study. Infiltration rates in the sand dunes declined from their initial peak, but remained at a satisfactory level during the last few years.

Amortization for investment amounts to about $US 0.57/$m^3$/year, calculated with an interest rate of 8 per cent for a 25-year period of total amortization at the 1971 rate of exchange. Operating expenses are about $US 0.05/$m^3$. The entire plant is operated by Mekoroth Water Co. Ltd., under the water laws of Israel. It is desirable to solve the above-mentioned problems, but operations will, in any case, continue.

Artificial replenishment by surface water from the Menashe Streams

The four seasonal streams, Snunit, Ada, Barkan and Mishmaroth, drain an area of 110 sq km in the region of the Menashe Hills toward the Mediterranean Sea. The watersheds of the rivers are underlain by chalky limestone which forms a shallow aquifer. The seasonal river-flow lasts from December to April and averages $15 \times 10^6$ $m^3$/year, within a significant range of $3-40 \times 10^6$ $m^3$/year. The river-flow is composed of a base flow fed from numerous springs, and superimposed short periods of floods. The base flow accounts for about 70 per cent of the total. The project diverts the four streams by gravity, recharges the water into the aquifer of the coastal plain and recovers it by pumpage in bore-holes. The project was undertaken for the purpose of seasonal storage and exploitation of surface water.

A diversion canal, mainly earth, about 10 km long with a carrying capacity of about 10 $m^3$/sec, crosses the four streams with a diversion structure on each, and enters into the detention and desilting reservoir of $2.4 \times 10^6$ $m^3$ capacity. From here, another earth canal about 2 km long carries the water into the spreading-basins, permitting intermittent operation aimed at the prevention of clogging by suspended matter and the restoration of infiltration capacity by drying after partial clogging.

The maximum piezometric level in the aquifer is about 25 m below the bottom of the spreading-basins. Due to low-lying areas in the vicinity, the aquifer storage is somewhat limited. The aquifer is 30-50 m thick and its transmissivity is from 800 to 1,000 $m^2$/day; the coefficient of storage is about 0.20. The underground reservoir is exploited by 10 pumping wells surrounding the spreading-basins and discharging into a local network that is connected to the National Water Carrier.

The major part of the project was constructed in the summer of 1966, was put into operation in the winter of 1966/67 and was finally completed prior to the winter of 1967/68.

The following operational records are available. All figures are in millions of cubic metres.

| Hydrological year | Diverted flow | Spills | Infiltration | | |
|---|---|---|---|---|---|
| | | | In spreading grounds | In reservoir | In canals |
| 1966/67 | 12.0 | 0.15 | 7.5 | 2.8 | 1.7 |
| 1967/68 | 3.8 | - | 0.2 | 2.9 | 0.7 |
| 1968/69 | 20.5 | not measured | 10.2 | 4.5 | 5.8 |

The silt-load is small, from 160 to 300 ppm for river-discharges of 1-3 $m^3$/sec and from 50 to 100 ppm for smaller river discharges.

The underground storage capacity is small and the distance from the sea is only about 3 km; therefore, the site is not suitable for many years of storage. Eventually, additional bore-holes may have to be drilled to enable quicker extraction of ground water before it escapes into the sea. The watershed area of the rivers is now heavily settled and partly industrialized. Pollution of the raw water may become a problem.

References:

Aberbach, S. and A. Sellinger. Review of artificial groundwater recharge in the coastal plain of Israel. Bulletin of IASH year XII, 1:65-67, March 1969.

Schmorak, S. Salt water encroachment in the coastal plain of Israel. International Association of Scientific Hydrology, publication No. 72, pp. 305-318, March 1967.

# DANUBE RIVER VALLEY, ROMANIA-BULGARIA*

The background information for the Danube river valley project is as follows:

(a) Region: eastern Balkans;

(b) Geography: long alluvial river-valley, narrow in its upper part (200 m near Calafat) and broad near the delta area (30 km at Braila);

(c) Climate: temperate; average annual rainfall diminishes to the east from 800 to 300 mm; average January temperature 1°C; average July temperature, 22°C;

(d) Reservoir type: alluvial fill in older rocks;

(e) Methods of investigation: hydrogeological investigation and observation of bore-holes to determine water-balance. The observation bore-holes were drilled along profiles perpendicular to the valley, bore-hole spacings vary from 100 m to 3 km. Approximately 16 profiles were installed, from 14 to 40 km apart. Water-level measurements and pumping tests were made in the bore-holes.

## Ground-water reservoir and utilization

The alluvial fill of the valley is a clear-cut unit along the river, increasing in width down-stream.

The structure of the alluvium is complex. Above the main aquifer are thin zones of clays and other fine materials, sometimes exerting a confining action. The aquifer is typically a zone of sand and gravel; underlying the aquifer are horizontal layers of lower permeability, consisting of clayey sands, silts, marls and clays. The alluvial aquifer is 10-15 m thick. The surface area of the reservoir is approximately 4,000 $km^2$. The specific yield of the aquifer is about 5 per cent; total storage capacity is approximately 4,000 $km^2$ x 10 m x .05 = 2 x $10^9 m^3$.

The aquifer is in close hydraulic continuity with the river water of the Danube and movement between the two occurs in accordance with their relative hydraulic head. Between November and April the water supply generally increases. Movement is generally down-stream. The water-table is normally between 0 and 5 m below the surface of the alluvial plain. From April through September important water losses occur through underflow and evaporation.

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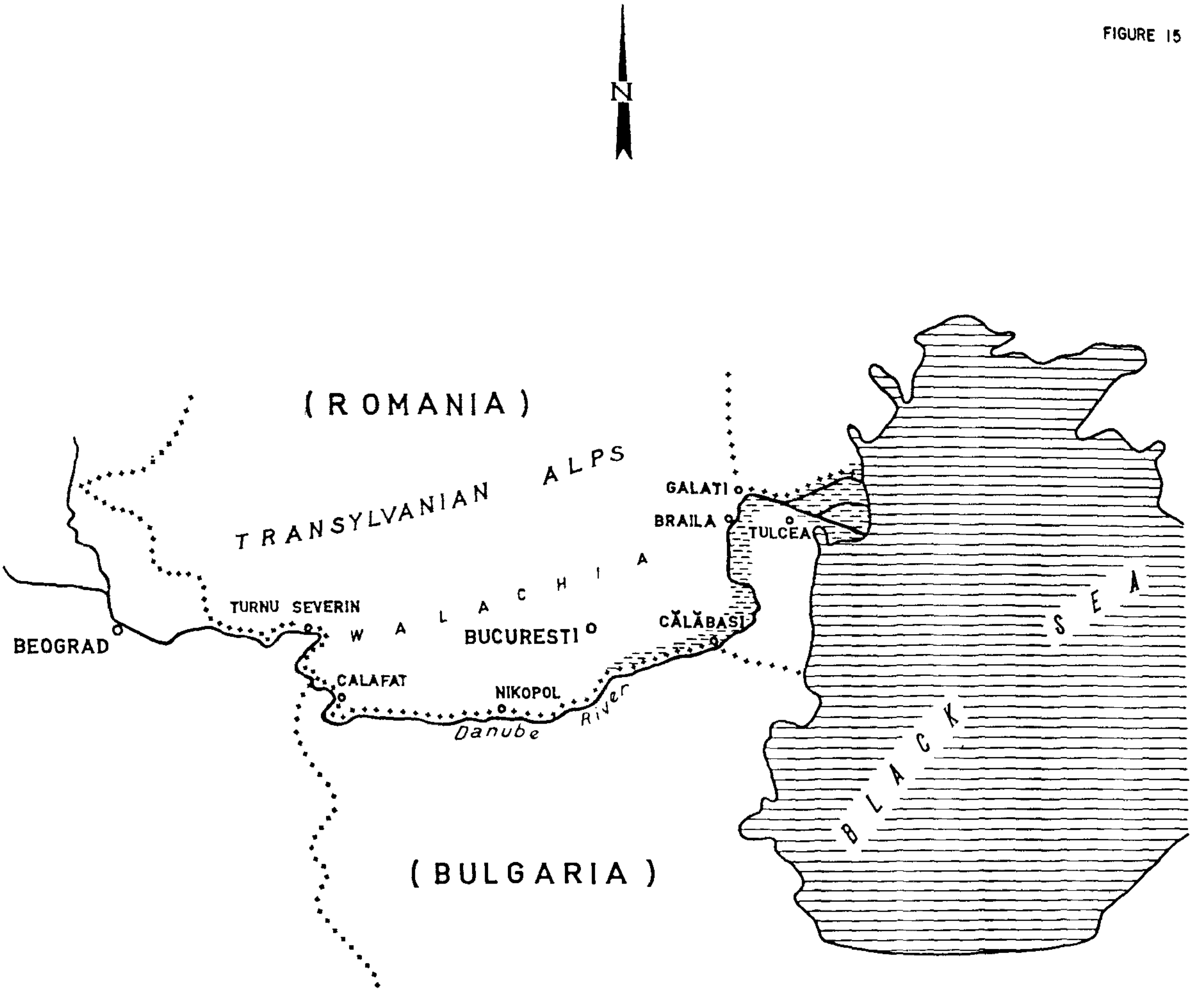
* Case study No. 7 prepared by G. Castany (France).

FIGURE 15



## DANUBE RIVER VALLEY,
## ROMANIA - BULGARIA

SCALE

CASE STUDY Nº 7

The water balance for the period October 1962-October 1963 has been tabulated as follows:

| Units | Gains of ground water |  | Losses of ground water |  | Increment |
|---|---|---|---|---|---|
|  | Underflow | Infiltration | Underflow | Evaporation |  |
| $10^3 m^3/km^2$ | +54 | +403 | -162 | -283 | +12 |
| Percentage | 12 | 88 | 36.5 | 63.5 |  |

Total storage capacity for replenishment is about $2 \times 10^9 m^3$ of water. A large amount of this water could be utilized, instead of being lost through evaporation, by pumping the alluvium during the dry season for irrigation. The storage capacity thus created would be replenished during the high-water season.

A joint United Nations Development Programme/United Nations Food and Agriculture Organization project of ground-water exploitation for irrigation was carried out in Romania applying the above principle.

References:

Enea, I. et E. Frugina. Considération sur le bilan des eaux phréatiques de la vallée du Danube. UGGI publication No. 77, General Assembly of Bern, 1968.

# DONZERE-MONDRAGON, FRANCE*

The background information for the Donzere-Mondragon project is as follows:

(a) Region: lower valley of the Rhone River, south of Montelimar, between Donzere and Mondragon, France;

(b) Geography: broad alluvial plain of the Rhone River;

(c) Climate: Mediterranean; average annual rainfall, 615 mm; average annual temperature, 14°C; minimum temperature, 5°C; maximum temperature, 23°C; average annual evapo-transpiration (calculated), 500 mm;

(d) Reservoir type: river alluvium of gravel and sands, overlying an impervious substratum;

(e) Methods of investigation: detailed hydrogeological study; electrical geophysical prospecting; reconnaissance drilling and wells; pumping tests; piezometric study and observation of piezometric levels and their fluctuation; artificial recharge tests; theoretical study of the movement of the injected water.

## Ground-water reservoirs

The geological log is as follows:

(a) A layer of silt, clay, sands, from 3 to 8 m thick, heterogeneous, of low permeability, topping the aquifer. The hydraulic conductivity coefficient is in the range of from $10^{-4}$ to 1 m/day, depending upon location;

(b) A layer of alluvial gravel and coarse sands, in beds of variable thickness;

(c) An impervious substratum of Pliocene clays presenting an irregular surface.

The aquifer is composed of river alluvium, heterogeneous, built of alternating layers of gravels and sands. This aquifer is generally unconfined, but is locally confined under the clayey silts. This situation is frequently found in the alluvial valleys of the Rhone and its tributaries.

The thickness of the aquifer is in the range of from 4 to 8 m, with an average of 7 m. The area of the aquifer is 15 $km^2$. The aquifer is stratified, with the permeability coefficient greater horizontally than vertically. The horizontal hydraulic conductivity coefficient as evaluated by test pumpings is $K$ = 170 m/day. The estimated average volume of water in storage is $1.4 \times 10^6$ $m^3$ per $km^2$.

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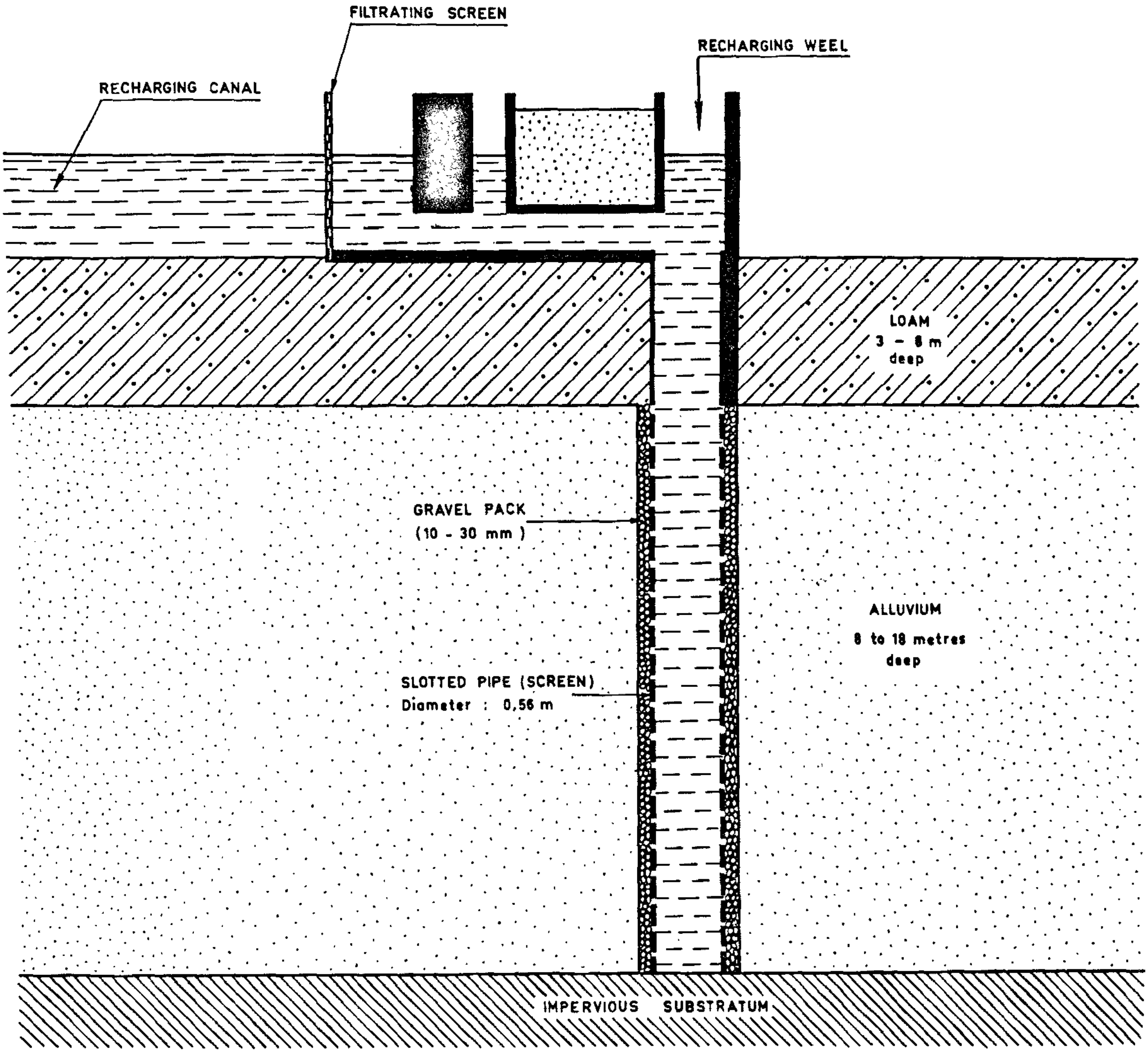
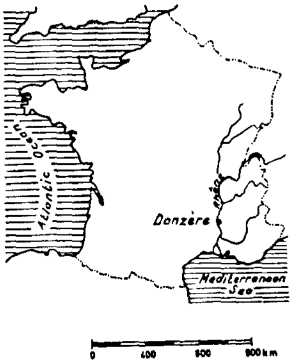
* Case study No. 8 prepared by G. Castany (France).



## DISPOSITIVE OF INJECTION



## DONZERE-MONDRAGON, FRANCE

CASE STUDY N°8

Artificial recharge utilizes waters of the Rhone River. This water contains suspended matter, the composition of which depends upon the flow. Flood waters have a quite high content of suspended solids. Except for flood periods, the average is 50 parts per million (ppm).

Recharge takes place through infiltration from rainfall (100 mm/year); infiltration of water from the river during flood periods (1-2 months per year); and underground flow from the aquifers located on the edges of the valley. Total recharge exceeds several tens of million cubic metres per year. The piezometric surface fluctuates during the hydrological year (starting in March and ending in February of the following year). The amplitude is in the range of from 0.50 to 1.50 m, with a maximum level of from 0 to 2 m above the land surface. Ground water flows from north-east to south-west, towards the river. The hydraulic gradient is low. The aquifer discharges into the Rhone during most of the year. The flow from the aquifer is in the range of 50 l/sec per km; the total is 1.5 $m^3$/sec. The balance is positive, with a surplus of several tens of million cubic metres/year.

## Artificial recharge

Ground water is used mainly for agriculture. The purpose of the artificial recharge project is to maintain the water potential of the aquifer and to maintain the piezometric level of ground water on the two banks of the out-flow canal of the hydroelectrical plant of Donzere-Mondragon. This canal has caused a drawdown of the piezometric surface.

The hydroelectric project in the broad alluvial valley of the Rhone, south of Montelimar, includes a diversion canal parallel to the river-bed on the left bank, 28 km long, between Donzere and Mondragon. The sluice-gate was built, for geological reasons, at km 17 of the diversion, giving a length of 11 km to the out-flow canal. The latter has been dug through the impervious substratum, thus acting as a drain. Therefore, a drawdown would result in the unconfined aquifer, and would have damaging effects on the agricultural development of the region. Thus, the piezometric level had to be maintained at an optimum elevation, through artificial replenishment, to avoid any disturbances to agriculture, on both banks of the out-flow canal.

The first tests were conducted in 1952. On each bank of the out-flow canal a parallel canal was dug, and fed by an intake upstream from the lock. Pits, dug in the bottom of the canals, penetrate into the aquifer under the layer of clayey silts. These pits have the shape of a truncated pyramid of which the small base (100 $m^2$ section) penetrates 1 m into the alluvium. The bottoms are covered by coarse screens. Their yield was low (around 30 l/sec). Additional penetration into the alluvium has increased the yield to an average of 50 l/sec per installation, and as much as 250 l/sec in some cases. The piezometric study showed that the radius of influence of these injections was limited.

Owing to the low yield of the large pits, vertical bore-holes were constructed with a diameter of 1.40 and 0.56 m, penetrating the entire depth of the aquifer, to a maximum depth of 20 m. Experience indicated that the bore-hole of 0.56 m diameter was the best solution, taking into account its cost and the amount of water which can be injected. The bore-holes allow an average injection flow of 80 l/sec, and the cost of their construction is only 10 per cent of the cost of ditches.

The present scheme of artificial recharge includes:

(a) A water intake with regulating gates and trash racks;

(b) A horizontal feed-pipe of 40 cm diameter, opening into the loading-room, which caps the injection bore-hole;

(c) A bore-hole of 56 cm diameter, equipped with an internal pipe of 30 cm, screened the entire thickness of the aquifer. The annular space between the pipe and the casing is filled with gravel of from 10 to 30 cm diameter. In view of attaining the desired results, two injection lines, 300 m distant from each bank of the out-flow canal have been installed;

(d) On the right bank of the canal the artificial recharge front of 6.5 km includes 121 pits or bore-holes, with an injection capacity of 4.5 $m^3$/sec;

(e) On the left bank the artificial recharge front of 5 km includes 112 pits and bore-holes, with an injection capacity of 4 $m^3$/sec. The total injection can therefore reach 8.5 $m^5$/sec.

As a result of this scheme, the hydraulic gradient has been multiplied by 20. A hydraulic barrier has been constituted which acts as an obstacle to the lowering of the piezometric surface. The recharge capacity for the pits is 30 to 250 l/sec (0.3 to 2.5 l/sec/$m^2$) under a water layer of 7-8 m, and for the bore-holes 80 l/sec.

Routine maintenance includes the cleaning of the trash racks twice a day during the summer. They are quickly obstructed by algae that develop in the bottom of the out-flow canal. The canal is cleaned twice a year. Periodic dredging of the canal also takes place in order to remove the deposits originating from the suspended matters contained in the injection waters.

The recharge is halted when the floods of the Rhone occur, bringing heavily silted waters. Studies have shown that the clogging is located in the pack of gravel which is set in the bore-hole. Clogging occurs when the injection stops; the bore-hole then acts as a drain, and the fine grains of the surrounding formation are carried into the bore-hole. Unclogging tests, which were carried out by air-lift, showed that if the original flow was recovered, subsequent clogging occurred more rapidly.

The life expectancy of a bore-hole is estimated at approximately eight years. Maintaining the required recharge capacity, therefore, requires the drilling of 15 bore-holes each year.

The average annual expense for maintenance and exploitation of the artificial injection system is:

| | |
|---|---|
| Routine maintenance | \$52,000 |
| Drilling of new bore-holes | \$28,000 |
| Total | \$80,000 |

The effect of the artificial recharge is spread over 1,200 ha, giving an annual cost of \$65/ha.

Future plans call for the study for the protection against the clogging of the injection bore-holes to reduce the cost of replacement of bore-holes.

References:

Alimentation artificielle des nappes souterraines. Etude documentaire provisoire. J. Archambault et autres. Bulletin du Bureau de Recherches géologiques et minières (Orleans), section III: hydrogéologie, 1:1-32, 1968.

Gerraud, J. Conditions d'exploitation du dispositif de réalimentation de la nappe le long du canal de fuite de Donzere-Mondragon. La houille blanche (Grenoble), 3:253-259, 1965.

# EIGULAI WATER INTAKE, LITHUANIAN SOVIET SOCIALIST REPUBLIC*

The background information for the Eigulai water intake is as follows:

(a) Region: vicinity of Kaunas, Lithuanian SSR;

(b) Geography: flow plain in the valley of the Neris River;

(c) Climate: temperate-humid; yearly rainfall averages from 550 to 850 mm;

(d) Reservoir type: alluvium;

(e) Surface waters: abundant (0.4 km of hydrographic network per km$^2$); but for municipal water-supply, ground water has proved more economical;

(f) Methods of investigation: to solve hydrogeological, hydrotechnical, sanitary and other problems arising from artificial recharge usage in the Lithuanian SSR, the Eigulai water intake will be reconstructed and equipped with a scientific-industrial base. The work consisted of studying the exploitation régime of the existing recharge plants, of experimental investigations of the output of infiltration installations; and also of physical, chemical and bacteriological aspects of water-quality change. The estimate of underground water reserves being artificially recharged was made by mathematical simulation methods.

## Ground-water reservoir

The area where water intakes are being installed is situated on the underflood terrace-lands of the valley of the Neris River. The thickness of the alluvial aquifer ranges from 9 to 20 m and is situated in sandy-gravel sediments.

The régime of the underground water level depends completely upon the fluctuations of the water level of the Neris. Operational wells are located at a distance of 150-500 m from the river, with a spacing of 25 m, and are joined into two lines with a common length of 1,550 m. The average annual capacity of the water intake, without artificial recharge of the aquifer, is 15.5 x 10$^3$m/day.

## Artificial recharge

Water from Eigulai intake is utilized for the municipal water-supply system of Kaunas, a major city of the Lithuanian Soviet Socialist Republic. Artificial recharge of ground water commenced in 1963 and is practised using two infiltration basins, each having a filling depth of 3.2-3.4 m and a surface area of 4,250 and 3,790 m$^2$. From the bottom of the infiltration basins to a depth of 1.5-2.0 m there is a covering of coarse-grained sands having a hydraulic conductivity coefficient

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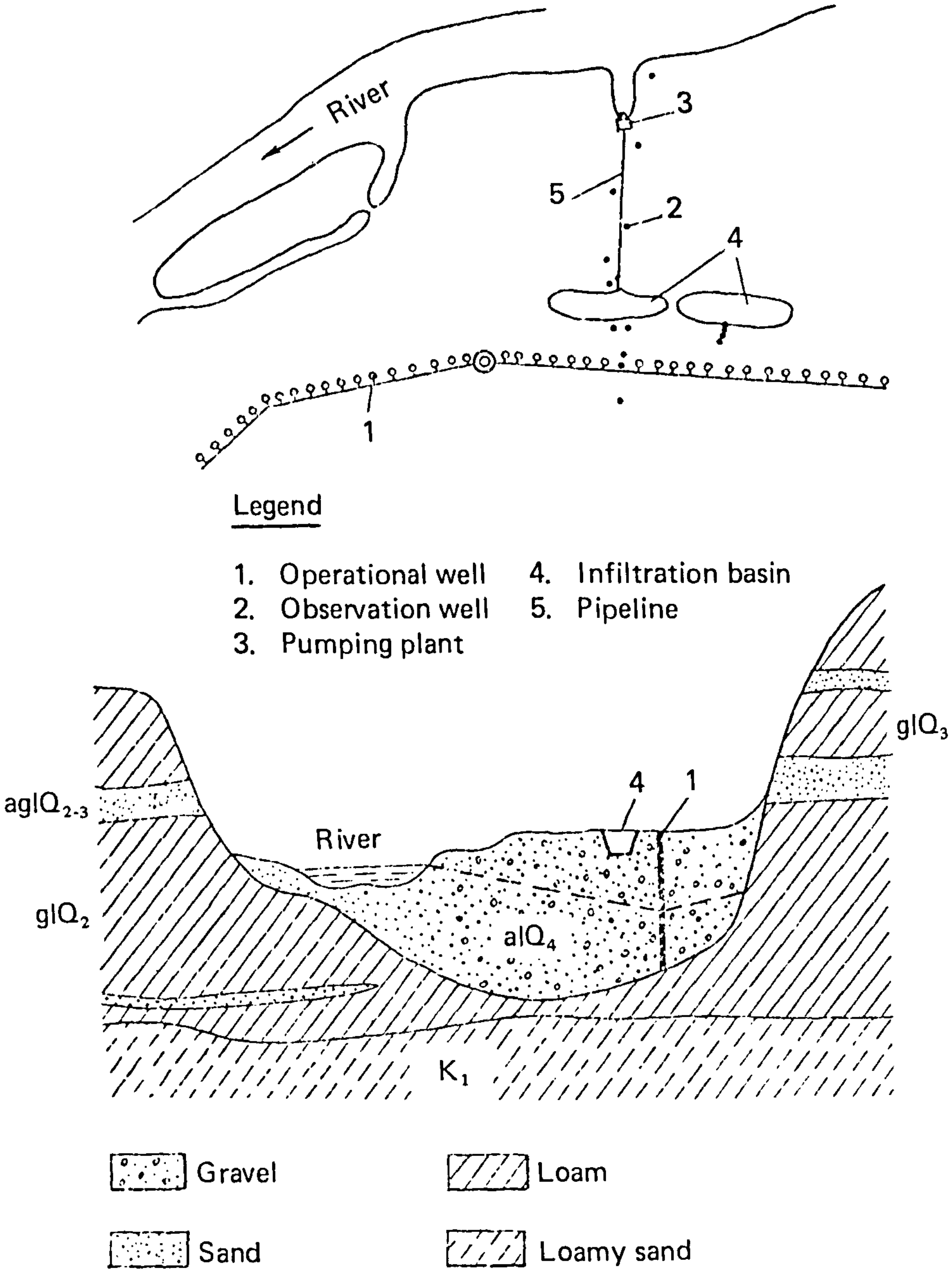
* Case study No. 9 prepared by V. Kunin and I. Diliunas (Union of Soviet Socialist Republics).

Figure 17. Eigulai water intake, Lithuanian Soviet Socialist Republic



of 30 to 40 m/day. These sands overlie a gravel bed. The value of the coefficient for gravel exceeds 100 m/day. The basins are operated from 9-12 months per year. The infiltration water is obtained from rivers with from 20 to 30 g/$m^3$ of suspended matter. The basins are recharged within a 20-30 day period, and they later work under a constant head of water. Their intake rate during the infiltration cycles varies from 12 to 0.7 x $10^2 m^3$ per day and increases the rate of water intake an average of 30 per cent. Most of the water, about 70-80 per cent, reaches the aquifer during the first 3-4 months.

The level of underground waters during the whole filtration cycle is 6.0-6.5 m below the bottom of basins.

The rise of the underground water level begins after one day of infiltration and continues for 1.5-2 months. The volume of artificial water accumulated in ground storage in the course of this time reaches 360 x $10^3 m^3$. During the first three months, the increase of consumption of the water intake is obtained from influent flow to ground water and by direct inflow of infiltration and, subsequently, by ground-water storage. The infiltration rate during the filtration cycle changes from 2.8 to 0.05 m per day, with an average of 0.35 m per day. During the first 30-50 days, the grain size of the bottom of the basin greatly influences the infiltration rate, and its subsequent decrease is determined by the amount of suspended matter deposited on the bottom of the basins. During infiltration cycles, clayey matter, on average 33.7 mm thick, settles as a coating ("mud cake") on the bottom of the basins. The amount of suspended matter retained by 1 $m^2$ of filtrating surface is 4.2 kg. The hydraulic conductivity coefficients of the coating ranges downwards from 2.8 x $10^{-3}$ to 8.5 x $10^{-4}$ m/day. As a result of silting, the filtration rates of grounds at a depth of 10 cm are 2-7; and at a depth of 5 cm are about 100 times smaller than before silting. The regeneration of the filtrating surface requires the removal of a superficial stratum of ground 5-10 m thick.

Frequent cleaning of filtrating surfaces, resulting in ground-removal from them, renders necessary and costly overhauling of the filtrating layers. Over the years, efforts have been made for improving the quality of recharge water. Concerning water quality common values for total dissolved solids in waters of the Neris River are in the vicinity of from 120 to 500 parts per million. A vertical filtration run of 6-7 m and a horizontal filtration run of 30 m improve the physical properties of the water as quality improves in its move through the ground. In fact, computations made using the equation of mixing show that by doubling the capacity of the water intake through artificial infiltration, water mineralization decreases 15 per cent; by tripling it, mineralization decreases by 25 per cent.

To assess epidemiological safety of water, analysis of bacteria coli and their activity in the filtration process of polluted water in the porous grounds were made. It was ascertained that, with the same concentrations in the infiltered water and with the same physical character of the ground, the main factor affecting the efficiency of bacteriological self-cleaning of water, at the beginning of filtration, is the route taken by the water. Self-cleaning efficiency of polluted water, during filtration through porous media, increases with a decrease of filtration velocity and with an increase of the amount of filtration passing through the ground. Thus, when the filtered concentrate is increased two times, the cleaning capacity of the ground over the same filtration route is increased about 10 times. It must be mentioned that, as a result of the decrease of filtration velocity, the time that bacteria remains in little-aerated medium increases, thus affecting the water-purification process. The results of investigations showed that, in a basin covered by a clayey coating, after 72 days of recharge, surface water does not support bacterial growth at a distance of 10 m from the basin. During 142 days of filtration, the water purifies completely in the clayey coating and in the aeration zone, the thickness of which at that time was 7.6 m.

As a result of the tests, it was determined that after additional purification of surface water in the horizontal storage pond, a possibility exists of reducing the mean infiltration rate during one filtration cycle to 0.84 m/day and to clean the basins only once a year. Additional basins, with a total filtration surface of 52.6 x $10^3 m^2$, will permit an increase of more than three times the water-intake capacity without reconstruction of the existing system of exploitation.

The risk of bacteriological pollution of ground water under the conditions of the water intake, where the source of supply for the basin is located 20-30 m from the capture, exists only during the first filtration period and for about 2-2.5 months. During this filtration period, there must be strict sanitary control, and waters extracted must be disinfected, if necessary.

On the basis of these investigations, a project for the reconstruction of the water intake was formulated and its implementation was begun.

Similar projects are envisaged for such other major cities of the Lithuanian SSR as Vilnius, Klypeda and Alytus.

# PLAIN OF GHAZVIN, IRAN*

The background information for the plain of Ghazvin is as follows:

(a) Geography: the plain of Ghazvin is situated about 120 km west of Tehran, between the Elburz Mountains in the north and the central mountain ranges in the south. It forms the westernmost extension of the great Iranian plateau. The area is approximately rectangular, extending over a maximum of 100 km from east to west and 70 km from south to north; it covers about 5,000 sq km, of which about 1,300 sq km are under cultivation. The plain varies in elevation from 1,150 to 1,500 m above sea level while the mountain ranges reach elevations of 2,900 m in the north-east and 2,600 m in the south. The total areal extent of the basins draining into the area is about 13,000 sq km. The two major steams, the Khar Rud and Abhar Rud, flow into a salt marsh on the eastern boundary of the area. There is only a small outflow from this swamp, drained by the Rud-E-Shur in an easterly direction;

(b) Climate: continental, characterized by a wide range of temperatures between summer and winter and sudden transitions between hot days and cold nights. The rainy season lasts from October-November to May-June, with a maximum during spring; average annual precipitation is around 300 mm, including the water equivalent of snow;

(c) Reservoir type: alluvium;

(d) Methods of investigation: detailed surveys and measuresments, interpretation by routine methods and, recently, with the aid of an electric analogue model.

## Ground-water reservoirs

The Plain of Ghazvin is a tectonic depression framed by the Elburz Mountains in the north and the central Iranian mountains in the south. In the mountains, and on their borders, Liassic to Miocene strata have been identified. The thickest stratum is composed of volcanic rocks, tuffs, andesites, trachytes, basalts etc.; it is of Eocene-Neogene age and reaches a thickness of 2,500 m. All the mountain strata have a predominantly impervious facies.

The flat alluvial plain is formed by sediments derived from the erosion of the surrounding mountains. A continuous aquifer of varying composition and thickness is formed by the alluvial Pleistocene-Recent strata in the plain. These are the principal aquifers. In the lower parts of the plain, confined conditions are frequently encountered owing to the inter-bedding of argillaceous formations with the elastic horizons. As is to be expected, coarse components predominate near the margins of the plain, whereas the proportion of fine material predominates towards its centre.

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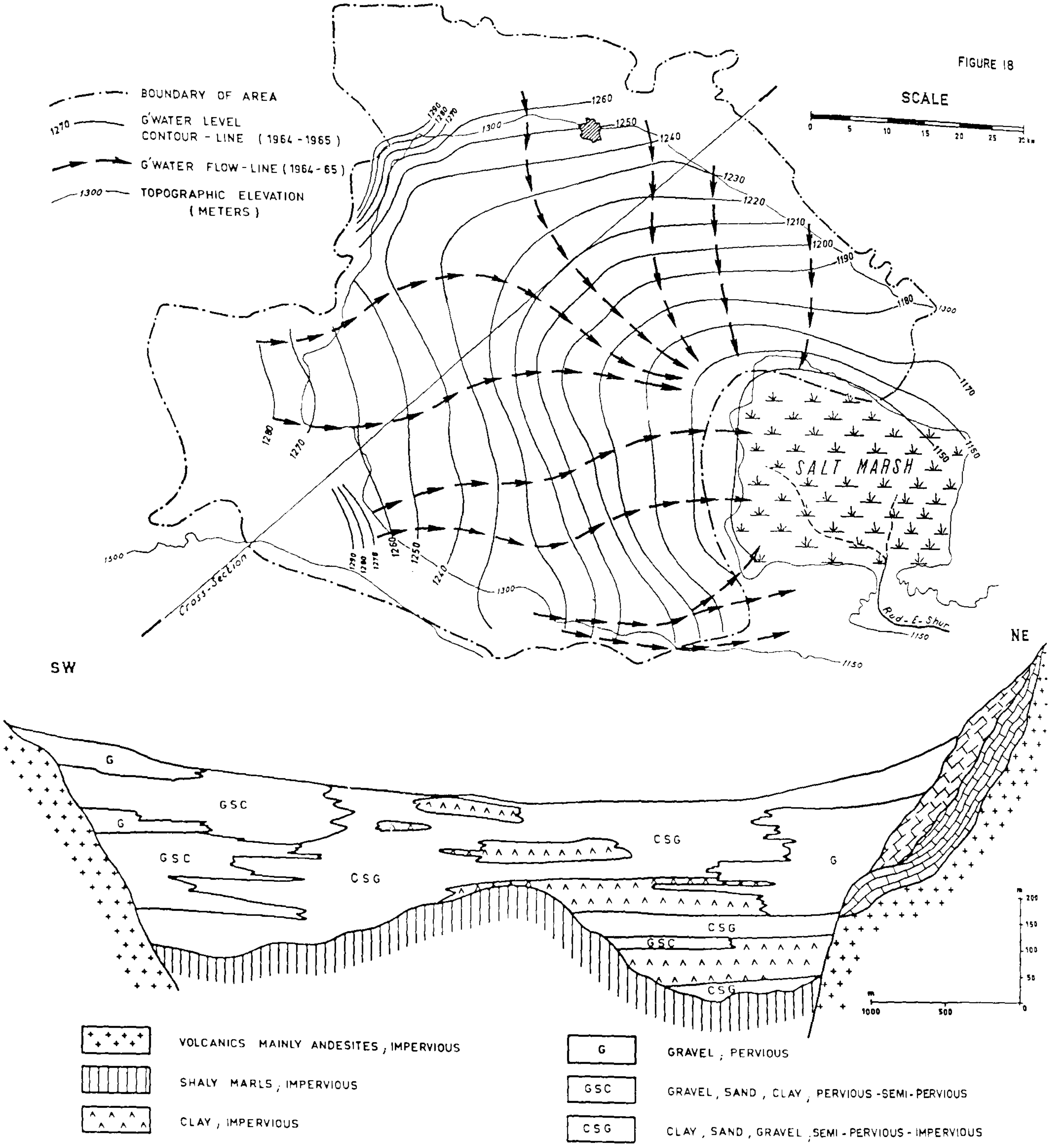
* Case study No. 10 prepared by S. Mandel (Israel).

FIGURE 18



## PLAIN OF GHAZVIN,
SCHEMATIC CROSS - SECTION,

**IRAN**

CASE STUDY Nº 10

The ground-water balance was determined by a hydrogeological method for the period 1964/65, for a large sample area covering 2,274 sq km and comprising almost the entire plain. The balance gave the following results:

| | |
|---|---|
| Replenishment on balance area | $189.1 \times 10^6$ m$^3$ |
| Inflow into balance area through boundaries | $92.2 \times 10^6$ m$^3$ |
| Total | $281.3 \times 10^6$ m$^3$ |

The estimated safe yield is about $260 \times 10^6$ m$^3$/year, leaving the remainder to overflow into the salt marshes.

## Utilization of ground water

Ground water has been exploited in the area by ghanats since the tenth century. A ghanat may be described as a slightly inclined, almost horizontal, hand-dug gallery, excavated stretch-by-stretch from a line of vertical shafts. The digging of the gallery is begun at ground level at its lower end, and carried upslope at a gradient of about 0.025 per cent. This slope, being less than the slope of the ground and less than the slope of the ground-water table, the gallery goes deeper below ground until it reaches the ground-water table. The gallery is then continued so as to tap ground water over a sufficient length, in order to give the desired yield. The last of the row of shafts is known as the "mother-well". In the Ghazvin area the longest ghanat is 11 km and the deepest mother-well is 70 m. The ghanat has a wet section into which the ground water seeps, and a dry section serving as a conduit for the water until it reaches ground level; from this point onward the water continues to flow in an open ditch. In some cases, where the material is too friable, the gallery is lined with oval shaped rings made of burnt clay or concrete.

The construction of a ghanat demands amazing engineering skills and a deep understanding of natural conditions, and has proved highly successful throughout many centuries. A ghanat is actually an artificial spring and, thus, its discharge strongly depends upon the height of the water-table. This, indeed, is its main drawback. High discharges commonly occur at the end of the rainy season, whereas in the dry season the flow decreases and, in some cases, ceases completely.

In the Ghazvin area there are 498 ghanats; 184 of them exploit perched horizons, about 70 to 80 m higher than the local water-table; but only 149 yield water now, the rest being dry. There are 314 ghanats in the plain proper; 207 now yield water and the rest are dry. Their combined discharge amounted to about $190 \times 10^6$ m$^3$ in 1965. About 25 per cent of the discharge is lost by seepage, and returns to the ground-water reservoir before it reaches the irrigated areas.

The ghanats are in the process of drying up owing to cave-ins and the lack of maintenance. Owners now prefer to drill wells, instead of laboriously repairing ghanats or lengthening their wet section.

Wells in the area are of two kinds: hand-dug shaft wells and machine-drilled bore-holes. In 1965, there existed 136 shaft wells equipped with pumps and motors, yielding about $52 \times 10^6$ m$^3$/year, and 198 deep wells yielding about $135 \times 10^6$ m$^3$/year.

It will be noted that present ground-water abstraction already exceeds replenishment. Therefore, the water-table will necessarily be lowered and the process of drying up of the _ghanats_ will be accelerated. It is intended gradually to replace _ghanats_ completely by bore-holes, with a controlled programme of exploitation.

In future, exploitation of ground water from the aquifer will be linked with the provision of surface-water supplies from rivers outside the area, so that the planned exploitation of part of the regulative reserves can be envisaged. As these reserves are very large, about 2,000 x $10^6$ $m^3$, it will be comparatively easy to manage the aquifer as a seasonal and long-term storage reservoir.

Many additional bore-holes have been drilled, and are now being put into operation. Hydrological observations are being continued and interpreted with the aid of an electrical analogue model. Accompanying the hydrological development of the area, agricultural development is being pushed by the introduction of fertilizers, new crops, new techniques of combating pests etc.

References:

Unpublished reports prepared for the Government of Iran.

# HALTERN SANDS RECHARGE PROJECT, FEDERAL REPUBLIC OF GERMANY*

The background information for the Haltern Sands Recharge Project is as follows:

(a) Region: region of the Ruhr;

(b) Geography: valley of the Lippe, right-bank tributary of the Rhine, 80 km down stream from Cologne;

(c) Climate: temperate, humid; average annual rainfall, 750-800 mm;

(d) Reservoir type: alluvium overlying thick sand layers.

## Ground-water reservoirs

The geological log includes recent alluvium of terraces of the Lippe River, a few metres thick; and so-called Haltern sands, of lower Senonian age.

The Haltern sands are a very important aquifer, one of the thickest in Europe. The extraction of ground water amounts to 100 x $10^6$ $m^3$/year, of which 25 per cent originates from native ground water and 75 per cent from artificial replenishment. The sands largely outcrop in northern part of the country, representing a recharge area of 900 $km^2$. The thickness of the sands may reach 250 m, with an average of 120 m. Hydraulic conductivity (K) is from 10 to 15 m/day; coefficient of storage (S) is 15 per cent.

The Haltern region is overlain by recent alluvial terrace formations. The entire region can be considered as a single aquifer system drained by the Lippe River. The estimated volume of water in storage is 12 x $10^6$ $m^3$/sq km. The waters which are extracted are those from the Stever River, because those from the Lippe are salty. However, the waters of the Stever are polluted by both urban- and industrial-waste waters.

The infiltration of rainfall on the recharge area is estimated at 10 l/sec/$km^2$. The aquifer feeds the Lippe River and is over-exploited, mainly in the valley.

## Artificial recharge

The ground water is used for municipal water supply. The artificial recharge of this portion of the Haltern aquifer is carried out for two purposes:

(1) Maintaining the direction of the ground-water flow towards the Lippe River. The over-exploitation of the aquifer causes a piezometric depression which

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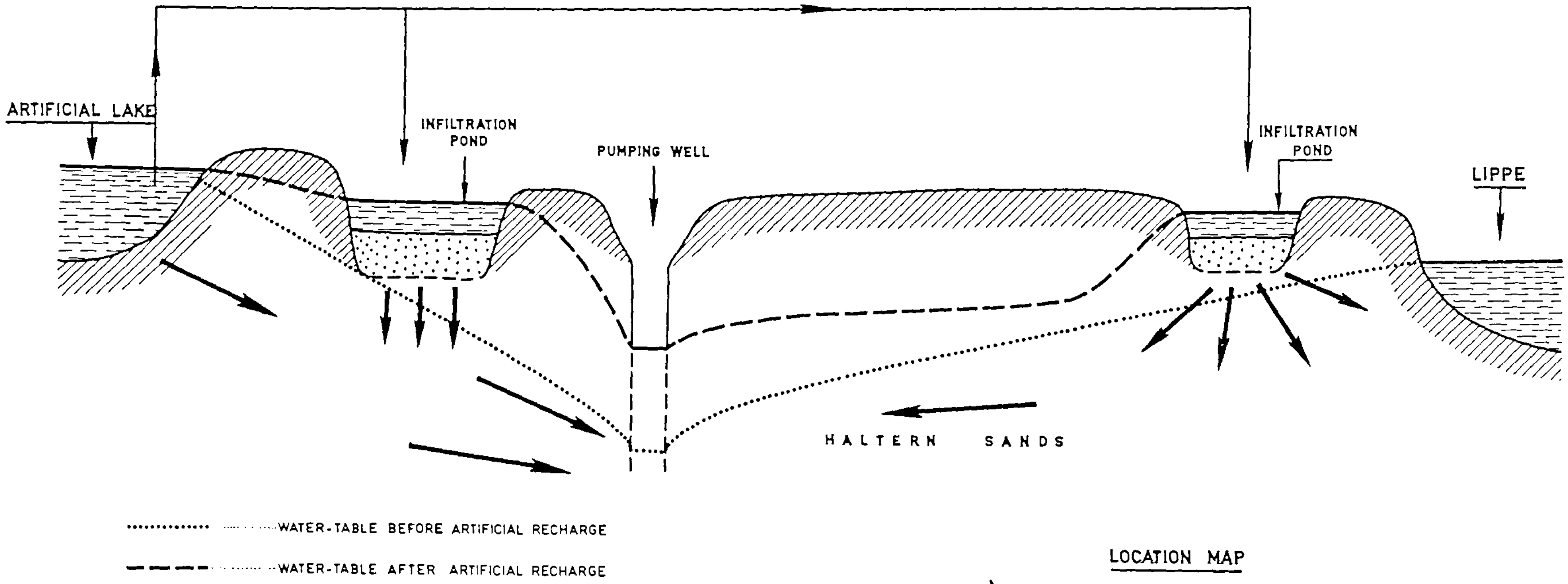
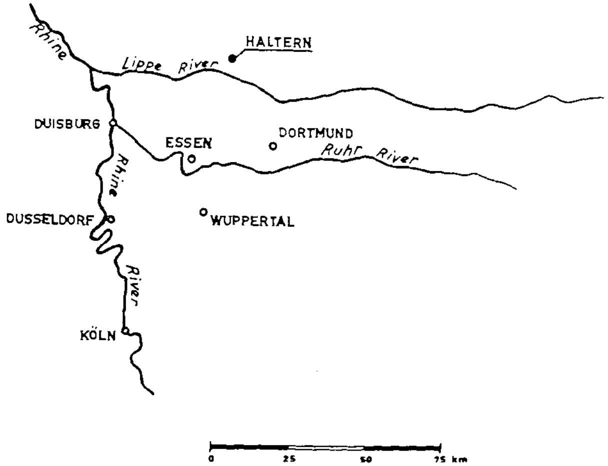
* Case study No. 11 prepared by G. Castany (France).

FIGURE 19



## HALTERN SANDS RECHARGE PROJECT, FEDERAL REPUBLIC OF GERMANY

LOCATION MAP



CASE STUDY Nº 11

might reverse the direction of this flow; and, therefore, would allow the infiltration of waters from the Lippe, which are highly salty, and the pollution of the ground-water body;

(2) Regulating the temperatures and purifying the water for artificial recharge.

The first installations date back to 1908. A battery of 38 wells, 35 m deep, was located near the Lippe valley, with an output reaching 60,000 $m^3$/day. A portion of the pumped water was reinjected into infiltration basins located between the wells and the river. Therefore, a hydraulic barrier was constructed to oppose the infiltration of surface waters.

In 1930, the output of wells became insufficient, and a dam was constructed on the non-polluted Stever. The amount of surface water stored by the dam is $4 \times 10^6$ $m^3$, which will be increased to $5 \times 10^6$ $m^3$. The waters are to be utilized only for the artificial recharge of the Haltern aquifer. The artificial recharge scheme will include 18 basins and the exploitation by 170 wells 35 m deep. The infiltration basins are located upstream of the ground-water flow, between the artificial lake and the exploitation wells. A second line of basins is located between the wells and the river, to avoid the infiltration of the waters of the Lippe River towards the ground-water body.

The polluted waters of the surface-water reservoir are purified through a natural process, and thermal regulation provides $9^\circ$-$14^\circ$C ground water as compared with $2^\circ$-$26^\circ$C for surface water.

References:

Vandenbergue, A. Etude de l'alimentation artificielle des nappes souterraines. Compte-rendu de mission. Rapport du Bureau de Recherches géologiques et minières (Orleans), No. 68 SGL 114 HYD, 1968.

# HODOGAYA INJECTION PROJECT, JAPAN*

The background information for the Hodogaya injection project is as follows:

(a) Region: northern part of the Tokyo metropolitan area, Kwanto, Japan;

(b) Geography: southern part of Kwanto coastal plain;

(c) Climate: humid, temperate zone; average rainfall about 1,500-2,000 mm/year;

(d) Reservoir type: diluvium;

(e) Methods of investigation: complete hydrogeological investigation, including pumping tests and chemical analyses.

## Ground-water reservoirs and utilization

Geological conditions are characterized by diluvium, consisting of unconsolidated clay, sand and gravel, which underlies the alluvial soil in the area. The water-bearing strata are layers of sand and gravel 60-80 m and 180-200 m below the surface of the ground, with a thick clay layer between the two water-bearing formations. The aquifer tapped by injection well No. 1 is 154-165 m and 184.5-210.5 m below the surface of the ground. The aquifer tapped by injection well No. 2 is 68.7-85.2 m below the surface of the ground. (See figure 20.) The permeability coefficient of the aquifer is 56 m/day and the estimated volume of water in storage for each aquifer is 8 x $10^6$ $m^3$/sq km. Natural recharge is by precipitation; discharge is by pumping only, there is no natural discharge. The ground water flows from north-west to east.

In 1961, at Johuku district (northern part of Tokyo metropolitan area), about 276 wells were in operation and the total quantity pumped was about 260,000 $m^3$/day, with an average pumping rate per well of about 1,000 $m^3$/day. There was an overdraught of ground water, with the piezometric surface falling year by year.

Ground water from the Johuku district is used mainly as industrial water. The piezometric surface is now at a level of from 60 to 80 m below ground level, and the regional decline is the most important problem.

Cost of water per cubic metre in the Tokyo metropolitan area is as follows:

| | Yen | Dollars |
|---|---|---|
| City water | 19.00 | 0.053 |
| Surface water | 2.38 | 0.00661 |
| Underflow of ground water | 0.16 | 0.00044 |
| Pumped ground water | 1.91 | 0.0053 |
| Average | 4.37 | 0.0121 |

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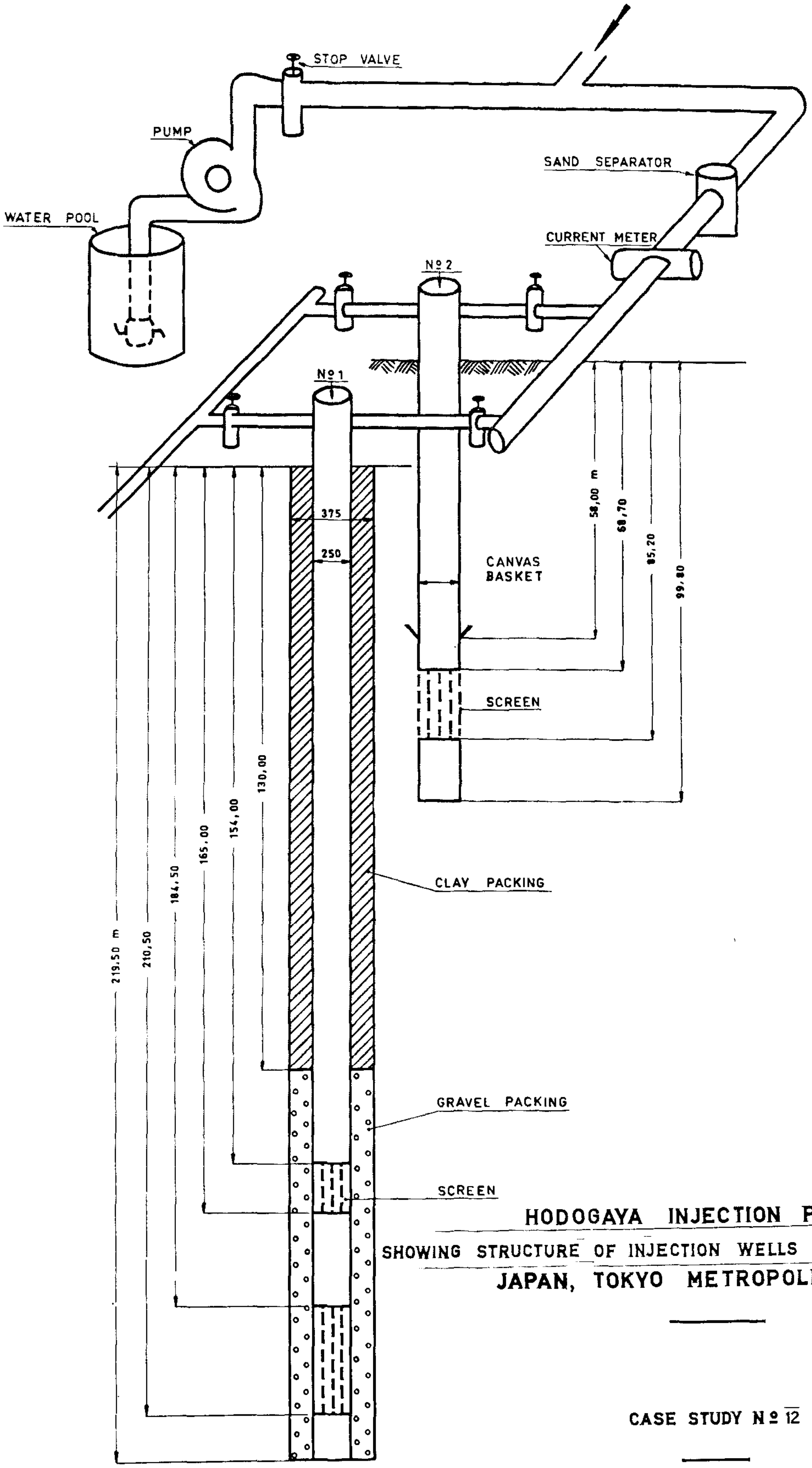
* Case study No. 12 prepared by T. Konishi (Japan).

FIGURE 2C



HODOGAYA INJECTION PROJECT,
SHOWING STRUCTURE OF INJECTION WELLS Nº1 AND Nº2,
JAPAN, TOKYO METROPOLITAN AREA

CASE STUDY Nº 12

Future utilization of ground water in this district will increase as industrialization increases.

## Artificial recharge

The water-table of this area had fallen every year, and by 1961 it had fallen to 40 m below ground level. Land subsidence was also rapid, and this project was undertaken in order to prevent these undesirable effects.

Two injection wells were drilled 3 m apart. No. 1 was 220 m deep with a diameter of 250 mm and No. 2 was 100 m deep, and also 250 mm in diameter. Gravel from 9 to 11 mm in diameter was placed in the annulus, between the casing pipe and the bore-hole wall, at depths of over 125 m at well No. 1, and a canvas basket was set at a depth of 66 m at well No. 2.

The method of operation was as follows: industrial cooling water was injected, the composition of which was almost the same as the ground water. The temperature was from 22° to 26°C and the rate of injection was from 40 to 60 $m^3/h$.

The rate of injection was held at 35 $m^3/h$ owing to the availability of waste cooling water. The water-table rose 6 m at well No. 1 (water-bearing strata at 140-200 m) and 8 m at well No. 2 (water-bearing strata at 60-80 m). These levels became stable after 25 min at well No. 1 and after 40 min at well No. 2, after which continuous injection was performed. Since this project was conducted using the pumping well for observation, the level of the water-table during recharge and under normal pumping conditions without injection were compared.

The level rose 15 cm when water at the rate of 33 $m^3/h$ was injected into well No. 1, and 63 $m^3/h$ of water was pumped from P-4 well. From 30 April to 2 May 1961 a step-wise injection test was carried out. Injection of 13.8, 30.0, 45.0 and 50.4 $m^3/h$ resulted in increases in the level of 9, 20, 38, and 52 cm, respectively. Next, 30, 40 and 51 $m^3/h$ of water was injected into No. 1, and a rise of 50 cm was observed at P-4 well; also water at the rate of 30, 40, and 51.6 $m^3/h$ was injected into well No. 2 every two hours, and the result was a rise of 25, 35, and 52 cm, respectively. The total amount of injected water reached 55,000 $m^3$ by the beginning of August 1961, and injection was stopped at that time.

Plugging of the well-screen is the most significant problem. The cause of the plugging is believed to be the result of chemical reaction within the water-bearing layers, owing to the difference of temperature between the injected water (22°-26°C) and the ground water (16°-17°C), contamination of the injected water and the excess oxygen dissolved in the added water.

The total amount of injected water reached 55,000 $m^3$ by the beginning of August 1961. At that time, the water level rose to the top of the casing by injection of 600 l/min, and, even at a rate of 400 l/min, the injection was stopped. No future injection tests are planned.

### References:

Kishi, K. Preliminary report of the artificial ground water recharge No. 3. Bulletin of the geological survey of Japan. 14:6, 1963.

# KALAUAO WELL-FIELD, HAWAII, UNITED STATES OF AMERICA*

The background information for the Kalauao well-field is as follows:

(a) Region: Island of Oahu, Hawaii (Pearl Harbor area);

(b) Geography: mid-ocean volcanic cone;

(c) Climate: subtropical; median annual rainfall over the recharge area is about 2,500 mm; evapo-transpiration is estimated to be about 750 mm;

(d) Reservoir type: basalt;

(e) Methods of investigation: classical hydrogeological methods and a laboratory hydraulic model study.

## Ground-water reservoirs

The island of Oahu is the result of the coalescence of two Tertiary volcanoes, Waianae and Koolau, arising from parallel fracture zones. A long period of quiescence and profound erosion followed cessation of flows. Thick interbedded terrestrial and marine sediments were deposited around the coastal margin. A second period of volcanic activity of the Koolau volcano resulted in basalts, ash and cinders of the Honolulu Series which, in places, are interbedded with the sediments.

The principal reservoirs and rocks are basaltic, except for limestone found in coastal areas. High-level dike water results from compartmentation of the permeable basalt flows by dense intrusive dike rocks. Perched water is neither common nor very important; but occurs upon old soil beds, ash and also upon dense flows of the Honolulu Series. From the dike zone to the coastal apron, ground water occurs in the permeable basalt as basal water which floats on the underlying denser salt water to form a fresh-water lens. The sediments in the coastal apron, popularly known as "cap-rock", are impermeable relative to the basalt. The cap-rock prevents fresh water from escaping into the ocean and hence thickens the fresh-water lens. However, thin-bedded coral aquifers containing brackish or salt water occur in the cap-rock and are open to the sea.

The basalt aquifer in the Honolulu coastal plain is compartmentalized by deep sediments filling buried stream valleys, impeding horizontal movement of water and creating isopiestic areas. However, the Pearl Harbor area, in which the Kalauao well-field is located, is characterized by a flat gradient of seaward ground-water flow.

Diked water and perched water are generally under water-table conditions. Basal water is also generally under water-table conditions, except for that part

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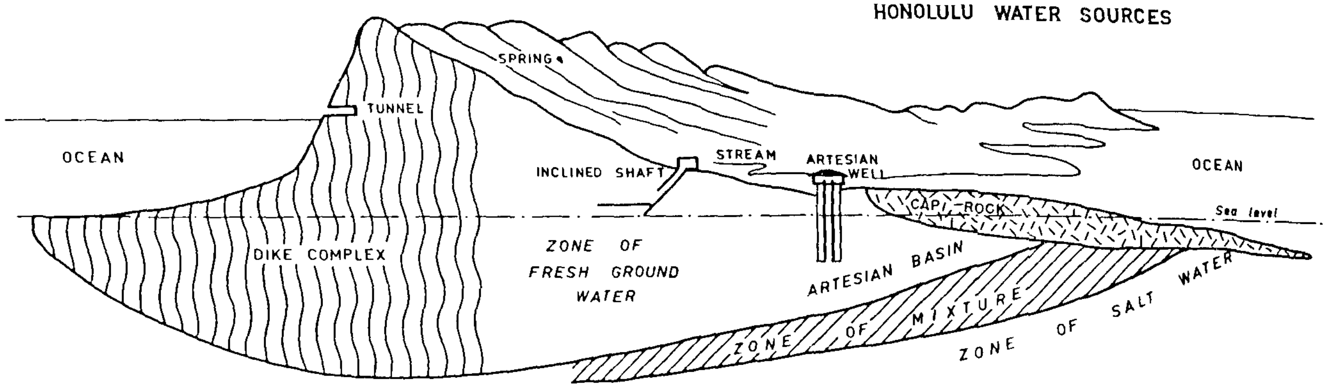
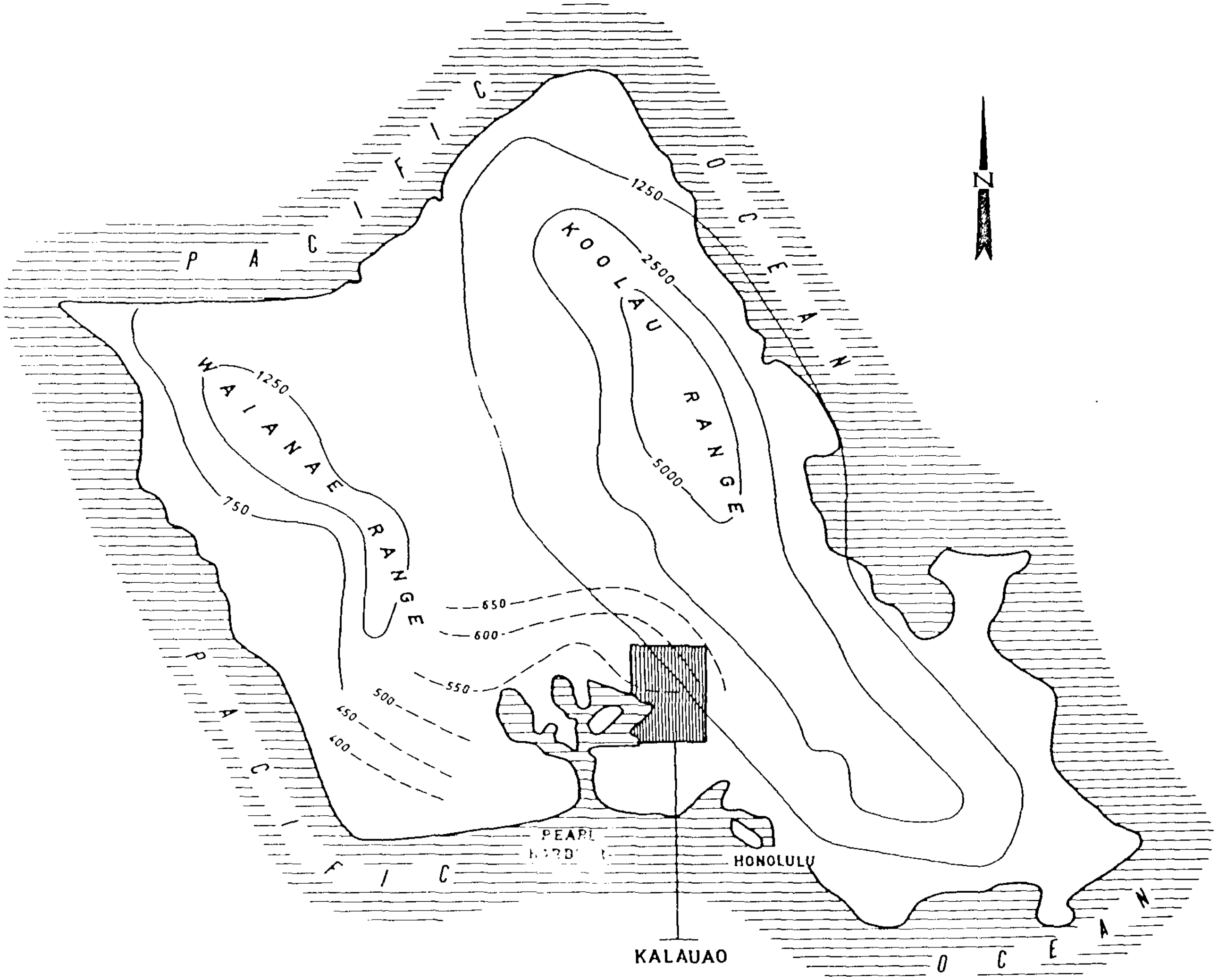
* Case study No. 13 prepared by R. De Wiest (United States of America).

FIGURE 21



SCHEMATIC CHART SHOWING HONOLULU WATER SOURCES



## KALAUAO WELL-FIELD, HAWAII, UNITED STATES OF AMERICA

SCALE

0 2,5 5 7,5 10 km

CASE STUDY N° 13

—2500— RAINFALL (mm)

—450— PIEZOMETRIC CONTOURS (cm)

under the cap-rock in artesian condition. Coral aquifers in the cap-rock can be either confined or unconfined. The most important water resources are by far the basal-water supply.

The principal aquifer is the basalt of the Honolulu coastal plain. The thickness of the fresh-water lens averages about 300 m. Water quality is excellent and meets United States Public Health Service standards for drinking water. Some years ago, chlorides and nitrates were higher than normal in some wells, owing to the return of irrigation water. Since 1966, sugar cane has not been cultivated over the recharge area, and there has been an improvement in water quality. In 1968, chlorides from two representative wells were in the range of 80-90 parts per million (ppm), and 50-60 ppm.

Recharge occurs primarily from infiltration of rainfall on the upland slopes of the Koolau Range. The average hydraulic conductivity (K) is about 100-200 m/day; coefficient of storage (S) ranges from 1 to 2 per cent. The volume of water in storage in the Pearl Harbor area is estimated at 4,800 x $10^6$ $m^3$. Visible spring discharge for the entire Pearl Harbor basin is 3 x $10^5$ $m^3$/day; pumpage is 6 x $10^5$ $m^3$/day.

The ground-water balance is shown in table 10.

Table 10. Pearl Harbor basin hydrological budget estimate

(Units in thousands of cubic metres per day)

| | | | |
|---|---|---|---|
| Rainfall | | 1,250 | |
| Stream run-off | 121 | | |
| Evapo-transpiration | 277 | | |
| | 398 | | |
| Net infiltration | | 850 | |
| Waiahole import-water | | 114 | |
| Ground-water recharge | | | 964 |
| Draught | 608 | | |
| Visible spring-discharge | 304 | | |
| Ground-water discharge | | | 912 |
| Leakage unaccounted for | | | 52 |

## Utilization of ground-water

Beginning about 1900, batteries of deep wells with large-capacity steam-driven pumps were installed in the coastal plain. Irrigation water from deep wells in the Pearl Harbor area was augmented by water pumped from the large springs; and since 1913, by water imported from northern Oahu through the Waiahole ditch tunnel. Beginning in the 1930s, shafts, inclined shafts and tunnels were constructed for water supply, for irrigation and for municipal and military use. There are several pumps discharging 40,000-120,000 $m^3$/day.

The zone of mixture of fresh and salt water (the transition zone), and its movement inland and upward is a constant danger. Skill is needed in extracting the fresh water. Much of the flow of the large springs is wasted. If the flow of the springs could be controlled, 280,000 $m^3$/day could be developed.

The following may be given as an example of the economics of utilization: in 1964-1966, the construction of four wells, drilled in basalt, averaging about 125 m in depth; three of 46-cm diameter and one of 30-cm diameter, cost over $1.5 million. These costs include capital cost of the well-field, pumping station and pipelines.

Retention of storm surface run-off in the Pearl Harbor area in temporary reservoirs, from which it will infiltrate to ground water, could salvage a large proportion of the run-off of 120,000 $m^3$/day. A study is recommended.

The fresh-water surplus in the east Pearl Harbor area, visibly wasted from springs, suggests exporting water to the Honolulu district. Development of additional water would be accomplished by pumping directly from the springs or by controlling the flow of the springs by pumping from wells.

References:

Lau, L. S. Water development of Kalauao basal springs hydraulic model study. Honolulu, 1962. 107 p. University of Hawaii study sponsored by the Board of Water Supply, City and County of Honolulu.

Lau, L. S. and J. F. Mink. A step in optimizing the development of the basal water lens of southern Oahu, Hawaii. Water Resources Research Center Contribution No. 2 at International Symposium of Scientific Hydrology, Haifa, Israel. 1966.

Visher, F. N. and J. F. Mink. Ground-water resources in southern Oahu, Hawaii. United States Geological Survey Water Supply Paper 1778. 1964. 133 p.

# KARA KUM PLAINS - TURKMEN SOVIET SOCIALIST REPUBLIC*

The background information for the Kara Kum plains is as follows:

(a) Region: Central Asia;

(b) Geography: alluvial plain; areal extent, approximately 300,000 km$^2$; flat terraces and deltas from glacial times, when the Amu Darya River flowed into the Caspian Sea (it now flows into the Aral Sea). This alluvial plain is known as the "Kara Kum desert" (Kara Kum means "black sand" in Turkish.);

(c) Climate: arid to hyperarid; yearly rainfall is usually less than 100 mm; in exceptional cases, it is 200 mm;

(d) Reservoir type: alluvium, deltaic formations.

## Ground-water reservoirs

Geological conditions are characterized by areas of dunes known as barkhans. Elsewhere, in scattered areas, known as takyr, the land is covered by a thin clayey-silty layer, up to a maximum of 1 m thick. These superficial formations cap the sands of the Kara Kum formation several hundreds of metres thick.

Most of the ground water is highly saline in depth. It is estimated that there are about 30,000-40,000 km$^3$ of brackish waters, with a concentration often exceeding 20,000 parts per million (ppm). Natural replenishment of ground water occurs by losses from river-beds or channels ending at the periphery of the desert. The role of precipitation in the replenishment of ground water is of interest. On most of the area of sand, replenishment is nil because of vegetation composed of desert grasses and desert brush, which fully utilizes all precipitation by transpiration. Only in special areas of dunes (barkhans), can precipitation infiltrate and reach the water-table in years of heavy rainfall. Therefore, there is fresh ground water under these areas. This is unique, as there is no other fresh ground water in the entire vast desert area.

There is a great flow of ground water under water-table conditions. However, this ground water may also be considered as a storage reservoir, as its flow is only on the order of 10 m/year. The gradient of the water-table is on the order of $10^{-4}$. The material consists of heterogeneous silting and sands with clay layers. Therefore, local confinement exists, but pressure is not higher than the water-table and the system is hydraulically homogeneous.

Many wells are in use in Kara Kum, tapping fresh or brackish water. The main use is for the watering of livestock, especially Karakul sheep and one-humped camels. These animals can live on waters containing from 7,000 to 10,000 ppm. In winter, they can live on water containing 13,000-15,000 ppm. However, in large parts of the desert, even waters of these salinities cannot be found.

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* Case study No. 14 prepared by V. Kunin (Union of Soviet Socialist Republics).

## Artificial recharge

For several centuries, nomads have been using the takyr clayey (takyr means "bald" in Turkish) areas as follows.

The slopes of the takyr are gentle, but sufficient for water run-off. An excavation of a moderate size was made at the lowest point of the takyr. Surface run-off was led to this excavation by a primitive net of small channels. Material excavated from these channels was left in isolated piles so that run-off was free to reach the excavation.

Spring rains fill the excavation and infiltrate through the zone of aeration; they eventually build a floating lens of fresh water at the level of the water-table. As ground-water movement is very slow, this lens in heterogeneous sands is stable. For accelerating the infiltration process, the nomads dig absorption wells around the periphery of the excavation. Casing for these wells is made from brush, and thus the infiltration conditions are very good.

The main difficulty is the large amount of colloidal particles in suspension in the recharge water, making it impossible to use settling basins. The excavation and wells become very muddy, and it is necessary to clean them about once a year. Cleaning out of colloidal particles has always been difficult for the nomads, as it is now, even when using modern techniques. Other problems were solved by the nomads hundreds of years ago in a manner no worse than the solution of these problems today. (The nomads, of course, are not aware of laws of filtration and other laws of hydrodynamics.) The wells were constructed so the lens was roughly circular in form. Wells that withdraw the water are close to the edge, or thin part, of the lens. Here, a mixture of fresh and underlying salt water occurs. These wells generally give water 5,000-10,000 ppm in quality, which is usable for livestock. Hence, the fresh rainwater is utilized most economically.

For his own use, the stock-breeder puts in two or three wells in the central part of the lens. In this way, he obtains water for human use of about 1,000 ppm in quality.

As previously mentioned, the average yearly rainfall does not exceed 100 mm. However, there are many dry winters and springs, with only one or two small useful rainfalls. Nevertheless, the takyr system is ready to accept water for recharge at any time. Summer showers are very rare, and do not occur every year. If a dry summer follows a dry winter and spring, the situation becomes critical. Fully aware of the conditions, the nomad does not use all the wells of his installation simultaneously, but rather one by one. This permits a more extended use of each lens. In addition, certain takyr systems are normally retained in reserve for use only in extremely dry years.

If all wells in a system yield only salt water, the nomad takes the following steps: the less saline wells are chosen; sand is poured into the bottom of the well; then the well gives more water (fresh) from the sides than from the bottom (saline). A flat leather bucket is used to obtain the shallowest water.

A special filter was created for running sands. It is a woven basket in the shape of a ring made of branches. The ring is one half-1 m high and the rim is one half m thick. The diameter of the ring is from 4 to 6 m. The openings are very tightly filled with desert grass and tied by ropes of camel wool which do not rot or decay in water. Such a well can operate from 20 to 30 years. Better than any other technique, this sophisticated empirical method permits the withdrawal of fresh water from a floating lens from 5 to 10 m thick. Areas outside of Central Asia where this amazingly efficient technique is used are not known, and it is likely that it originated in that part of the world. This method permits the extraction of fresh water by wells, in a vast area where, under natural conditions, nothing but saline water would be found; and, therefore, no water for current use. Some dug wells of the Iranian type, with brick casing, were constructed in this area, but proved to be unsatisfactory.

Scientists in the Union of Soviet Socialist Republics have conducted a study along the lines of artificial recharge and ground-water development described above, and on this basis devised methods to obtain ground water in the desert. Based on that study, ephemeral run-off was assessed at 5,000-20,000 $m^3/km^2$ of the <u>takyr</u> watershed. The optimum volume of the recharge excavation was calculated on this basis. It was not possible to find any method better than the traditional one of artificial ground-water recharge; storage tanks, for example, are too expensive.

Moreover, one scientist proposed a method of desalination by natural freezing. Fresh ice was obtained from saline ground water. This method may become the cheapest method in areas of saline water, where freezing temperatures are common during the winter period. The main obstacle to this method is the need for a storage reservoir. In this regard, no better method than the traditional one of artificial recharge could be found. Methods for collecting water from artificially treated watersheds were attempted. However, the storage problem is so severe that again the traditional method appears to be the best.

The cost of methods of artificially treating watershed and collecting water from areas of from 0.5 to 3.0 $km^2$ is not high. The cost of the primitive system is very low. Cleaning of the dug wells is necessary under any method of exploitation. The cost of cleaning the recharge excavation once a year is very low. The cost of water recharged in this manner, and then extracted, is only 10-20 per cent greater than that obtained simply from dug wells. As the system is traditional, it is very difficult to obtain a true cost. It is clear, however, that there have never been any obstacles from the economic point of view.

The costs can be assessed on the following bases: 10-20 dug wells are necessary for each <u>takyr</u> system; lights of wells being from 5-30, according to local conditions. The length of the net of channels is 2-3 km on 1 $km^2$, and the size of the recharge excavation varies from 1 to 10,000 $m^3$ in volume. The excavation can be cleaned by a caterpillar tractor.

The main cost is for the lifting of water, as in any system of dug wells. If the <u>takyr</u> system is well maintained, it functions for 30-50 years. The cost of water is thus in the range of that extracted from dug wells. This method is usable for all sediments under alluvial and fan-periphery conditions. Attempts to use mechanical pumps have destroyed the fresh-water lenses.

# GROUND-WATER RESERVOIR OF KARLSKOGA, SWEDEN*

The background information for the ground-water reservoir of Karlskoga:

(a) Region: region of Stockholm, Sweden;

(b) Geography: fluvio-glacial alluvium in the valley of the Tunsalver River;

(c) Climate: humid, cold;

(d) Reservoir type: alluvial sands and gravels with clayey horizons.

## Ground-water reservoirs

Geological conditions are characterized by alluvial deposits in a valley. The geological log is as follows: peat and clays; sands and gravels, very permeable, of fluvio-glacial origin; and a clayey substratum. The main aquifer is composed of sands and gravels. The average thickness of the aquifer is 10 m; the hydraulic conductivity coefficient is from 100 to 1,000 m/day. The volume of water in storage is estimated at 1 x $10^6$ $m^3$/sq/km.

Water quality is shown in the following table:

| | Temperature (centigrade) | Turbidity (parts per million) | $KMnO_4$ | Hardness (parts per million of CaO) | Fe (parts per million) | E. Coli (per hundred) |
|---|---|---|---|---|---|---|
| River | 0-19 | 25 | 31 | 10 | 0.37 | 23 |
| Swift infiltration | 0-19 | 23 | 29 | -- | - | 0 |
| Pumping | 4-7 | less than 5 | 7 | 40 | 0.10 | 8 |

The exploitation of 17 stations in the area gave the following results:

| Water from the river utilized for artificial recharge | Minimum | Average | Maximum |
|---|---|---|---|
| $KMnO_4$ (parts per million) . | 11 | 25 | 55 |
| E. Coli (per 100 ml) | 10 | 650 | 2,000 |
| Bacteria (per 1 ml) | 200 | 1,200 | 3,300 |
| Ground water | | | |
| $KMnO_4$ (ppm) | 4 | 9 | 21 |
| E. Coli (per 100 ml) | 0 | 0 | 38 |

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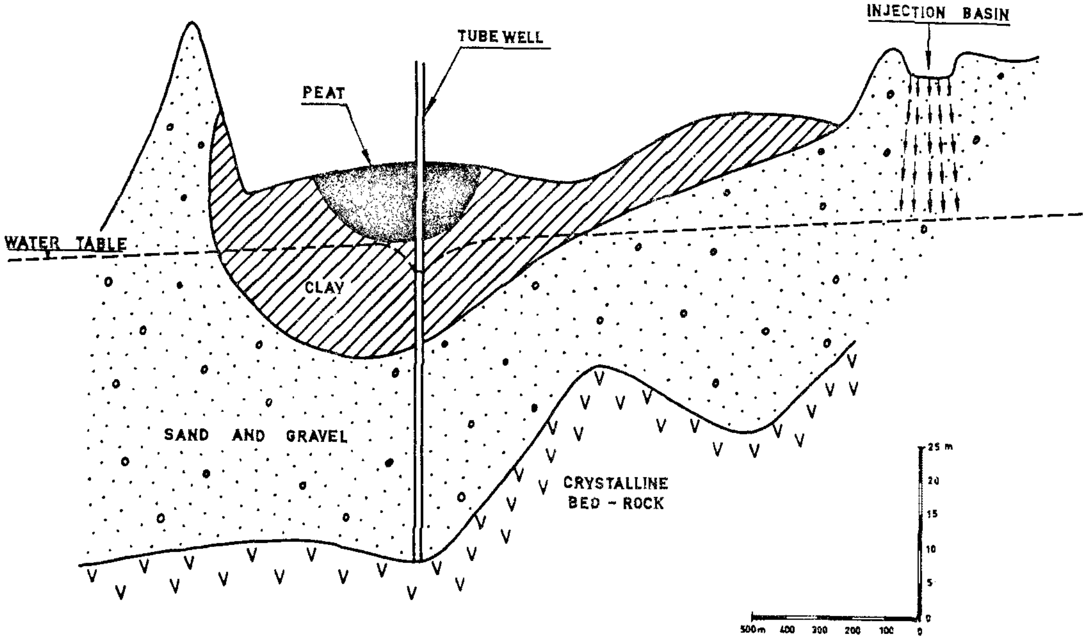
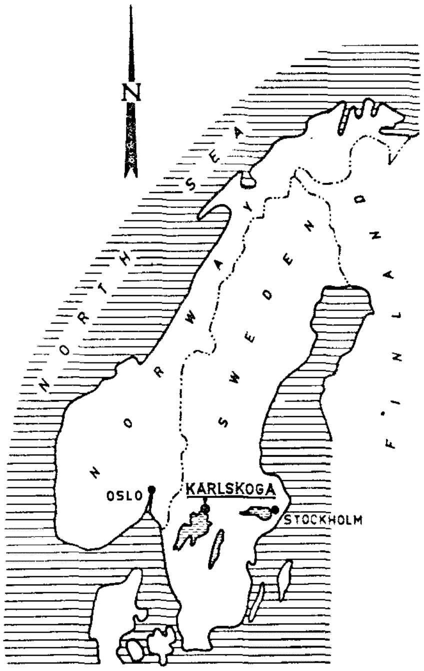
* Case study No. 15 prepared by G. Castany (France).

FIGURE 22



# KARLSKOGA GROUND-WATER RESERVOIR, SWEDEN



LOCATION MAP

CASE STUDY Nº 15

## Utilization of ground water

The ground water is used to supply the populated areas. All 17 stations have an output of 180,000 m$^3$/day, which will be increased to 400,000 m$^3$/day.

## Artifical recharge

The purpose of artifical recharge is for storage and natural filtration of surface water in the aquifer, leading to thermal regulation and an improvement of physico-chemical characteristics (see previous table). The Karlskoga station was constructed in 1946. Other stations have existed in Sweden since 1897.

Waters originate from the Tunsalver River. After treatment by rapid filtration, the water is brought into infiltration basins the bottoms of which are located 12 m above the piezometric surface. The installation includes four basins of 625 m$^2$ with vertical concrete walls. The bottom is filled with a layer of sand 1 m thick with an effective diameter of the grains from 0.2 to 0.3 mm. The theoretical filtration speed is 7 m/day. Flow infiltrated continuously 15,000 m$^3$/day. No treatment is given after pumping.

The characteristics of the 17 stations are as follows:

| | Minimum | Average | Maximum |
|---|---|---|---|
| Elevation of the infiltration basin above the piezometric surface (metres) | 2 | 8 | 30 |
| Effective diameter of the grains of the water-bearing formation (mm) | 0.2 | 0.4 | 1.7 |
| Rate of infiltration (metres/day) | 1.5 | 6 | 16 |
| Run made in the aquifer (metres) | 100 | 400 | 1,700 |

References:

Alimentation artificielle des nappes souterraines. Etudes documentaire provisoire. J. Archambault, *et autres*. *Bulletin du Bureau de Recherches géologiques et minières* (Orleans), section III: hydrogéologie, 2:7 et 30. 1968.

Jansa, O. Ve., Artificial ground-water supplies in Sweden. Rome, AIHS, pp. 269-275. 1954.

# DAKHLA AND KHARGA OASES, EGYPT*

The background information for the Dakhla and Kharga oases is as follows:

(a) Region: north-eastern Africa;

(b) Geography: extensive depressions (oases) in desert plains;

(c) Climate: arid: mean annual rainfall in the Dakhla oasis, 1 mm; in the Kharga oasis, less than 1 mm. Rainy season, if any, in the winter. Temperature, over 50°C during the summer;

(d) Reservoir type: sedimentary basin, artesian aquifer;

(e) Methods of investigation: geological mapping; geophysical exploration (gravimetric, aeromagnetic); drilling; age-dating by carbon-14. An electric analogue model is under construction

## Ground-water reservoirs

The Nubian sandstone (Cretaceous) uniformly underlies a vast region of the north-east of Africa several millions of square kilometres in area. The outcrop area of this formation is as far as 1,000 km to the south of the oases in Sudan and Chad. Maximum thickness is 2,500 m. Faults, anticlines, synclines and deep channels exist, and influence ground-water occurrence and flow.

Sandstone constitutes the principal reservoir rock. Interbedded shales of low permeability make the aquifer heterogeneous and highly anisotropic. Eight water-bearing zones have been distinguished. However, the aquifer may be considered one hydrological unit with vertical leakage. Temperature of the water increases with depth.

Two analogue models have been designed. The model of the two oases simulates an area about 270 x 180 km. A general model of the Western Desert simulates an area about 700 x 1,000 km.

Water in deep aquifers is fair to good in quality. Water in shallow aquifers, in some places, is poor in quality owing to high evaporation and salt deposition. Principal recharge of the ground-water reservoir took place during the Pleistocene period. The age of the water determined by carbon-14 dating, varies from 20,000 to 30,000 years. Abundant precipitation evidently took place in the Pleistocene period. Currently, recharge by precipitation is practically nil. The waters of the Nile River contribute locally, but their over-all effect is negligible.

The hydraulic conductivity coefficient ($K$) varies from 2 to 5 m/day.

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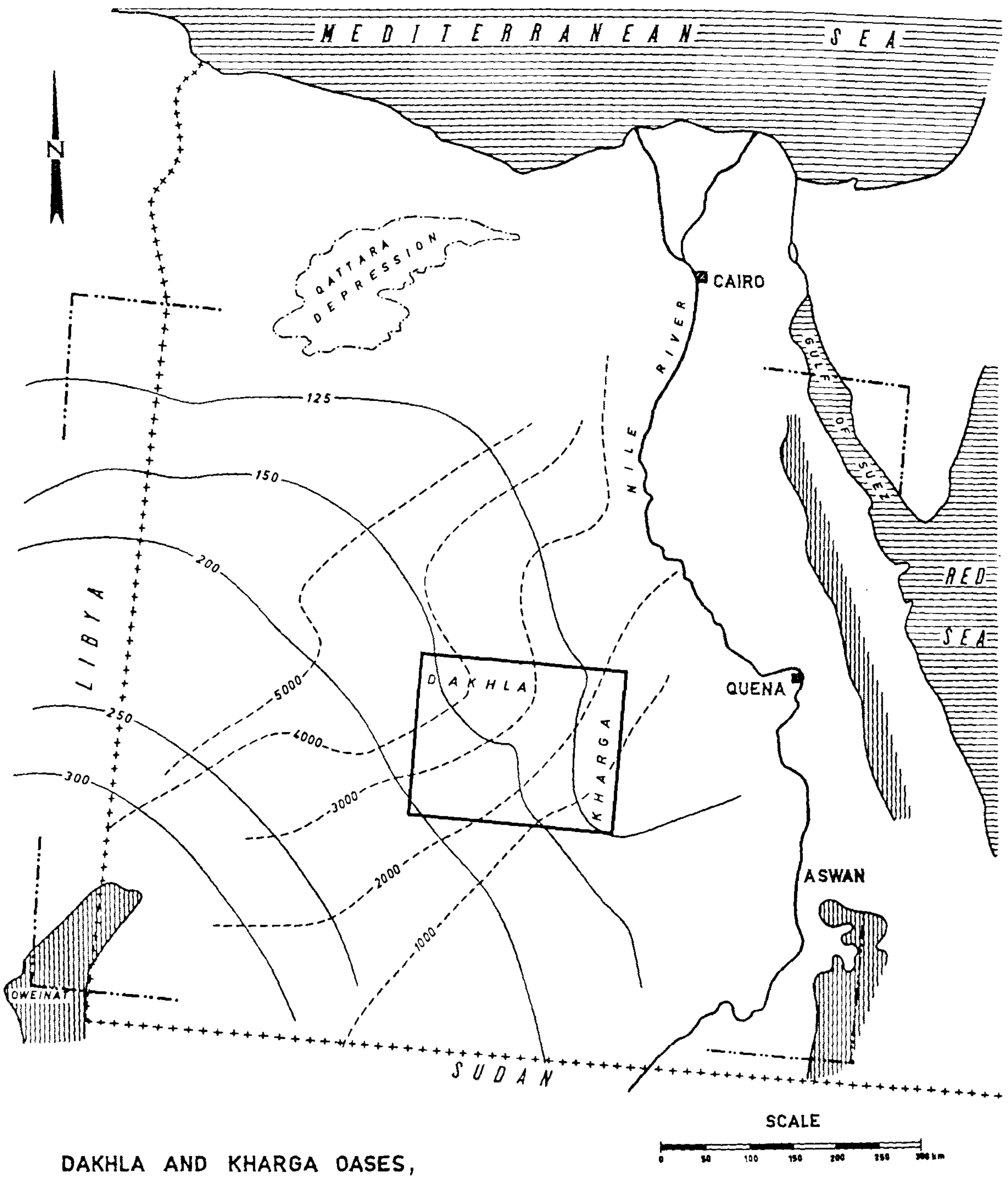
* Case study No. 16 prepared by R. De Wiest (United States of America).

FIGURE 23



## DAKHLA AND KHARGA OASES, EGYPT

WESTERN DESERT (UAR)
HYDROGEOLOGIC CHARACTERISTICS
RELATED TO ANALOGUE MODEL
(After M. BORELI-1968)

CASE STUDY Nº 16

EXPLANATION

| | |
|---|---|
| ┗‑··‑··‑ | BOUNDARY OF GENERAL RC ANALOGUE MODEL |
| ─125─ | CONTOUR LINE OF PIEZOMETRIC HEAD (Metres above MSL) |
| -2000-- | TRANSMISSIVITY CONTOUR LINES (m²/day) |
| ▥ | BASEMENT OUTCROPS |

At Kharga Oasis, coefficient of transmissivity (T), averages about 1,400 $m^2$/day. At Dakhla Oasis, T averages about 4,000 $m^2$/day; coefficient of storage (S) varies from 0.002 to 0.005 in the deeper zones.

Discharge is mostly through wells. Shallow wells (also called "native" or "Roman" wells) produce from the uppermost artesian zone; deep tube-wells produce from the lower artesian zones.

In the Kharga oasis shallow wells discharged 100,000 $m^3$/day in 1961; 130 deep wells discharged 450,000 $m^3$/day in 1962, but only 130,000 $m^3$/day in 1966. The principal reason for the decrease was the decline of artesian pressure. In the Dakhla oasis, shallow wells discharged 190,000 $m^3$/day.

The ground-water balance for the Nubian sandstone aquifer in the Western Desert will be computed with the aid of the analogue model.

## Utilization of ground water

Almost all wells are self-flowing at the time of construction. They flowed freely without control. As a result, the piezometric head declined, and many wells ceased to flow. Pumps were installed in some, but the construction of others did not permit pump installation. Efficiency of most wells was also reduced considerably owing to corrosion of casing and screens. Various kinds of casing and screens have been installed in an attempt to find the most suitable material and design. Water is used principally for human consumption and small-scale irrigation.

The economical-technical problems are: (a) The great depth of drilling, exceeding 1,000 m in some places; and (b) The anticipated lowering of the water level by future exploitation (1 m/year) will require deep-well pumps and a power supply. The hydrological problems are: (a) Inadequate spacing of wells, resulting in over-exploitation of the same water-bearing zone in the same area; and (b) Uncontrolled water flow.

Proper development of the ground-water reservoir is essential for the continued social and economic well-being of the region. It is hoped that the analogue models will simulate conditions accurately; and thus be utilized to determine either safe yield or the rate of mining and head decline, so that proper provision for suitable well-construction and pumps can be made.

## References:

Arab Technical Committee. Groundwater potential of the New Valley. Report No. 1. 1965.

Basis of analogue models of Kharga and Dakhla oases. M. Boreli *and others*. 1968.

Ezzat, M. A. Preliminary report of the hydrogeology of the New Valley, Western Desert. 1962.

Salem, M. H. Design of the analog model of the Western Desert. 1963.

Scientific report on the subsurface geology of El Kharga oasis. C. E. Jacob *and others*. Cairo. 1959.

# LONG ISLAND RECHARGE SCHEME, UNITED STATES OF AMERICA*

The background information for the Long Island recharge scheme is as follows:

(a) Region: Atlantic coast of the United States of America (New York state);

(b) Geography: island 200 km long and 25 km wide; areal extent, 3,500 $km^2$; maximum altitude, 120 m;

(c) Climate: temperate (oceanic), humid; average annual precipitation is from 1,000 to 1,200 mm;

(d) Reservoir type: unconsolidated clastic sediments, gravel, sand, silt and clay, and mixtures thereof;

(e) Methods of investigation: Hydrogeological surveys, test drilling and pumping, injection tests, analogue model studies, water balances assessment.

## Ground-water reservoirs

Long Island is underlain by consolidated bed-rock which, in turn, is overlain by a wedge-shaped mass of unconsolidated glacial deposits, up to 700 m thick, dipping to the south.

The aquifers are:

| Aquifer | Age | Thickness (metres) | Water-bearing character |
|---|---|---|---|
| Upper glacial aquifer | Quaternary | 120 | Sand and gravel |
| Jameco aquifer | Quaternary (Pleistocene) | 70 | Medium to coarse sand |
| Magothy aquifer | Upper Cretaceous | 300 | Coarse to fine sand |
| Lloyd aquifer | Upper Cretaceous | 100 | Sand and gravel |

Impervious layers of clays and silts come between these water-bearing superposed units.

The total volume of material saturated with fresh water beneath Long Island exceeds 1,200 $km^3$. The total volume beneath the water-balance area described hereafter is 750 $km^3$. (See shaded section of figure 24.)

Aquifer parameters are as follows:

(a) Porosity, 30 per cent;

(b) Total water in storage under water-balance area, 250,000 million $m^3$;

(c) Average specific yield, 5-10 per cent;

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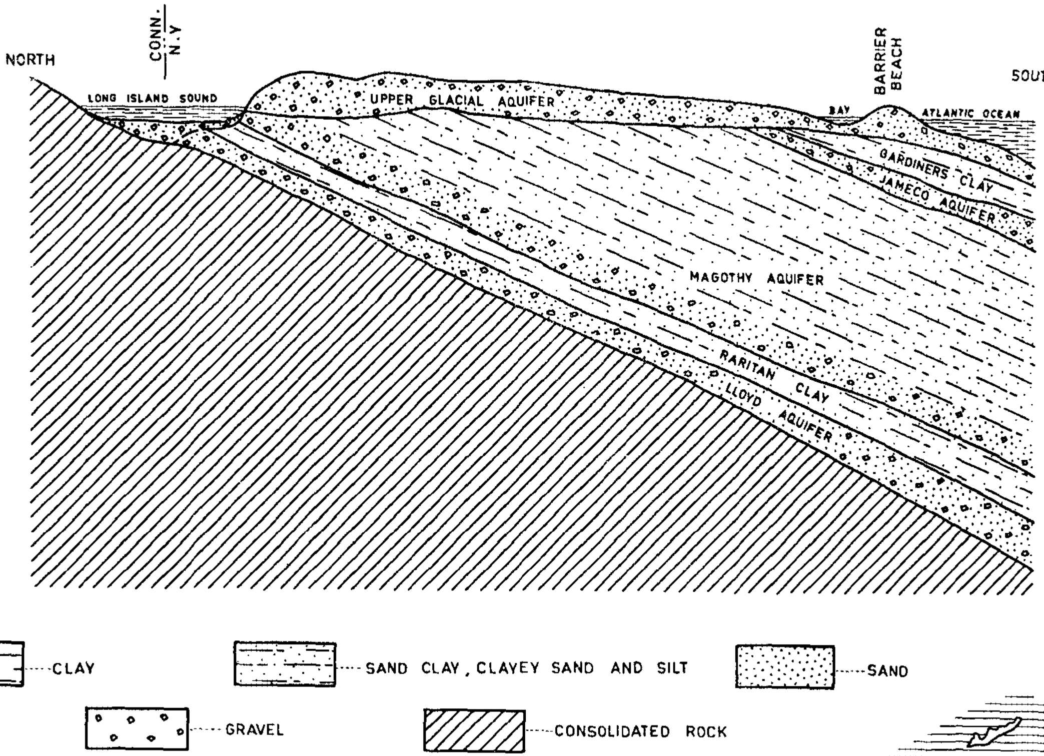
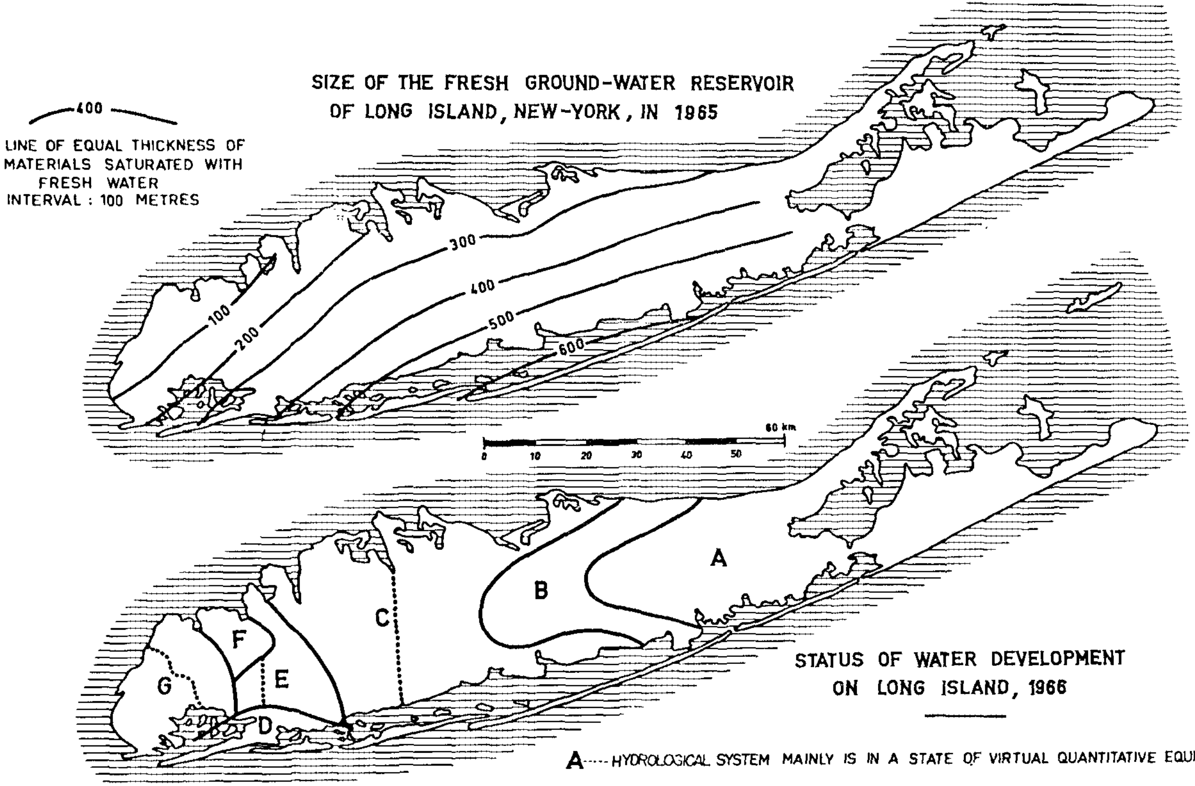
* Case study No. 17 prepared by R. De Wiest (United States of America).

FIGURE 24





SIZE OF THE FRESH GROUND-WATER RESERVOIR OF LONG ISLAND, NEW-YORK, IN 1965

STATUS OF WATER DEVELOPMENT ON LONG ISLAND, 1966

A ---- HYDROLOGICAL SYSTEM MAINLY IS IN A STATE OF VIRTUAL QUANTITATIVE EQUILIBRIUM

B ---- TRANSITIONAL IN DEVELOPMENT BETWEEN SUBAREAS A AND C

C ---- HYDROLOGICAL SYSTEM IS LOCALLY OUT OF BALANCE: LOCAL SALT-WATER INTRUSION

D ---- HYDROLOGICAL SYSTEM IS OUT OF BALANCE: WIDESPREAD SALT-WATER INTRUSION

E ---- HYDROLOGICAL SYSTEM IS OUT OF BALANCE: MAY BE SUBJECT TO SALT-WATER INTRUSION IN FUTURE

F ---- GROUND-WATER DEVELOPMENT IS NEGLIGIBLE AND THE HYDROLOGICAL SYSTEM IS IN BALANCE

G ---- LARGE PARTS OF THE SUBAREA ARE CONTAMINATED WITH SALTY GROUND WATER DUE TO FORMER INTENSIVE GROUND-WATER DEVELOPMENT AND RELATED SALT-WATER INTRUSION

## LONG ISLAND RECHARGE SCHEME, UNITED STATES OF AMERICA

CASE STUDY Nº 17

(d) Maximum amount of ground water available through drainage, 12,000-25,000 million m$^3$;

(e) Lloyd aquifer:

(i) Transmissivity (T), 2,300 m$^2$/day;

(ii) Hydraulic conductivity, 36 m/day;

(iii) Storage coefficient, 0.0003;

(f) Magothy aquifer: T, 600-3,000 m$^2$/day.

The content of dissolved solids is commonly less than 100 parts per million (ppm), often less than 50 ppm and the hardness is less than 40 ppm. Chloride content is from 10 to 30 ppm. Owing to this low mineralization the waters are corrosive. Deep ground water, originating from the Magothy and Lloyd aquifers, have an iron content exceeding the 0.3 ppm limit recommended for public supply use; an appropriate treatment removes the ferrous content and the corrosion-potential. Locally sulphate, nitrate and other salts indicate a contamination of the aquifer, due to agricultural, industrial and other activities of man. Sea-water intrusion occurs on the shore lines. The minimal mineralizations are found in the centre of the island in the vicinity of surface-water bodies and in areas of high infiltration rates.

Recharge amounts to 3.2 million m$^3$/year with an average of 600 mm/day. The average high is 825; the average low is 300. Ground-water movement is northward and southward, toward the shores, from a ground-water divide located near the centre of the island. About 1.2 million m$^3$/day of ground water are discharged from the upper glacial aquifer into surface-water bodies and streams. Total subsurface outflow to the swampy lowlands, to the bays and to the ocean is on the order of 1.9 million m$^3$/day. Evapo-transpiration of ground water and spring flow amount to 100,000 m$^3$/day. Total discharge is 3.2 million m$^3$/day. Recharge, ground-water movement and discharge, as expressed above, represent the water-balance existing under natural conditions in Long Island (except for the western and eastern ends), before it was modified by human activities from 1930 to 1940, described in the section which follows.

## Utilization of ground-water

Ground water is mainly exploited for the water supply of communities and for industrial use. The population of Long Island was about 7 million in 1965; 4.5 million were living in the westernmost part of the island and were supplied with water mainly from surface sources located in upstate New York. The other 2.5 million were utilizing ground water. Total gross pumpage for the island amounted to 1,720,000 m$^3$/day in 1965 (900,000 m$^3$ in 1940); community water supply accounts for 70 per cent of this total.

The rapid growth of urbanization tends to increase the surface-water flow (roofs, paved surfaces), but 2,000 recharge basins, or "sumps" have been dug and absorb most of the surface run-off. These sumps have a surface area of from 0.2 to 10 ha and are from 3 to 7 m deep. Infiltration is generally fast (less than one day). In addition, about 1,000 "diffusion wells", sometimes reaching a depth of

100 metres, are returning used ground water to the ground-water reservoirs of Long Island. Some can accept rates of infiltration exceeding 35 l/sec.

The intensification of ground-water exploitation in Long Island has resulted in: (a) Declining ground-water levels; (b) Sea-water intrusion in coastal areas; (c) Contamination of fresh ground water by domestic and industrial pollutants (detergents, cadmium and chromium salts) in some areas.

As urbanization is developing at an increasing rate in central and even eastern Long Island, the conservation of water resources requires special attention. An experimental tertiary treatment-plant for sewage waters has been operating at Bay Park for the past few years. The treated waters are injected into an experimental test well. Several possible management alternatives have been studied and are described in the following table.

References:

New York state. An atlas of Long Island's water resources. Water Resources Commission Bulletin C-2, 1968. Contains a great number of selected references.

| Possible management alternatives | Results |
|---|---|
| (1) Proposal to continue with the present methods: extraction of ground water from shallow unconfined and deeply confined aquifers; artificial recharge with polluted waste water through cesspools and septic tanks; injection of less contaminated water through diffusion wells; artificial recharge with direct run-off water through shallow basins; discharge into the sea of large amounts of treated sewage water; importation of surface water (in the western part of the island). | The hydrological imbalance will increase and ground-water levels will continue to decline. Salty ground water will continue to move inland at the rate of 30 m/year. Current conditions are of planned overdraught. However, the life of the reservoir will exceed 50 years, and, perhaps, several hundred years. |
| (2) Proposal to develop barrier-injection wells in Nassau County. | The injection of 100,000 $m^3$/day of highly treated sewage affluent will improve the water budget. |
| (3) Proposal to develop pumping troughs. | Prevention of salt-water encroachment without increasing availability of water. |
| (4) Proposal to inject treated waste-water through recharge basins. | Similar to (2), but deep aquifer will not be recharged. |
| (5) Proposal to permit salt-water intrusion. | More ground water will be extracted. This method is to be employed in conjunction with others. |
| (6) Proposal to develop shallow skimming wells (other alternatives exist). | This will permit recovery of surface water presently lost to the sea (more than 1 million $m^3$/day). But some of this water is poor quality and should be treated. |

# LOS ANGELES COUNTY, UNITED STATES OF AMERICA*

The background information for Los Angeles County is as follows:

(a) Geography: coastal plain and inland valleys;

(b) Climate: semi-arid. The rainfall varies from a high of 1,100 mm in the mountains to a low of 100 mm along portions of the coastline, with an average of 400 mm. The rainy season extends from 15 October to 15 April, although almost 80 per cent of the rainfall occurs during the months of December, January, February and March;

(c) Reservoir type: unconsolidated continental and marine deposits;

(d) Methods of investigation: geological mapping, geophysical and geochemical studies, deep drilling, pumping tests, modelling by digital computer and other methods.

## Geological conditions

The ground-water reservoirs of Los Angeles County consist of unconsolidated Pleistocene and Recent sedimentary fill in basins surrounded by older, largely non-water-bearing rocks. The configuration of the valleys and basins is shown in figure 25. In the northern part of the area, the San Gabriel Mountains are made up almost entirely of old crystalline rocks (igneous and metamorphic), and thus do not contain significant amounts of ground water. However, the run-off from rainfall on these steep-sided mountains begins to infiltrate as soon as it reaches the alluvial valleys, and is the main source of ground water in the valleys.

The San Fernando and San Gabriel Valleys are the principal ground-water basins at the foot of the San Gabriel Mountains. Elevations in these valleys vary from about 300 m at the base of the mountains to about 75 m in the lower sediments having moderate to high permeabilities. Aquifers are generally not confined, and the permeability is sufficiently high that the basins are very receptive to replenishment by infiltration from the surface.

In a few small areas, lower Pleistocene and older sediments of moderate permeability are also present. Most of these occur in blocks uplifted along the many active faults of the region.

Farther to the south, the central and west coast basins also contain excellent water-bearing materials. These are unconsolidated sediments of Recent and Pleistocene age, and include both continental and marine beds. Permeability of aquifer materials varies from moderate to high.

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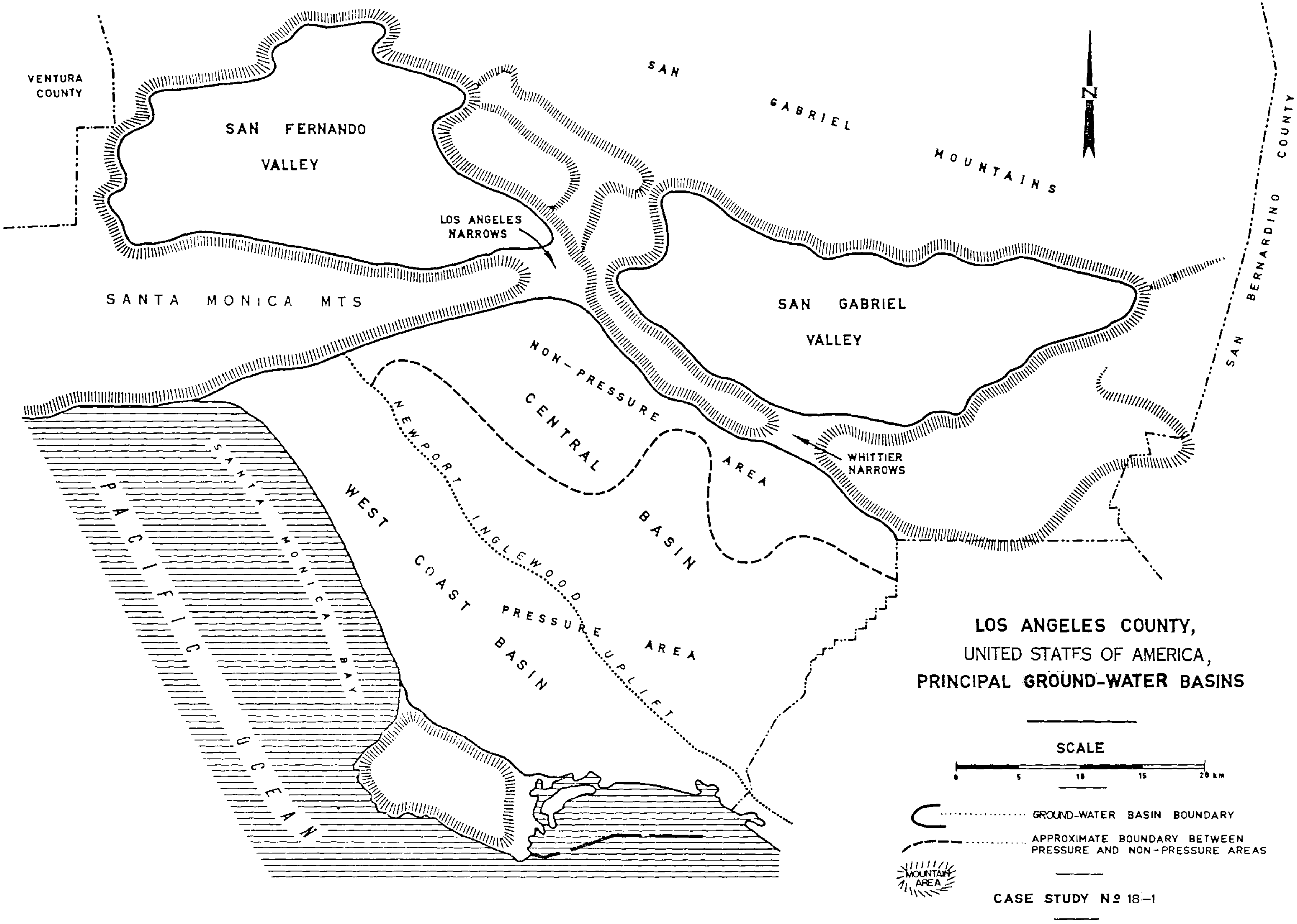
* Case study No. 18 prepared by C. Milne (United States of America).

FIGURE 25



**LOS ANGELES COUNTY,**
UNITED STATES OF AMERICA,
**PRINCIPAL GROUND-WATER BASINS**

CASE STUDY Nº 18–1

True water-table conditions exist in the central basin only, in the area labelled "Non-pressure area" on figure 25. Elsewhere, ground water is mostly confined, and direct recharge from the surface is greatly reduced, although apparently not entirely eliminated.

The two principal natural recharge areas for the central basin occur just south of the Los Angeles Narrows and the Whittier Narrows (see figure 25). The Los Angeles River enters the basin at the Los Angeles Narrows, and both the San Gabriel River and Rio Hondo enter at the Whittier Narrows, which is called the Montebello Forebay. Intense urban development has essentially eliminated recharge south of the Los Angeles Narrows, but the Montebello Forebay contains the largest spreading-grounds complex in the Los Angeles area and is the subject of one of the following discussions.

The coastal margin of the west coast basin and near-coast portion of central basin are subject to sea-water intrusion. To prevent the further advancement of this intrusion, three barrier projects of the injection-well type are being developed. Two are operative and are the subjects of later discussions.

## Principal aquifers

Figure 25 shows the principal ground-water basins in Los Angeles County. For ease in presentation, only the four major basins are shown; these include many sub-basins and each basin includes many aquifers.

Estimated or calculated storage capacity of the ground-water basins is based on the specific yield of the various materials encountered in wells, followed by weighted averaging of specific yield for each pertinent depth zone in the area under consideration.

The San Fernando basin covers an area of about 530 km$^2$. The easterly portion of this basin is the best for ground-water replenishment from surface infiltration. It is estimated that this ground-water basin has a storage capacity of about 1,200 million m$^3$.

The San Gabriel Valley basin covers an area of about 520 km$^2$. Most of it is amenable to ground-water replenishment from surface infiltration. It is estimated that this ground-water basin contains a storage capacity of over 10,000 million m$^3$. Most of the spreading-grounds and basins in Los Angeles County are located in this area, principally along the base of the San Gabriel Mountains on the north.

The central basin and west coast basin together comprise the coastal plain. The central basin covers an area of about 750 km$^2$. The west coast basin covers an area of about 465 km$^2$. Together they have an estimated storage capacity of about 35,000 million m$^3$.

The fresh-water-bearing sediments of the coastal plain extend to depths of more than 600 m. Study of the materials penetrated by wells in the coastal plain has made it possible to identify aquifer sequences which include, in some places, at least seven aquifers, with their intervening low-permeability beds. The aquifers are principally composed of unconsolidated sand and gravel, while the low permeability beds are high in silt and clay.

Transmissivities in the various aquifers range from less than 100 $m^2$/day to over 5,000 $m^2$/day. The highest transmissivities occur in the Silverado aquifer (Upper Pleistocene), which locally attains a thickness of about 150 m. Transmissivity of the combined aquifers is more than 10,000 $m^2$/day in some locations.

Leakage coefficients, obtained from pumping tests in the various aquifers, range from $6.6 \times 10^{-11}$ $m^2$/day to $2.9 \times 10^{-9}$ $m^2$/day. Estimated vertical permeability between aquifers thus ranges from $6.5 \times 10^{-10}$ m/day to $1.5 \times 10^{-7}$ m/day. Storage coefficients in these tests ranged from $4.2 \times 10^{-5}$ to $1.6 \times 10^{-2}$, and are illustrative of the confined conditions encountered.

Water quality is generally acceptable for domestic, industrial and agricultural uses, except for areas near the coast, where sea-water intrusion has essentially curtailed all uses except as injected water for the secondary recovery of oil. An estimated 850 million $m^3$ of sea-water has intruded the ground-water basins along the coast of Los Angeles County.

Replenishment of ground water occurs through infiltration of water from various sources, subsurface inflow and injection of water for sea-water intrusion barriers. The sources of infiltration are natural infiltration of run-off, infiltration of precipitation and water applied for irrigation, and artificial recharge of natural run-off and of imported and reclaimed water. Original ground-water movement, which was generally south in the inland basins and toward the coast in the coastal plain, has been modified and is now toward the areas of heaviest extraction in all basins.

Artificial discharge of ground water through wells has increased greatly over the years. A marked increase of extractions followed the Second World War until the last decade, when adjudication of water rights in the basins began, and resulted in more stabilization of ground-water extractions. No significant natural discharge of ground water remains.

Artificial extractions of ground water and safe yields were as follows:

| | Hydrological year 1968/1969 (millions of cubic metres) | Safe yields per annum (millions of cubic metres) |
|---|---|---|
| San Fernando Valley | 130 | 75 |
| San Gabriel Valley | 258 | 215 |
| Central basin | 264 | 160 |
| West coast basin | 75 | 25 |

Water levels in the various basins, as well as all items of water supply to and disposal from the basins are now monitored carefully. Artificial recharge with natural run-off and imported and reclaimed water has reduced the accumulated over-draught in all basins. Both the California State Department of Water Resources and local agencies have drafted management plans basically on the safe-yield concept. Artificial recharge has now essentially eliminated the accumulated over-draught in the coastal plain.

## Utilization of ground water

Ground water is being utilized for domestic, industrial and agricultural purposes, with maximum utilization being achieved. Ground water is also being utilized in conjunction with an imported water programme. Two thirds of the water used in this programme is from sources about 400 km from the Los Angeles area; in 1972, new sources 800 km away became available. The optimization of uses of imported water requires that peaking problems be solved by ground-water extractions.

Problems are associated with over-draught, including prevention of sea-water intrusion; pollution by industrial works; and salt balance. Present utilization is about maximum; future utilization will stress greater efficiency. Ground-water reservoirs are now being used for storage of imported and reclaimed water; in future greater use will be made of them for such purposes.

## Artificial recharge

Purposes of artificial recharge are:

(a) Conservation of local storm run-off;

(b) Prevention of sea-water intrusion;

(c) Utilization of ground-water basin storage;

(d) Replenishment of the ground-water basins with imported and reclaimed water; further treatment of reclaimed water also occurs;

(e) Management of the ground-water basins as the result of adjudications;

(f) Secondary recovery of oil;

(g) Disposal of wastes;

(h) Prevention or control of land subsidence (differential subsidence could pose serious problems).

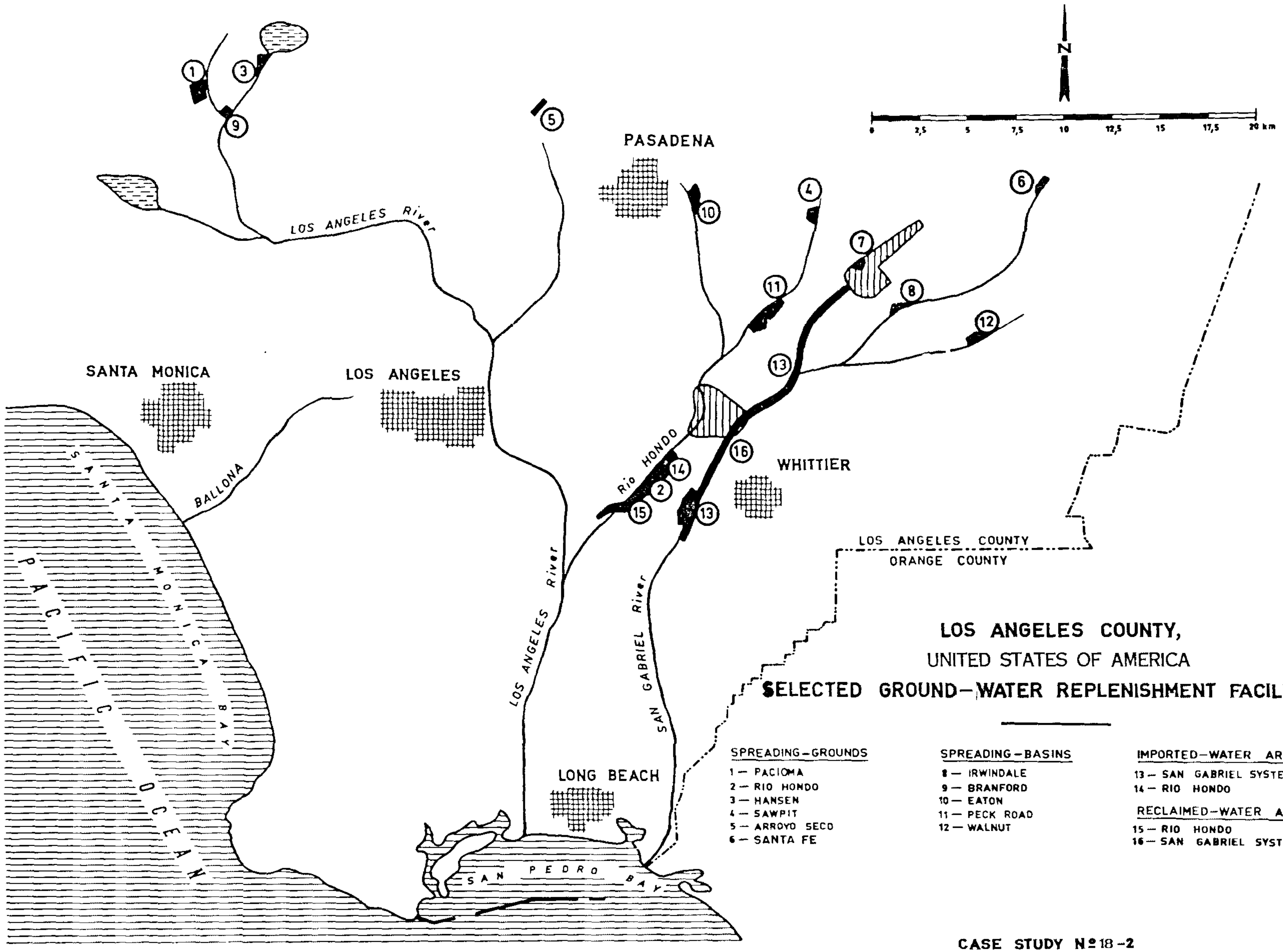
The first five items are of principal concern to the water interests; while the last three are of principal concern to the oil and other industries.

The total gross areal extent of spreading-grounds and basins in Los Angeles County is approximately 1,400 ha, with a combined infiltration capacity of about 60 $m^3$/sec. The Los Angeles County Flood Control District operates 28 spreading-grounds and basins. Of these, seven spreading-grounds and five spreading-basins were selected for further discussion. Costs per thousands of cubic metres of water recharge are listed in tables 1-3. The following sections contain brief descriptions and explanations of the spreading grounds; figure 26 shows their locations.

Recharge costs are affected by wet and dry cycles and whether the sources of water for spreading originate from uncontrolled run-off or from controlled dam-releases. In addition, the location of the facility has a bearing on the cost. If located in a heavily developed area, supervision of the operations must be carried out on an around-the-clock basis.

All of the spreading-grounds were justified and developed on the basis of

FIGURE 26



## LOS ANGELES COUNTY,
UNITED STATES OF AMERICA
## SELECTED GROUND-WATER REPLENISHMENT FACILITIES

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SPREADING-GROUNDS

1 — PACIOMA
2 — RIO HONDO
3 — HANSEN
4 — SAWPIT
5 — ARROYO SECO
6 — SANTA FE

SPREADING-BASINS

8 — IRWINDALE
9 — BRANFORD
10 — EATON
11 — PECK ROAD
12 — WALNUT

IMPORTED-WATER AREAS

13 — SAN GABRIEL SYSTEM
14 — RIO HONDO

RECLAIMED-WATER AREAS

15 — RIO HONDO
16 — SAN GABRIEL SYSTEM

CASE STUDY Nº 18-2

spreading local storm run-off. On this basis, the costs of spreading imported and reclaimed water (reclaimed sewage effluent) represent only operation and maintenance costs, except for a few capital outlay costs associated only with the delivery of imported or reclaimed water.

## Pacoima spreading-grounds

The spreading-grounds are located in San Fernando Valley (see figure 26) in a heavily developed area.

The 38 basins have a depth of about 1.5 m, occupy a gross area of 71 ha, with a wetted, or net, area of 49 ha. Infiltration capacity is about 3.1 $m^3$/sec and storage capacity is 407,220 $m^3$ of water. At this time only storm water is spread, although plans are being developed for spreading imported water in the near future. Reclaimed water may also be spread here within a few years. The storm water represents both uncontrolled run-off and controlled releases from Pacoima Dam. The maximum intake flow ($\underline{Q}$) is 11.3 $m^3$/sec. This is the oldest spreading-grounds in the district. When first constructed, the surrounding area was lightly developed. The current development has dictated the use of screen plantings to make the spreading-grounds aesthetically acceptable. Control of insects is now becoming a problem.

## Rio Hondo spreading-grounds

This spreading-grounds complex is the district's largest. It, along with the San Gabriel spreading system, are located in the Montebello Forebay and are the only ones described in these case histories which lie within the coastal plain; all others are located in the inland valleys. It, too, is located in a heavily developed area.

The 45 basins have a depth of about 1.5 m, occupy a gross area of 231 ha (the largest single basin alone has an area of about 8 ha), and a wetted area of 185 ha. Total infiltration capacity is about 13.75 $m^3$/sec and storage capacity is 2,313,750 $m^3$. A maximum flow of 21.2 $m^3$/sec can be diverted into the east grounds and a maximum of 3.70 $m^3$/sec into the west grounds; when flows in the Rio Hondo are 57 $m^3$/sec or lower, but above the intake capacities, the difference is "undershot" through the gates; when flood flows are above 57 $m^3$/sec in Rio Hondo, the radial gates are maintained in an "up" position and all water is wasted to the ocean. This spreading-ground is now operated on a year-round basis, as it is used for imported and reclaimed water-spreading as well as for storm run-off. Because of this continuous use and because it is a heavily developed area, there have been insect problems. The water creates an ideal environment for insect propagation and operations must be guided to minimize these insect problems.

In general, the district has found the best control to be one of interruption of the life cycle of the insect. Most of the problems have originated with chironomid midges. These insects readily develop in moving water. (Mosquito problems have been minimal because they propagate best in stagnant-water conditions.) The life cycle is interrupted by an operation termed "battery spreading". This simply involves operating only a portion of the spreading grounds at a time; generally one third of the grounds is wet, one third is drying and one third is dry; the period of each lasting from seven to 10 days. This has been very effective for insect-control, much better than the application of insecticides.

In fact, it seems that insecticides also tend to kill off the natural enemies of the midges, thereby disrupting the ecological balance, with the usual result that the midges return much more quickly than their natural enemies, thereby creating a greater infestation than existed before the application of insecticides. This battery spreading also seems beneficial in maintaining infiltration rates which tend to drop off under long-term wet conditions.

From 1937-1953, only local storm-water was available for spreading; spreading of imported water began in 1953 and reclaimed water in 1962. On 30 June 1967, the end of fiscal year 1967, 227,675,000 $m^3$ of local water, 719,583,000 $m^3$ of imported water and 51,222,000 $m^3$ of reclaimed water had been spread. Although developed for local storm run-off, these grounds are now used predominantly for spreading imported water. Because they lie at the down-stream end of a well-developed flood-control system, during the wet winters spreading of local water can extend well into the summer.

Because of the size and importance of this facility, only relatively desilted waters are diverted into the grounds for spreading. Under conditions of normal operation, the silt content is not permitted to exceed 500 mg/l although, in other district facilities, this limit is 1,000 mg/l. To avoid the loss of much valuable water, the district has for many years been using and experimenting with flocculents to remove the silt-load prior to introducing the water into the spreading-grounds. In the case of the Rio Hondo spreading-grounds, the flocculent is introduced into the water in the Rio Hondo just as it leaves Whittier Narrows Dam; and by the time it reaches the still water created in the forebay up-stream from the diversion works flocks have formed and are dropped out in the forebay. The silt-load is then concentrated in a relatively small area for easy and inexpensive removal by truck; or if enough storm water is available, simply by flushing and wasting into the ocean.

The flocculents have been relatively successful in reducing the silt content from a few thousand milligrammes per litre to a few hundred. Costs per 1,000 $m^3$ of water spread have varied from $0.80 to $1.60, and have been reflected in the cost analysis shown. (Of the projects reported here, flocculent facilities are being utilized at Pacoima, Hansen and Irwindale as well as Rio Hondo.)

### Hansen spreading-grounds

This spreading-grounds is located in the San Fernando Valley, down-stream from two flood-regulating dams, Big Tujunga Dam and Hansen Dam. The facility is in an area only lightly residential, a golf course on one side and mostly industrial development on the remaining sides. Only in moderate-to-wet years is water spread on these grounds, and all water results from controlled dam-releases. As a result, problems tend to be minimal and operations are of a routine kind, that is, scheduled, rather than short-notice, emergency-type operations. Accordingly, costs are lower, and these grounds are among the most efficiently operated in the district. They are currently used only for local water-spreading.

The 19 basins each have a depth of about 1.5 m and occupy a gross area of 63 ha, with a wetted area of 45 ha. They have a storage capacity of 284,000 $m^3$ and an infiltration capacity of 5.25 $m^3$/sec. The inlet capacity is 11.3 $m^3$/sec and the outlet capacity 4.25 $m^3$/sec. All of the spreading-grounds, and about half of the spreading-basins, are equipped with outlet facilities (waste-ways), and often spreading operations can be optimized by running a portion of the water through the grounds and back into the channel system. This permits maintaining maximum heads on the water, resulting in maximum infiltration rates, and carries floatable material on through the grounds, thus eliminating the later need of cleaning deposited floatables from the grounds. Normally such passed-through water is not wasted, as there will be another water-conservation facility farther down-stream.

## Sawpit spreading-grounds

This facility is located in the San Gabriel Valley and is the smallest district spreading-grounds. The four basins are shallow and occupy a total area of only 5 ha and a wetted area of only 1.6 ha. The total wetted area is smaller than many of the individual basins at the Rio Hondo spreading-grounds. The Sawpit spreading-grounds are located at the foot of the San Gabriel Mountains, in an area which is excellent for infiltration, as evidenced by the high infiltration capacity of 0.35 $m^3$/sec. Although the grounds are very efficient in terms of spreading, the small total rate of capacity makes this one of the most expensive grounds to operate. If large-volume operations were possible it would be among the least expensive to operate.

## Arroyo Seco spreading-grounds

This spreading-grounds in Raymond Basin, a tributary of the San Gabriel Valley, is composed of 12 shallow basins occupying a gross area of 10 ha, with a wetted area of 5 ha. The down-stream two thirds is located within the limits of Devil's Gate reservoir, and the up-stream one third within a no-cost easement from the City of Pasadena; no-cost because the Pasadena Water Department is the principal beneficiary of ground-water replenishment. Although costs of the rights of way were nothing, the minimal operation makes this one of the more expensive grounds to operate. The grounds have an infiltration capacity of 0.4 $m^3$/sec and a storage capacity of 37,000 $m^3$. The head-works are composed principally of a sand dike which washes out during larger storms and must be replaced. A residential development is on one side of the facility; the spreading-grounds and a portion of the Devil's Gate reservoir are in the centre; and the Jet Propulsion Laboratory complex is on the other side. The grounds are now used only for spreading storm run-off, although plans are being developed for using them in connexion with a water-treatment plant and also for use in spreading water imported from northern California via the California Water Plan facilities.

## Big Dalton spreading-grounds

The basins are located in San Gabriel Valley, just down-stream from Big Dalton Debris Basin and receive controlled releases from this facility. The spreading-grounds lie at the base of the San Gabriel Mountains and occupy a gross area of 10 ha, with a wetted area of 5 ha. They have a storage capacity of 30,000 $m^3$ and an infiltration rate of 0.4 $m^3$/sec. The intake capacity is 1.25 $m^3$/sec. Farther up-stream lies Big Dalton Dam and Reservoir, which permits storage and controlled releases, so that spreading operations can be scheduled. Accordingly, this is one of the least costly facilities to operate. These grounds are used only for spreading storm run-off.

Santa Fe spreading-grounds

These spreading-grounds lie in San Gabriel Valley within the Santa Fe Flood Control Basin, a facility operated by the United States Army Corps of Engineers. The district has a licence for the operation of the spreading-grounds and the costs of the rights of way were nothing in so far as the spreading-grounds were concerned. The grounds lie just up-stream from the spillway of the Santa Fe dam and down-stream from the foot-hill freeway. Most of the development represents the work of caterpillar tractors; there are a minimum of permanent structures. The grounds lie down-stream from three large dams on the San Gabriel River system and, therefore, only receive controlled releases of storm water. Because of the location and type of operation, the operational costs are minimum. This, combined with free right of way and minimal development costs, makes the spreading costs the lowest of any operated by the district. At this time, only local water is spread, although it is quite likely that imported water will be spread in future, when additional imported water-supply pipelines are completed.

The grounds are located on coarse alluvial materials deposited by the San Gabriel River, which is an excellent area for quarrying gravel. The facility occupies a gross area of 78 ha, with a wetted area of 54 ha. Its storage capacity is 247,000 $m^2$ and the infiltration capacity is 6.25 $m^3$/sec. The intake capacity is 21.25 $m^3$/sec. Being located in the up-stream limits of the flood-control basin minimizes the risk of fine silt being deposited in the grounds. Although lying within the limits of the basin, not once since the spreading-grounds were completed has the high-water line reached into them.

Irwindale spreading-basin

This spreading-basin in San Gabriel Valley has a maximum depth of 15 m. It covers a gross area of 7 ha, with a wetted area of 6.5 ha. It has an infiltration capacity of 1.15 $m^3$/sec. The intake capacity is 14.1 $m^3$/sec and the storage capacity is 610,000 $m^3$. Development costs principally involved a radial gate for the diversion works, as the basin lies in an excellent area for quarrying gravel and the excavation was done for the district by a contractor who paid for the materials removed. The cost received for material removed approximated the costs of development of the basin.

The selection of a spreading-basin or pit rather than shallow spreading-grounds is influenced by the following factors:

(a) In areas of lower permeability, the storage capacity of the pit provides a means of retaining a greater quantity of water for replenishment;

(b) Deep pits can be constructed to penetrate tight surface-strata in order to provide access to deeper, more permeable materials;

(c) In areas where problems of rights of way are critical, a pit requires less land to accomplish the same amount of replenishment under certain hydrological and operating conditions.

Table 11. Los Angeles County Flood Control District spreading-grounds: cost per 1,000 cubic metres for spreading local storm-water run-off

(Dollars)

| | Pacoima | Rio Hondo | Hansen | Sawpit | Arroyo Seco | Big Dalton | Santa Fe | Average cost |
|---|---|---|---|---|---|---|---|---|
| Operation and maintenance | 3.27 | 3.05 | 2.07 | 7.51 | 7.25 | 2.86 | 0.70 | 3.82 |
| Supervision of operation and maintenance a/ | 0.62 | 0.91 | 0.49 | 0.61 | 0.97 | 0.65 | 0.41 | 0.66 |
| Office engineering | 0.17 | 0.28 | 0.10 | 0.44 | 0.15 | 0.11 | 0.02 | 0.18 |
| Rights of way | 0.45 | 2.02 | 0.71 | 1.57 | -0- | -0- | -0- | 0.68 |
| Development | 3.41 | 5.75 | 1.90 | 8.73 | 2.69 | 1.71 | 0.24 | 3.48 |
| Clearing | 0.92 | 1.14 | 0.58 | 2.09 | 0.85 | 0.58 | 0.14 | 0.90 |
| Repairs | 0.83 | 1.54 | 0.47 | 1.00 | 0.55 | 0.39 | 0.04 | 0.69 |
| Total cost per 1,000 $m^3$ | 9.67 | 14.69 | 6.32 | 21.95 | 12.46 | 6.30 | 1.55 | 10.41 |
| Total water spread (1,000 $m^3$) | 126,207 | 227,674 | 146,918 | 8,226 | 13,164 | 12,821 | 148,481 | |
| Gross area (hectares) | 71 | 231 | 63 | 5 | 10 | 10 | 78 | |
| Period of operation | 1932-1967 | 1937-1967 | 1944-1967 | 1946-1967 | 1948-1967 | 1953-1967 | 1954-1967 | |

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a/ This item represents general charges against the spreading-grounds. In the district's accounting procedures, it is not identified with specific projects, but does represent a spreading-grounds cost and has, therefore, been proportionately assigned according to amounts of water spread, in order to more correctly reflect actual costs.

Nothwithstanding the above, the district's experience has shown that it is generally preferable to construct spreading-grounds, especially where it is intended to operate facilities on a sustained basis. This is primarily because the spreading-grounds offer more flexibility of operation to maintain infiltration rates, control insects and to perform routine maintenance.

Irwindale spreading-basin has been used principally for spreading local water, although 1,115,000 $m^3$ of imported water have been spread. It is possible that considerable quantities of imported water will be spread in future.

## Branford spreading-basin

The Branford spreading-basin in the San Fernando Valley, has a maximum depth of 13 m and occupies a gross area of 5 ha, with a wetted area of 2.8 ha. It has an infiltration capacity of 0.4 $m^3$/sec and a storage capacity of 166,590 $m^3$.

Only uncontrolled storm-run-off water is spread in this facility. Storm-drain flows enter and fill the basin, then flow through the outlet into a large channel. As a result, the inlet is designed to accommodate a flow of 43.6 $m^3$/sec, and the outlet can accommodate a flow of 43.1 $m^3$/sec, the difference reflecting the loss due to infiltration and a minor effect of the basin acting as a flood-retention basin.

Here the problem created by a silt-load is manifested. Normally, only relatively desilted water is spread in the facilities of the district because the siltation of a spreading-grounds or spreading-basin materially reduces infiltration rates, and the cost of removing a thin layer of silt is very high per unit of volume. Most of the spreading facilities of the district receive only controlled releases, and water with too great a silt-load can be bypassed. Of the project discussed here, Branford and Peck Road spreading-basins are the exceptions. Both are an integral part of the flood-control system and receive uncontrolled storm run-off. This problem is reflected in the high costs for maintenance and repairs.

## Eaton spreading-basin

At present, the basin has a maximum depth of 15 m, a gross area of 6.5 ha, a storage capacity of 271,000 $m^3$ and an infiltration capacity of 0.3 $m^3$/sec. It is used only for spreading local water. Although in operation since 1956, it is not yet fully developed, as some excavation remains to be done at the down-stream end of the basin. The district is attempting to achieve this development at minimal cost by permitting the material to be removed by contractors who wish to use it for such work as road construction. This method is slow. The high cost of development, shown in table 12, is largely the result of the high cost of the diversion works.

## Peck Road spreading-basin

Although not yet fully developed, this is by far the largest spreading-basin which the district owns. It is located in San Gabriel Valley and will have a depth of at least 18 m; it covers a gross area of 64 ha, with a wetted area of 34 ha; its present storage capacity is near 5 million $m^3$ and its ultimate storage capacity is 8.3 million $m^3$. It now has an infiltration capacity of 1.85 $m^3$/sec.

This basin lies at the confluence of Sawpit and Santa Anita washes and it forms the up-stream end of Rio Hondo channel. The spillway leading out into the Rio Hondo channel has a capacity of 850 $m^3$/sec. Like Branford, this basin principally receives uncontrolled storm run-off, although during non-storm periods controlled releases can be made from up-stream reservoirs for conservation at this facility. At this time, only storm run-off is spread.

This basin is located in an area which is excellent for the quarrying of gravel, and development is proceeding on the basis of an arrangement made with the City of Arcadia and a gravel company. The district receives no payment for the mined gravel; as most of the land was owned by the City of Arcadia, it receives the payment, but development is proceeding at little cost to the district.

Here, the low cost for water spread is a reflection of the magnitude of the operation. There are no control-type operations and the cost of operations principally reflect that associated with making observations and patrolling of the area. Patrol is very necessary as the basin is an "attractive nuisance" and, with its steep sides, poses problems of liability. Although fenced-in as are most of the facilities of the district, patrol is still necessary.

### Walnut wash-spreading basin

This basin, in the San Gabriel Valley, is utilized for conserving storm run-off as well as excess irrigation water. The irrigation water is introduced into the basin directly from the irrigation line of Covina Irrigating Company. Both controlled and uncontrolled storm run-off are diverted into the basin by a rubber dam in the adjacent channel. The rubber dam is inflated by water and is designed to deflate automatically by siphon action, should the channel flows be too large for safety. The basin has a maximum depth of about 15 m and covers a gross area of 6.5 ha, with a wetted area of 3.2 ha. It has an infiltration capacity of 0.2 $m^3$/sec and a storage capacity of 205,000 $m^3$. Compared with other district programmes, this is small and the unit costs are particularly high. The operations have only been carried out since 1959, and unit costs are expected to go down with time.

## Imported and reclaimed water programme

The imported water programme is carried out principally in the unlined portion of the San Gabriel River, the Rio Hondo spreading-grounds and the San Gabriel spreading-grounds. All of these facilities were developed for the purpose of conserving local water and, as previously mentioned, the costs in the analysis principally represent operational costs. This accounting procedure combined with complete control of deliveries, large quantities and clean water results in low spreading costs.

Rubber dams, about 61 m wide and separated by a concrete wall, are used to divert water from the San Gabriel River into the San Gabriel spreading-grounds. When fully inflated the dams are about 2.1 m high and work on the same principal as that described under Walnut spreading-basin.

About 135 ha of the unlined San Gabriel River are utilized for water-spreading. Infiltration rates are quite good and the infiltration capacity totals about 8.65 $m^3$/sec.

Table 12. Los Angeles County Flood Control District, spreading basins: costs per 1,000 cubic metres for spreading local storm-water run-off

(dollars)

| | Irwindale | Branford | Eaton | Peck Road | Walnut Wash | Average cost |
|---|---|---|---|---|---|---|
| Operation and maintenance | 3.53 | 4.70 | 5.71 | 1.31 | 3.75 | 3.79 |
| Supervision of operation and maintenance a/ | 0.53 | 1.05 | 0.73 | 0.70 | 0.92 | 0.79 |
| Office engineering | 0.11 | 0.20 | 0.29 | 0.03 | 0.32 | 0.19 |
| Rights of way | 0.80 | 3.42 | 3.33 | 1.00 | 9.60 | 3.63 |
| Development | 2.10 | 4.13 | 5.83 | 0.88 | 6.49 | 3.89 |
| Clearing | 0.19 | 0.75 | 1.14 | 0.14 | 1.42 | 0.73 |
| Repairs | 0.61 | 4.53 | 1.26 | 0.55 | 1.43 | 1.68 |
| Total cost per 1,000 $m^3$ | 7.87 | 18.78 | 18.29 | 4.61 | 23.93 | 14.70 |
| Total water spread (1,000 $m^3$) | 20,187 | 3,690 | 9,870 | 59,590 | 5,460 | |
| Gross area (hectares) | 7 | 5 | 6 | 64 | 6 | |
| Period of operation | 1952-1967 | 1954-1967 | 1956-1967 | 1958-1967 | 1959-1967 | |

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a/ This item represents general charges against the spreading-basins. In the district's accounting procedures, it is not identified with specific projects, but does represent a spreading-basins cost and has, therefore, been proportionately assigned according to amounts of water spread, in order to more correctly reflect actual costs.

Table 13. Los Angeles County Flood Control District: investment in spreading-facilities and in spreading-grounds

(dollars)

| | Period | Fixed assets | Rights of way | Operation and maintenance | Total investment |
|---|---|---|---|---|---|
| Spreading-grounds | | | | | |
| Pacoima | 1932-1967 | 521,814.45 | 41,544.67 | 704,127.56 | 1,267,486.68 |
| Rio Hondo | 1937-1967 | 1,672,292.28 | 462,156.69 | 1,488,450.91 | 3,622,899.88 |
| Hansen | 1944-1967 | 390,188.24 | 108,968.01 | 514,892.11 | 1,014,048.36 |
| Sawpit | 1946-1967 | 82,885.40 | 16,366.32 | 101,914.29 | 201,166.01 |
| Arroyo Seco | 1948-1967 | 50,347.10 | -0- | 114,364.40 | 164,611.44 |
| Big Dalton | 1953-1967 | 51,196.21 | 40,717.80 | 66,628.36 | 158,542.37 |
| Santa Fe | 1954-1967 | 64,422.55 | -0- | 147,812.68 | 212,235.23 |
| Spreading Basins | | | | | |
| Irwindale | 1952-1967 | 113,513.74 | 34,678.66 | 87,983.21 | 236,175.61 |
| Branford | 1954-1967 | 28,502.98 | 24,280.57 | 39,862.93 | 92,646.48 |
| Eaton | 1955-1967 | 123,033.52 | 73,846.34 | 77,782.44 | 274,662.30 |
| Peck Road | 1958-1967 | 192,910.03 | 116,141.26 | 127,945.42 | 436,996.71 |
| Walnut Wash | 1959-1967 | 206,774.17 | 123,895.26 | 38,182.09 | 368,851.52 |

Table 14 does not include any costs for the purchase of imported water. In 1969 the price was $16.20 per 1,000 m$^3$, but it is increasing each year.

The principal difference between the reclaimed water programme and the imported water programme is the quantity of water which is spread. The same facilities are utilized, and often the waters are blended (in fact a blending operation is preferred). The higher unit costs for reclaimed water, shown in table 14, reflect the magnitude of the programme. When the waters are blended, the unit costs are essentially the same. However, the imported water programme is not continuous, as water is not available during the hot summer months, while the reclaimed water programme is continuous. A minimum crew is required to oversee the spreading of the 0.55-0.85 m$^3$/sec of reclaimed water and, therefore, the unit costs rise when that is the only water being spread. The Whittier Narrows water reclamation plant is situated in Whittier Narrows basin. It is of the activated sludge type. Water from this plant can be diverted either into the Rio Hondo or into the San Gabriel system. Additions to the plant are planned, along with plants at other sites, which will provide much greater quantities of recharge resulting in lower unit costs for spreading.

Table 14 does not include the price of purchasing the reclaimed water. The price of the water from the present plant is tied to the price of imported water. However, upon completion of the planned facilities, the price from these additional facilities is expected to be $4/1,000 m$^3$.

## Barrier projects

Figure 27 shows the extent of sea-water intrusion along the Los Angeles County coast line, and its planned control by underground fresh-water pressure-barriers.

Three projects are shown. The West Coast basin barrier project is almost fully operative and the Alamitos barrier project is partially operative. The construction of the Dominguez-Gap barrier project is now under way. The first two projects are discussed here.

### West Coast Basin barrier project

This project began in the early 1950s as a pilot programme to prove the feasibility of preventing sea-water intrusion by the injection of fresh water to form a pressure ridge. The successful results made this initial pilot-programme the nucleus of the basic project. From a 2.4 km reach the project has now been expanded to cover a 16 km reach. It involves the following:

(a) Approximately 100 injection wells, reaching to depths as great as 230 m and costing from $165 to $210 per vertical metre for construction;

(b) Approximately 300 observation wells;

(c) Over 24 km of supply pipelines up to 114 cm in diameter;

(d) Pipelines for disposing of well-development and redevelopment water;

(e) A pressure-regulation station;

(f) Chlorination facilities;

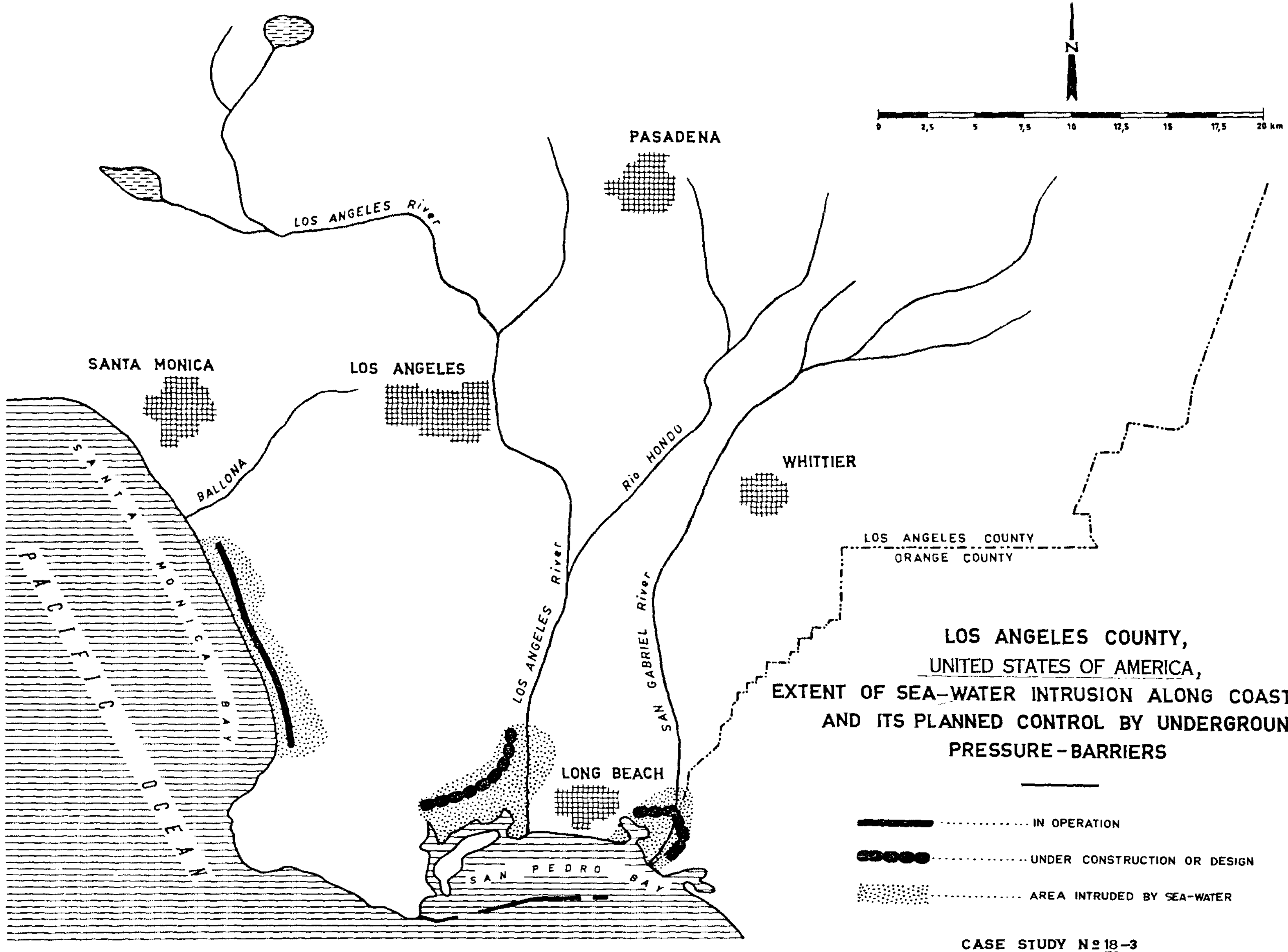
(g) Office and field-yard facilities.

Table 14. Los Angeles County Flood Control District. Local, imported and reclaimed water-spreading costs, San Gabriel and Rio Hondo

(Dollars)

|  | San Gabriel system | Rio Hondo | Remarks |
|---|---|---|---|
|  |  | Imported water spreading costs |  |
| Total water spread in 1,000 $m^3$ | 752,519 | 719,582 | Operation and maintenance only |
| Cost per 1,000 $m^3$ | $ 0.70 | $ 0.87 | Operation and maintenance only |
| Period of operation | 1953-1967 | 1953-1967 |  |
|  |  | Reclaimed water spreading costs |  |
| Total water spread in 1,000 $m^3$ | 13,857 | 51,222 | Operation and maintenance only |
| Cost per 1,000 $m^3$ | $ 1.64 | $ 1.64 | Costs combined |
| Period of operation | 1962-1967 | 1962-1967 |  |
|  | Local, imported and reclaimed spreading costs |  |  |
| Cost per 1,000 $m^3$ | $ 1.20 | $ 4.05 |  |

FIGURE 27



LOS ANGELES COUNTY,
UNITED STATES OF AMERICA,
EXTENT OF SEA-WATER INTRUSION ALONG COASTLINE
AND ITS PLANNED CONTROL BY UNDERGROUND
PRESSURE-BARRIERS

CASE STUDY Nº 18-3

## Table 15. Los Angeles County Flood Control District: West coast basin barrier project costs

(Dollars)

### Fixed assets

| Year | Right of way | Engineering | Construction | Total |
|---|---|---|---|---|
| 1963/64 | 6,653.14 | 320,528.66 | 1,983,524.51 | 2,310,706.31 |
| 1964/65 | 22,983.62 | 249,279.18 | 1,494,643.97 | 1,766,906.77 |
| 1965/66 | 12,137.04 | 243,652.33 | 892,201.07 | 1,147,990.44 |
| 1966/67 | 88,025.14 | 184,154.26 | 297,143.80 | 569,323.20 |
| | | | Total | $5,794,926.72 |

### Services and supplies

| Year | Operation | Maintenance | Water | Total |
|---|---|---|---|---|
| 1963/64 | 265,077.07 | a/ | 154,588.97 | 419,666.04 |
| 1964/65 | 296,461.15 | 71,553.93 | 520.643.17 | 888,658.25 |
| 1965/66 | 278,628.66 | 137,480.69 | 930,524.70 | 1,346,634.05 |
| 1966/67 | 237,751.29 | 169,397.75 | 969,557.60 | 1,376,706.64 |
| | | | Total | 4,031,664.98 |

| Year | Amounts of injected water in 1,000 $m^3$ | Km of coast line protected |
|---|---|---|
| 1963/64 | 9,227 | 2.4 |
| 1964/65 | 31,655 | 4.8 |
| 1965/66 | 54,680 | 9.7 |
| 1966/67 | 54,384 | 10.8 |

a/ 1963/64 maintenance cost included in operation cost.

Where contact is made with water, non-corrosive materials are used throughout. Pipelines are lined and coated with concrete or with asbestos cement. Casings for injection wells are asbestos cement and casings for observation wells are 10.16 cm polyvinyl chloride. Upon completion, about $7 million will have been expended for fixed-assets costs alone.

Using the 1966/67 operation and maintenance cost of $7.49/1,000 $m^3$, total fixed-assets cost of $7 million amortized over a 50-year period at 4 per cent interest and, assuming 55,530,000 $m^3$ of annual injections, results in a unit cost of $13.35/1,000 $m^3$, exclusive of the cost of water.

The costs for operations and maintenance per 1,000 $m^3$ of water injected exclusive of the cost of water are (dollars):

| | |
|---|---|
| 1963/64 | 28.73 |
| 1964/65 | 11.63 |
| 1965/66 | 7.61 |
| 1966/67 | 7.49 |

Each well is designed for injecting about 0.025 $m^3$/sec; some wells penetrate two principal aquifers and, to save on water costs, they are designed for injection into each aquifer separately. These are termed "dual wells". They are characterized by a single casing perforated in both aquifers. Hydraulic separation is maintained by grouting the annulus within the limits of the aquiclude separating the aquifers and by installing an inflatable packer inside the casing, as shown in figure 28.

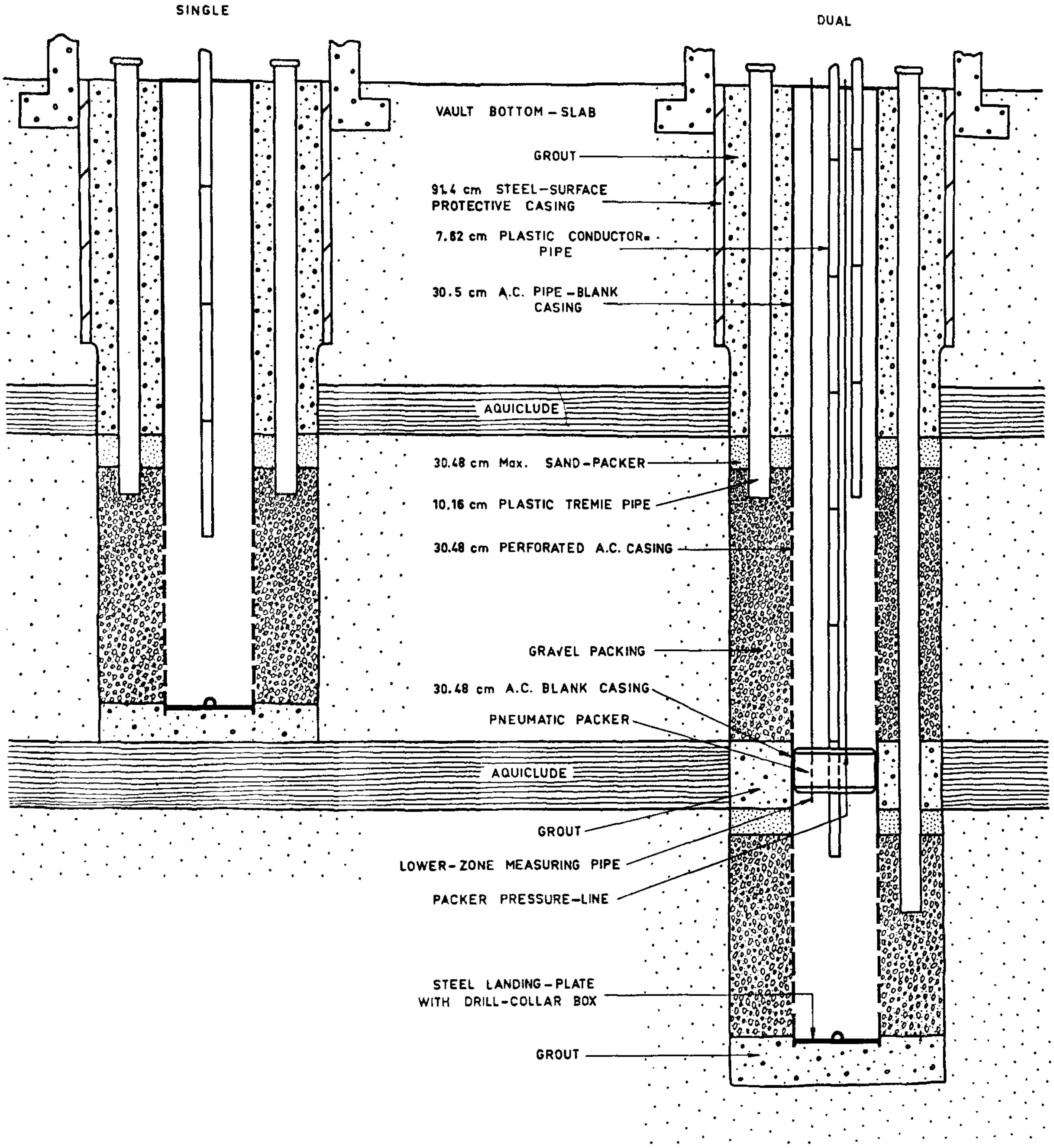
Figure 28 is a schematic diagram of the injection wells. Over 90 per cent of the water injected moves landward of the barrier and is then available for pumping, and is, therefore, not lost. This salvage value of the water must be considered. Facilities are capable of accommodating well over 2.8 $m^3$/sec of water, although the present injection rate is about 1.4 $m^3$/sec. This project involves large quantities of water and unit costs of injecting water should be relatively low.

### Alamitos barrier project

This project is a co-operative project between the Los Angeles County Flood Control District and the Orange County Water District, as the project benefits both counties. It is small in scope, compared with the West-Coast basin barrier project and, as expected, unit costs are considerably higher.

The project is not yet fully developed. Thus far, expenditures for work involving fixed assets have totalled about $2.4 million. This includes costs for about 9.6 km of pipeline up to 69 cm in diameter, 18 injection wells, 82 observation wells, three extraction wells, a pressure-regulation station, a chlorination station and a field headquarters. Non-corrosive materials are used throughout the system: steel pipe, lined and coated with mortar; stainless-steel casings for both the injection wells and extraction wells; and plastic casings for the observation wells. The project is designed to inject a maximum of 0.65 $m^3$/sec; however, the current rate is about 0.20 $m^3$/sec.

FIGURE 28



**LOS ANGELES COUNTY,**

UNITED STATES OF AMERICA,

SCHEMATIC INJECTION WELL

CASE STUDY Nº 18-4

The extraction wells are located seaward of the injection wells and serve the purpose of lowering the ground-water level, against which the barrier must be formed to prevent intrusion, with the result that less injection is required. Intruded sea water is extracted by these wells. Nearly all of the injected water moves landward and can be reclaimed by inland pumpers.

Table 16. Los Angeles County Flood Control District: Alamitos barrier project

(dollars)

Fixed assets

| Year | Right of way | Engineering | Construction | Total |
|---|---|---|---|---|
| 1964/65 | 4,072.58 | 110,017.03 | 1,413,724.66 | 2,038,167.64 |
| 1965/66 | 9,886.53 | 43,070.29 | 32,880.33 | 85,837.15 |
| 1966/67 | 23,606.20 | 26,612.18 | 189,778.19 | 239,996.57 |
| 1967/68 | 2,618.60 | 27,387.76 | 5,172.64 | 35,179.00 |

Services and supplies

| Year | Injection wells | Extraction wells | Total |
|---|---|---|---|
| 1964/65 | 84,882.59 | 15,488.15 | 100,370.74 |
| 1965/66 | 171,888.70 | 33,654.14 | 205,542.84 |
| 1966/67 | 159,711.61 | 48,593.83 | 208,305.44 |
| 1967/68 | 210,115.55 | 57,450.59 | 267,566.14 |

| Year | Amounts of injected water per thousand cubic metre | Cost of injected water | Amounts of water extracted per thousand cubic metre |
|---|---|---|---|
| 1964/65 | 2,015 | 32,656.00 | 1,028 |
| 1965/66 | 5,030 | 85,602.30 | 2,998 |
| 1966/67 | 4,502 | 80,258.20 | 2,734 |
| 1967/68 | 5,591 | 104,210.70 | 2,211 |

Using the 1967/68 operation and maintenance cost of \$36/1,000 $m^3$, adding the \$57,450.59 operation and maintenance cost associated with the extraction wells to the total fixed assets cost of \$2.5 million amortized over a 50-year period at 4 per cent interest, and assuming 5,590,000 $m^3$ of annual injections, results in a unit cost of \$67.20/1,000 $m^3$, exclusive of the cost of water.

The costs for operations and maintenance per thousand cubic metre of water injected, exclusive of the cost of water are (dollars):

| | |
|---|---|
| 1964/65 | 42.12 |
| 1965/66 | 34.17 |
| 1966/67 | 35.49 |
| 1967/68 | 35.96 |

The costs of operations and maintenance per thousand cubic metre of saline water extracted are (dollars):

| | |
|---|---|
| 1964/65 | 15.95 |
| 1965/66 | 11.22 |
| 1966/67 | 17.77 |
| 1967/68 | 25.98 |

## Administration and future operation

The Statutes of the State of California, by which the Los Angeles County Flood Control District was formed, specified that the district be responsible for flood control and water conservation. Artificial recharge is a part of this water-conservation responsibility. Funds are derived from special appropriations.

The programmes are economical and are an integral part of the management of the water resources. The programmes will continue and will be expanded, particularly the programme of ground-water replenishment with reclaimed and imported water.

## References:

Los Angeles County Flood Control District. Unpublished reports and files.

California, State of. Ground-water geology of the coastal plain of Los Angeles County. Department of Water Resources, Bulletin No. 104. 1961.

West coast basin barrier project, 1963-1967. F. S. Solari *and others*. Los Angeles County Flood Control District.

Hunt, D. B. and F. D. Seares. Alamitos barrier project, 1967-68. Los Angeles County Flood Control District.

# LOWER DURANCE, FRANCE*

The background information for the Lower Durance is as follows:

(a) Region. lower part of the Durance valley in the region of Avignon and the Chateaurenard basin;

(b) Geography: the broad alluvial plain of the Durance River, 90 km from its confluence with the Rhone River, is, in fact, a series of successive basins connected by geological passes. The basin described here is the Chateaurenard, located on the left bank;

(c) Climate: Mediterranean; average annual rainfall, 600 mm; average annual temperature, 14°C, average yearly evapo-transpiration, 500 mm;

(d) Reservoir type: river alluvium overlying an impervious substratum;

(e) Methods of investigation: detailed hydrogeological study; electrical geophysical prospecting; reconnaissance drilling and wells; pumping tests; piezometric study and observation of piezometric levels and their fluctuations tests of artificial recharge; specific study of the relationship between the alluvial aquifers and the river; theoretical studies of non-permanent flow in porous media and practical application of water-injection.

## Ground-Water reservoirs

The geological log consists of (a) a layer of superficial muds and silts, of low permeability, which increases in thickness down-stream up to 4 m; (b) a layer of alluvial gravel with a maximum thickness of 30 m, (c) an impervious substratum.

This is a shallow aquifer with an average thickness 20 m and an average width 5 km. The area involved in the tests is 4,000 ha. There is an unconfined aquifer up-stream and in the centre of the basin. The annual amplitude of fluctuation of the piezometric surface is from 0.20 to 0.50 m in the centre, and more than 1 m up stream. Down-stream the water-table is higher and becomes confined under the muds and silts. The effective porosity, which is evaluated by matching the injected quantities of water and the volume of material involved in the rise of the water-table, is from 4 to 14 per cent, depending upon time. Total porosity is about 24 per cent. The average horizontal hydraulic conductivity coefficient (K) has been estimated at 700 m/day; coefficient of storage (S) is 10-12 per cent. The estimated average volume of water in storage is from 2.5 to 3.0 x $10^6$ $m^3/km^2$.

Direct recharge takes place by rainfall. From the regional water-balance studies it appears that this is not large. Water replenishment from the surface flow on the basin slopes is important, but difficult to evaluate.

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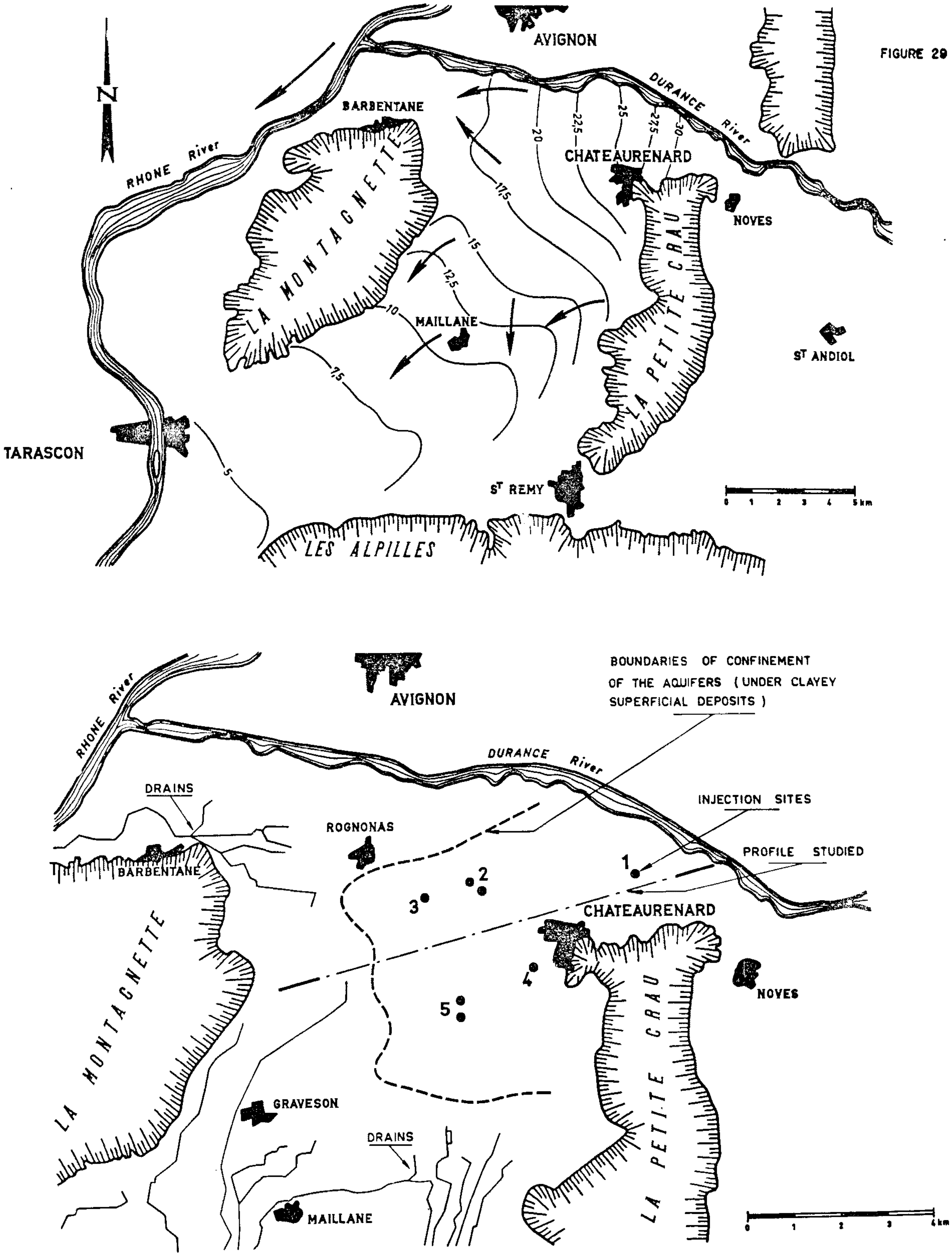
* Case study No. 19 prepared by G. Castany (France).

FIGURE 29



LOWER DURANCE,
FRANCE

CASE STUDY Nº 19

During flood periods (from one to two months per year), the Durance River feeds the aquifer up-stream from the basins, for a flow of the order of magnitude from 1 to 2 $m^3$/sec for the whole of the valley. This recharge will be reduced when the dams and canals are built. However, the supply from the Durance waters in the drainage areas will be maintained (2 $m^3$/sec over a distance of 80 km).

The ground-water flow is complex, and varies depending upon the cross-section which is considered:

(a) In the centre the ground-water flow is parallel to the river-bed; the piezometric level stands above the water level;

(b) Up-stream, the ground-water flow is towards the aquifer;

(c) Down-stream, near the narrow pass which opens on the basin which follows, the piezometric surface rises and approaches the ground surface (0.50-1 m). The flow is towards the river, which acts as a drain.

## Artificial recharge

The ground water is used principally for irrigation. The purpose of the project was to maintain the piezometric level of the phreatic aquifer, which is used for irrigation of 4,000 ha - in an alluvial plain where hydraulic works have modified the original rate of flow of the surface water. The hydraulic project of the lower Durance consists of the diversion of a flow of 250 $m^3$/sec up-stream from the area mentioned here, by means of a canal 80 km long. The diversion and the storage dams cut off the flood peaks and lower the low-water flow of the river. Therefore, serious changes will result in the alluvial aquifer system, reducing recharge during flood periods.

A study has been undertaken to demonstrate that it is possible to artificially maintain the piezometric surface, mainly during the summer period, at a convenient elevation through an artificial recharge scheme. The area of concern has a surface of 40 sq km and the flow to be injected is 1-2 $m^3$/sec.

The first tests, which were carried out in 1953 in the largest basin (at Plan d'Orgon and at La Saignone, near Avignon), were conclusive, and a second test was carried out in 1956 at Chateaurenard and at Peyrolles. The test at Chateaurenard is described below.

The purpose of the test was to create a piezometric rise of 1 m up-stream and 2.20 m down-stream on a surface of 40 $km^2$ in a region where the depth of the water-table is from 1 to 4 m. This rise corresponds to the amplitude of the annual fluctuation. The test-period was 29 days. The scheme which was selected involved the drilling of injection bore-holes at five injection stations. The injected flows are in the range of from 100 to 400 l/sec.

Surface waters are filtered in a battery of three filters at each injection station: two are functioning while the third one is being regenerated. Dimensions are 5 x 30 m, for a flow of 100 l/sec; and 5 x 60 m, for a flow of 200 l/sec. The flow through the filters is therefore 1 l/sec/$m^2$. The thickness of the sand filter is 0.30 m and the effective diameter of the sand is 0.10-0.42 mm. The water is injected into the aquifer by the means of bore-holes 56 cm in diameter, penetrating the whole aquifer. They are equipped with a 30 cm casing and screened for their entire length. The annular space is filled with gravel from 30 to 60 mm in diameter.

Five centres were equipped for a total injection of 1,100 l/sec.

| Centre number | Number of bore-holes | Litres per second |
|---|---|---|
| 1 | 4 | 200 |
| 2 | 7 | 300 |
| 3 | 3 | 100 |
| 4 | 3 | 100 |
| 5 | 4 | 400 |

During a 29-day period, the average injection flow was maintained at 830 l/sec. The injected volume exceeded 2 x $10^6$ $m^3$ and the rise of the piezometric levels was from 0.20 to 0.60 m.

References:

Alimentation artificielle de la nappe alluviale de la Basse Durance. Etude des dispositifs d'injection. M. Gualton *et autres*. Commission internationale des irrigations et du drainage. San Francisco. 1957.

Exemple d'alimentation artificielle de la nappe phréatique d'un bassin alluvial de 5,000 hectares situé en Basse Durance. A. Decelle *et autres*. Commission internationale des irrigations et du drainage. 1954.

Muller-Feuga, R. et P. Ruby. Alimentation artificielle de la nappe des alluvions de la Basse Durance. *La houille blanche* (Grenoble), 3:261-266. 1965.

# MENUMA INJECTION PROJECT, JAPAN*

The background information for the Menuma injection project was as follows:

(a) Region: Saitama Prefecture, Kwanto district, Japan;

(b) Geography: Kwanto plain, the largest coastal plain in Japan;

(c) Climate: humid, temperate zone; average rainfall from about 1,000 mm to 1,500 mm/year;

(d) Reservoir type: diluvium;

(e) Methods of investigation: Hydrological investigation, including pumping tests and chemical analyses of ground water.

## Ground-water reservoir and utilization

The area is located in the largest plain of Japan, with the terraces covered by diluvium and the flatlands by alluvium. Diluvium underlies the alluvium, and is 500 m thick in the central part of the plain. The hydrogeology of the central part of the plain and the cross-section at the project site are shown in figure 30. The figure shows that a thick clay formation is found near a depth of 100 m, with a shallow pressurized ground-water layer above, and the deep pressurized ground-water layer below the clay.

There are two main aquifers. The average depth of the first aquifer below ground level is about 100 m and it is about 40 m thick. The second aquifer is about 50 m thick. It is the second aquifer which is injected. The transmissivity coefficient (T) is 2.2 x $10^{-2}$ $m^2$/sec; hydraulic conductivity (K) is 80 m/day. The estimated minimum volume of water in storage in each aquifer is 4 x $10^6$ $m^3/km^2$.

Water quality is given in the following table.

| | Depth of well | pH | $CaCO_3$ | Cl | $SO_4$ | Na | K | Ca | Mg | Fe | Mn | $SiO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (metres) | value | | | | (parts per million) | | | | | | |
| Injection well | 200 | 7.8 | 96.0 | 14.2 | 2.8 | 17.5 | 2.1 | 20.3 | 6.1 | 0.08 | 0.08 | 49.6 |
| Observation well | 200 | 7.6 | 96.5 | 14.9 | 3.0 | 17.0 | 2.2 | 20.2 | 6.0 | 0.07 | 0.06 | 50.7 |
| Injection-water well | 15 | 6.9 | 136.6 | 17.0 | 29.1 | 12.9 | 4.2 | 40.2 | 12.9 | 3.40 | 2.24 | - |

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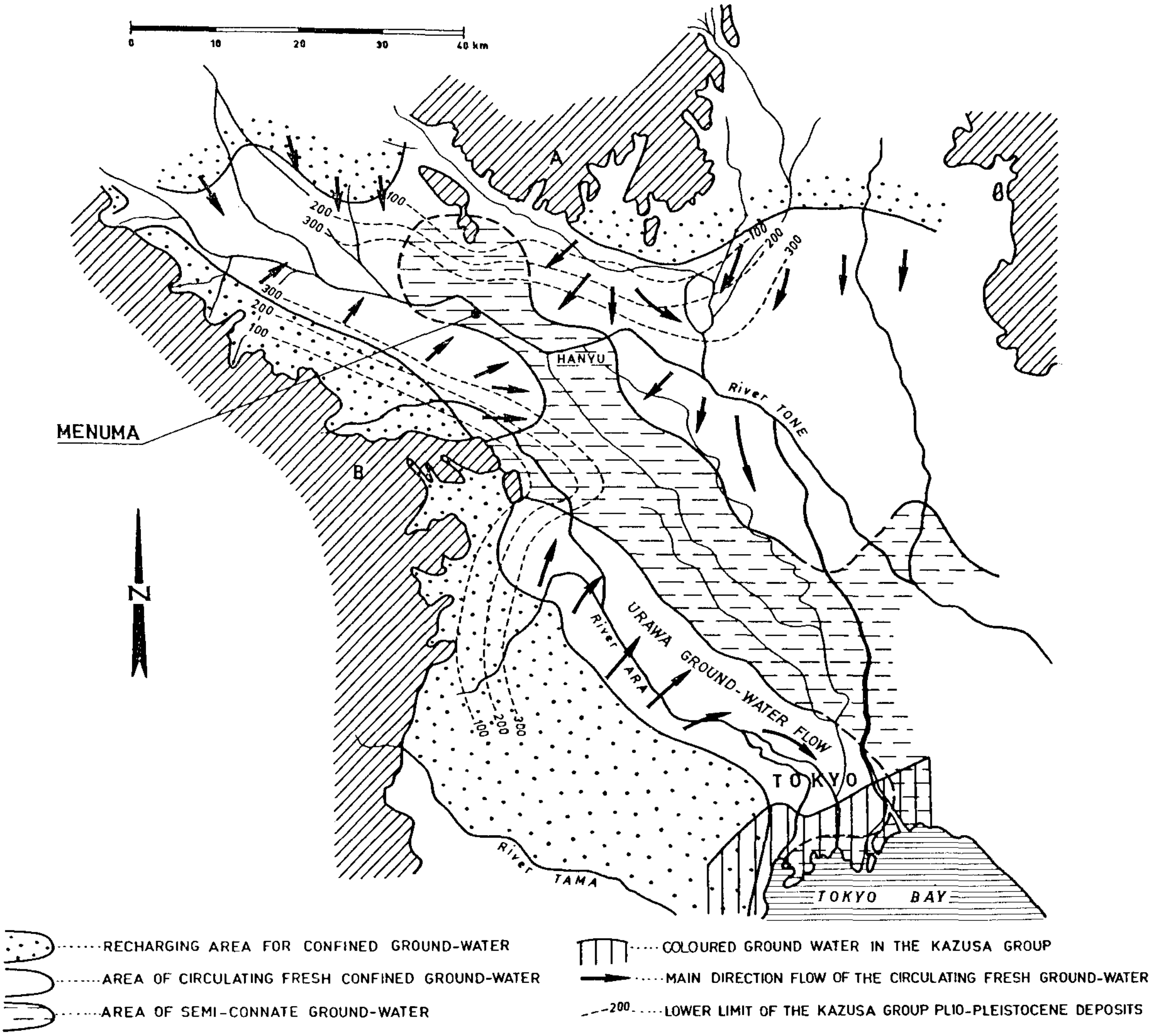
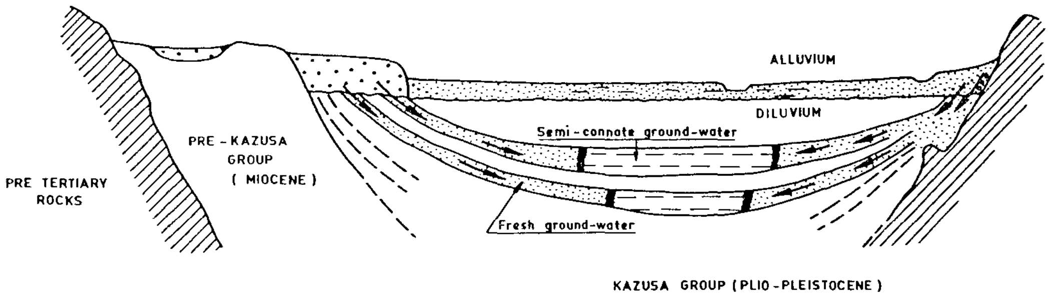
* Case study No. 20 prepared by T. Konishi (Japan).

HYDROGEOLOGICAL MAP OF THE KWANTO PLAIN

FIGURE 30





GENERALIZED SECTION A B

## MENUMA INJECTION PROJECT, JAPAN

CASE STUDY Nº 20

Natural recharge occurs from precipitation; discharge occurs by pumping of ground water: ground-water movement is generally to the south-east. In general, the Kwanto ground-water basin is over-draughted, but in this area there are few pumping wells and it is now in equilibrium.

The facility is used to provide municipal water for the town of Menuma; industrial use is only 200 $m^3$/day. Average pumping is from 2,000 to 2,500 $m^3$/day.

Cost of water per cubic metre in Saitama Prefecture is as follows:

| | Yen | Dollars |
|---|---|---|
| City water | 16.63 | 0.0462 |
| Surface water | 3.49 | 0.0093 |
| Underflow of ground water | 6.63 | 0.0184 |
| Pumping ground water | 2.30 | 0.0064 |
| Average | 2.77 | 0.0077 |

Future utilization will increase owing to increasing water requirements for industrial uses.

## Artificial recharge (experimental study)

The injection well and observation well, located 5 m from the former well, were drilled in 1968, the survey well of the previous year being used as an observation well. The water for recharging was to be pumped from a well 15 m deep and 300 mm in diameter.

Pumping tests were carried out for the water source and the results indicated that the safe pumping rate would be about 2,000 $m^3$/day. Thus, the first step was planned for injection at this rate. The source-water contained a fair amount of iron, while the water of the deeper layer contained only a small amount. In order to prevent the solution of oxygen, the pumped water was injected directly into the injection well through a flow meter, without using ponds.

In 1969, long-term natural-flow injection was carried out. One injection well, 200 m in depth, and a 15 m well for a water-source were drilled. This latter injection well has been operated at 2-3 kg/$cm^2$ pressure, injecting 4,000 $m^3$/day.

References:

Kino, Y. Hydrogeological map of the central part of the Kwanto plain. Hydrogeological map of Japan, No. 2, Geological Survey of Japan, 1962.

Konishi, T. Artificial recharge and Menuma injection site, Geological survey news, 178: 1969.

# NIIGATA INJECTION PROJECT, JAPAN*

The background information for the Niigata injection project is as follows:

(a) Region: Niigata, north-central Honshu, Japan;

(b) Geography: coastal plain;

(c) Climate: humid, temperate zone; average rainfall from 1,500 to 2,000 mm/year;

(d) Reservoir type: diluvium;

(e) Methods of investigation: Complete hydrogeological investigation, including pumping tests and chemical analyses of ground water.

## Ground-water reservoirs and utilization

Geological conditions are characterized by a Pleistocene Uonuma group, composed of sand and conglomerates. The principal aquifers are of diluvium. There are many aquifers, two of which are considered as principal ones. Thickness of aquifers ranges from 10 to 30 m. The depth to the top of the shallowest principal aquifer is about 100 m below ground level and the depth of the bottom or deep aquifer is about 1,020 m. The area of the aquifer is unknown, but is at least 130 $km^2$. The hydraulic conductivity coefficient is from 120 to 500 m/day. The porosity is over 25 per cent and the order of magnitude of compressibility is possibly $10^{-3}$. The estimated volume of water in storage is $72 \times 10^6$ $m^3/km^2$. Natural recharge is by precipitation. The mining of natural gas dissolved in water in the Niigata area has increased rapidly since 1949 and, in 1955, $10 \times 10^9$ $m^3$ of water were pumped.

Ground water is used as a source of natural gas, which is dissolved in the water. The ratio of water to gas is 1:1. The most important problem of this area is the prevention of land subsidence.

The following table shows the cost of water per cubic metre in Niigata Prefecture.

| | Yen | Dollars |
|---|---|---|
| City water | 11.59 | 0.0322 |
| Surface water | 2.59 | 0.0072 |
| Underflow of ground water | 1.83 | 0.00508 |
| Pumped ground water | 1.63 | 0.00452 |
| Average | 2.96 | 0.00822 |

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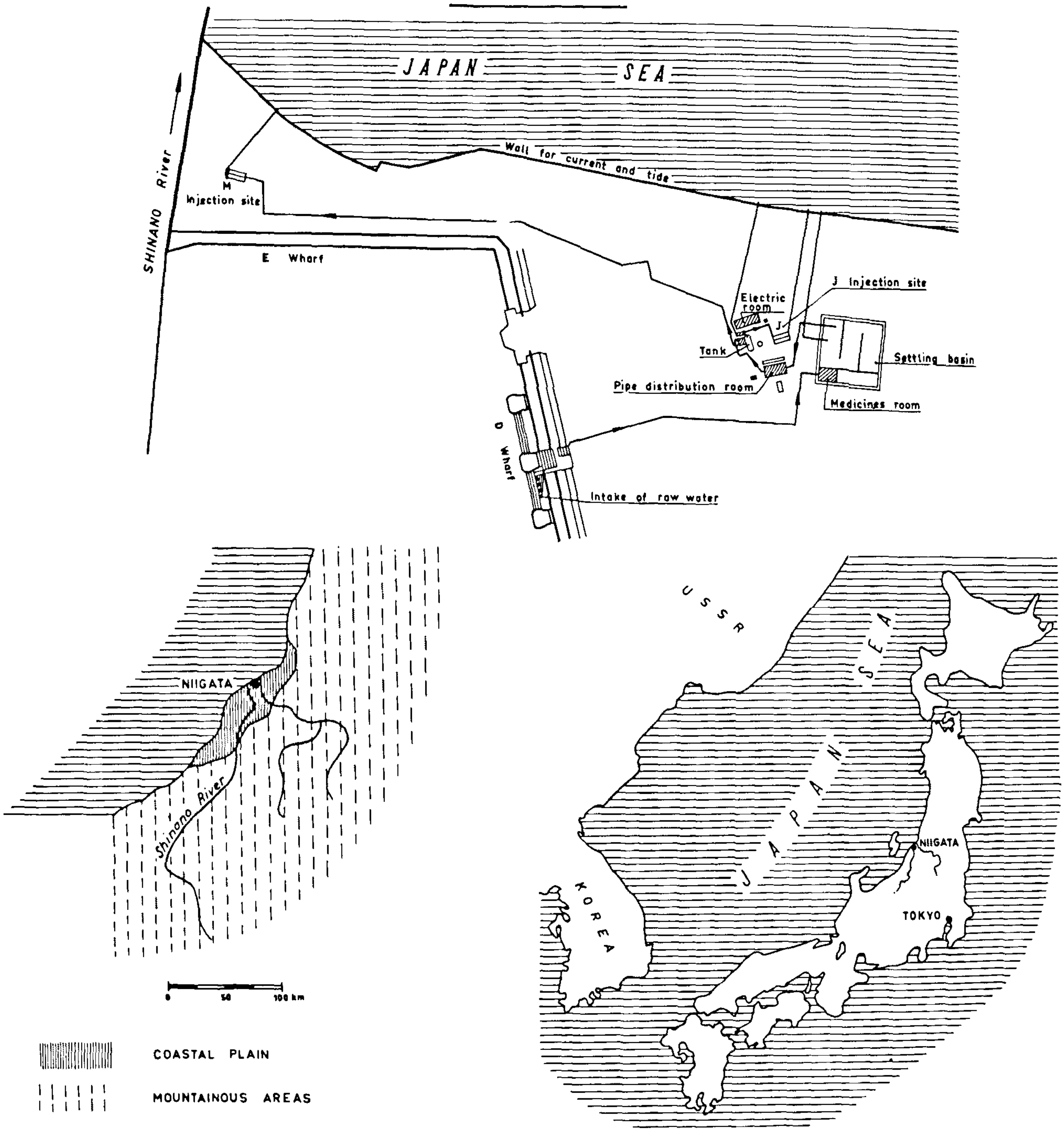
* Case study No. 21 prepared by T. Konishi (Japan).

FIGURE 31

MAP SHOWING FACILITIES OF INJECTION SITES



## NIIGATA INJECTION PROJECT, JAPAN

CASE STUDY Nº 21

Future utilization: Natural gas is separated from the pumped ground water and the water is returned to the aquifer by injection through wells. Future utilization of ground water for purposes above ground may result in a reduction in recharging.

## Artificial recharge

The purpose of the project was to maintain pressure for prevention of land subsidence with continuation of the production of methane gas from ground water. The objective of the project was to determine: (a) The feasibility of injecting sea water; (b) The best technical method of pressurized recharge and the properties of gas-producing layers, in preparation for large-scale recharge projects.

The flow sheet of injection facilities is shown in figure 31. the facilities are designed to treat 20,000 $m^3$ of water per day. Treated water from a branch of the Shinano River is used for injection. The facilities were completed in December 1961, and injection began in January 1962. At first the natural inflow of water was adopted as a rule. During the first 10 days, only No. 3 well of J base was pumped in; and during the next 10 days, only the wells of M base were pumped; then No. 6 was pumped in.

Later, it was decided to inject under pressure, in order to increase the rate of flow. Beginning 4 June 1962, pump-injection began at wells J-7, J-5 and M-9, with a pressure of 2 $kg/cm^2$ at the well-heads.

The injection at J-5 was 3,000 $m^3$/day, by natural inflow from 11 January 1962; it was stopped on the twelfth day, and injection was resumed on 1 February at 2,800 $m^3$/day. After a few days of operation, the pressure became positive, and pressurized injection at 0.3 $kg/cm^2$ was applied. Reverse washing was done after the injection volume dropped below 1,500 $m^3$/day. After this washing, injection was increased to 2,500-3,000 $m^3$/day. Pressure-injection was applied after 4 June, and the volume injected increased to 4,000-5,000 $m^3$/day at 2 $kg/cm^2$. Reverse washing is done when the amount injected decreases to 2,500-3,000 $m^3$/day; it is then done every 8-20 days. The time necessary for this wash is 6-25 hours. The average amount injected is 1,860 $m^3$/day under natural inflow, and 3,460 $m^3$/day at a pressure of 2 $kg/cm^2$.

The operation of J-7 began on 11 January 1962 with a natural inflow of 2,500 $m^3$/day, decreasing to 1,600 $m^3$/day on the twelfth day. Injection was resumed on 1 February at a pressure of 0.2-0.3 $kg/cm^2$ and at an injection rate of 1,500-2,000 $m^3$/day. Reverse washing was done after the injection volume dropped below 1,000 $m^3$/day. Pump injection was applied and the volume increased to 1,000-3,500 $m^3$/day, at 2 $kg/cm^2$, after reverse washing, which was done when the volume decreased to 2,300-2,800 $m^3$/day. The average amount of injected water was 1,200 $m^3$/day and 2,700 $m^3$/day at 2 $kg/cm^2$.

The major problem of the project is the high cost of operations. In order to decrease these costs, the scale of the project must be enlarged and the chemical treatment of the water must be simplified, or some other type of treatment must be devised. Existing old wells were used in this project; but even with new wells, the functions of the wells must be tested thoroughly before selecting those that are operational.

The cost of the water, excluding the facilities, was $US 0.02/m$^3$, which would rise considerably if the seven-year depreciation for the equipment were included.

The mining of natural gas in water in the Niigata area has increased rapidly since 1949, and, in 1955, 10 x 10$^9$ m$^3$ of water were pumped, which caused land subsidence on quite a large scale. In 1958, the pumping of natural gas was restricted. Since then, all water pumped for mining is returned into the aquifer.

Since the river water used for recharge was not artificially contaminated, but chemically active, with large amounts of dissolved oxygen, it was thought that the ferrous ions dissolved in the ground water under reducing conditions would react with the charged water to form ferric precipitates, which would plug the sand and gravel pores. It was, however, proved during the course of the experiments that this was of little hindrance, and that under appropriate pressure, recharge can be continued for long periods. This project was successful for the purpose it was undertaken because: (a) The nature of ground water was well known; (b) The wells were properly constructed; (c) Funds were available for the treatment of water used for injection because of the large scale of the project; (d) Good observation wells were available. This experimental injection will be continued.

References:

Report on land subsidence in Niigata district. Series 1 and 11.

Ishiwada, Y. and I. Makino. Experiments of injection into aquifers at Niigata gas field. Journal of natural gas, 6:7, 1963.

# PRUT RIVER VALLEY INFILTRATION BASINS, UKRAINIAN SOVIET SOCIALIST REPUBLIC*

The background information for the Prut river-valley infiltration basins is as follows:

(a) Region: foot-hill of the Carpathian mountains; the Prut River is a tributary of the Danube and the down stream section of the river constitutes the border between the Ukrainian Soviet Socialist Republic and Romania;

(b) Geography: the area includes three geographical units:

- (i) the Kolomyian-Chernovtsy alluvial plain;
- (ii) the Pokutian Precarpathian (foot-hill) area within the interfluve of the Prut and Cheremosh rivers;
- (iii) the Prut-Seret interfluve.

The Podolian Upland spurs are on the left bank of the Prut River.

(c) Climate: the climate is moderate continental, with mild winters and warm summers. Air average annual temperature is 7.9°C; thaws are frequent during the first 10-day period of March, and at the end of November. Thus, there is a 266-day period without frost. Annual precipitation rises towards the Carpathians from 600 to 800 mm; in the mountains it reaches 800-1,100 mm. The great bulk (76 per cent) of precipitation occurs during the warm period;

(d) Surface waters: in the mountains, the Prut river valley is narrow and deep; in the Precarpathian area the benches become wider. The terraces are present on the left bank only. The width of the flood plain is 30-500 m. The width of the first terraces, located 3-4 m above the river level, reaches 3 km. The width of the second terraces, 5-8 m above the river level is 4 km. The other four terrace-levels are at elevations ranging from 15 to 150 m above the level of the river.

## Ground-water reservoirs and utilization

Tectonic movements in the area occurred during formation of the south-western margin of the Russian platform, Precarpathian trough and Folded Carpathians. There are outcroppings of the Archean and Proterozoic crystalline rocks in some valleys of the left-bank tributaries of the Dniester River. A thick stratum of the Palaeozoic, Mesozoic and Cenozoic deposits occurs on the Pre-Cambrian base in the Prut river valley. The Miocene clays are exposed everywhere in the bench socle. The total thickness of the Quaternary formations is 3-10 m. Sandy-shingle

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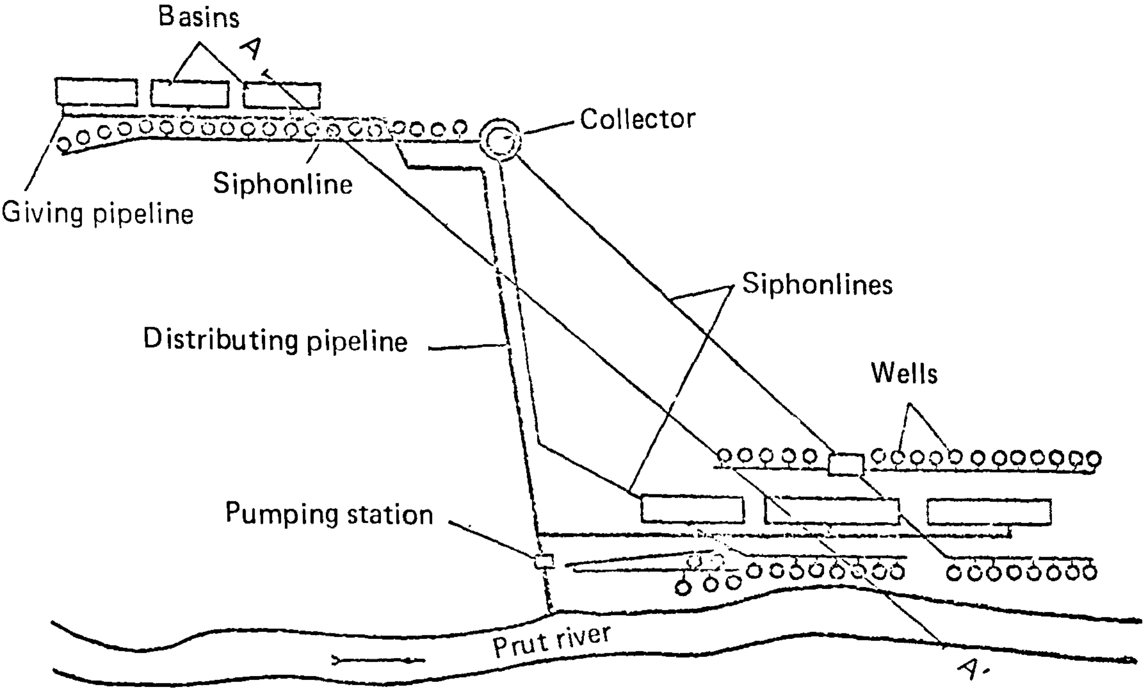
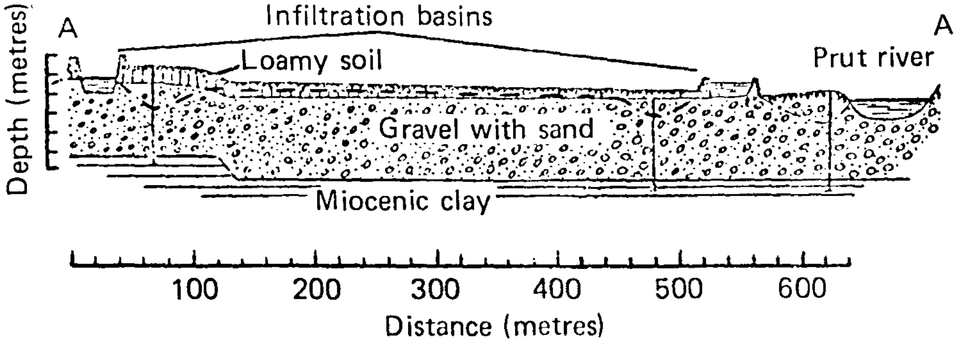
* Case study No. 22 prepared by V. Kunin, Y. But and V. Yanchev (Union of Soviet Socialist Republics).

Figure 32. Prut river valley infiltration basins, Ukrainian Soviet Socialist Republic



Location of the infiltration basins



Cross-section A-A' of plan view of the area of the infiltration basins deposits with thin interbeds and lenses of loamy light sand, loam and clay are distributed chiefly within the flood plain, and the first terraces.

Flood plain and terrace sediments have a hydraulic conductivity coefficient ranging from 10 to 650 m/day. The flysch strata of Upper Cretaceous and Paleogene deposits in the Folded Carpathians, and clay deposits of the trough contain no horizons of fresh ground waters. Other aquifers were identified in the Silurian, Upper Cretaceous and Miocene limestones, sandstones and sands of the south-western Russian platform margin in the Prut river valley.

Ground-water quality data:

(a) Flood plains: waters are of the hydrocarbonated type with total dissolved solids (TDS) of 300-400 parts per million (ppm);

(b) First terrace: waters are of the sulphate-hydrocarbonate sodium-calcium type. TDS is from 300 to 1,000 ppm;

(c) Other aquifers contain waters with a concentration from 2,000 to 3,000 ppm.

## Utilization of ground water

Only ground water from alluvial deposits is utilized for drinking supplies, owing to its low content in TDS. However, because they are only 2-10 m thick and vary greatly in lithological composition, the exploitable reserves of ground water in this horizon are limited, and great numbers of wells must be drilled to satisfy water requirements. To increase water inflow, the wells are drilled in immediate proximity to the river-bed; but, because of unfavourable geological conditions, it is not always possible to meet the growing demand of towns for water by extending the lines of wells.

## Artificial recharge

Artificial recharge of ground-water reservoirs in alluvial shingles in the Prut river upper valley has been taking place since 1954. Some infiltration basins were constructed at that time, and resulted in considerable improvement in conditions of the water supply. Analysis of a water installation in the city of Chernovtsy is presented below.

One of the most suitable ways for recharging underground waters is from infiltration basins situated in the river valley. The basins are 80-150 m long, their width at the bottom is 3.0. Depth of the basins is 1.3-1.8 m. A 10-15 cm thick layer of sand is periodically put onto the bottom of the basin. Operating wells, connected by siphon lines, are located on both sides of the basin. The wells are equipped with frame-rod filters with 300 mm/diameter wire coil. The distance between the wells is 16 to 70 m; the distance between the wells and the basin is 20 to 50 m.

Recharge water is pumped from the Prut River. The highest average silt-content is 2,800 g/m$^3$. The annual maximum value of silt-content, 11,000 g/m$^3$, was measured on 9 November 1954; the minimum value, 210 g/m$^3$, was measured on 11-20 November 1947. The average number of days with silt-content less than 50 g/m$^3$ is 235: the maximum number of days is 314; the minimum number is 161.

The main body of suspended material consists of 0.05 mm diameter particles. Water-clarification occurs in 12 hours. The infiltration basins are cleaned after the spring floods.

Putting the infiltration basins into operation made it possible to increase output of catchment construction by 58 per cent in summer and by 85 per cent in winter. The recharge effect accounted for 17 per cent in summer and for 11 per cent in winter.

The reasons for changes in the catchment output were studied more thoroughly during operation of the experimental infiltration basins during 1965-1966. Water intake by the wells under conditions of artificial recharge increased by 16-380 per cent. Such variations reflect the heterogeneity of alluvial deposits. The recharge resulted in the rise in temperature of the ground water from 9.8°-10.6°C to 11.6°-14.0°C; iron content dropped from 5.3-8.0 ppm to 0.00-0.07 ppm; coli-concentration increased from 0.1-37 to 4-250, but was insufficient to justify chlorination. The well-debit decrease, as shown by analysis of rock monoliths and filter cleanings between the catchments and infiltration basin, is related to chemical clogging of the screens, of the gravel pack and of the sands within a 15-30 m radius with ferrocarbonate cement. The thickest layer of compact cement, 5-7 mm, was formed within the range of the dynamic-level fluctuations.

Thus, to provide long-term operation of catchment constructions in the areas of infiltration basins, necessary measures for preventing or eliminating chemical clogging of the wells, and the surrounding aquifer, should be taken; in addition to periodic cleaning of the basins themselves. This will make artificial recharge of the ground-water reservoirs in the Prut river valley still more profitable.

# RHINE VALLEY, WIESBADEN, FEDERAL REPUBLIC OF GERMANY*

The background information for the Rhine Valley (Wiesbaden) project is as follows:

(a) Region: Rhine Valley; Frankfurt-am-Main region;

(b) Geography: broad alluvial valley of the Rhine River;

(c) Climate: temperate, humid; average annual precipitation from 750 to 800 mm;

(d) Reservoir type: river alluvium.

## Ground-water reservoirs and utilization

The aquifer is composed of a layer of coarse alluvium with a maximum thickness of 7 m. The effective grain size is 0.24 mm, with a uniformity coefficient of 1.46. The coefficient of hydraulic conductivity is 100 m/day. The estimated volume of water in storage is 1.4 x $10^6 m^3/km^2$. The ground-water flow occurs from the mountains towards the Rhine River, under a hydraulic gradient of 1/3,000.

The ground water is utilized for urban water supply. The pumping station presently provides some 10 x $10^6 m^3$/year, covering 75 per cent of municipal demand. Without artificial replenishment, the installations provides 3 x $10^6 m^3$/year of native ground water. The purpose of the project was to restore the original piezometric levels which were depressed through over-exploitation.

## Artificial recharge

From 1920 to 1924, four infiltration basins were constructed between the Rhine and the pumping installations. As over-exploitation became worse, additional measures were taken in 1959: (a) The number of basins, previously limited owing to the lack of available land, was increased; (b) Injection wells were constructed. In 1965, injection by the means of a buried drain was introduced.

The water from the Rhine, being polluted, undergoes the following treatment:

(a) Decanting in a ditch 2 m deep;

(b) Aeration by means of a cascade;

(c) Settling in a basin 580 m long, 42 m wide, with a detention period of 2.5 days;

(d) Infiltration in basins 500 x 40 m, located between the river and the line of pumping wells. These basins penetrate into the aquifer;

(e) A line of 42 wells pumping at a distance of 230 m from the infiltration basin, and at 460 m from the Rhine.

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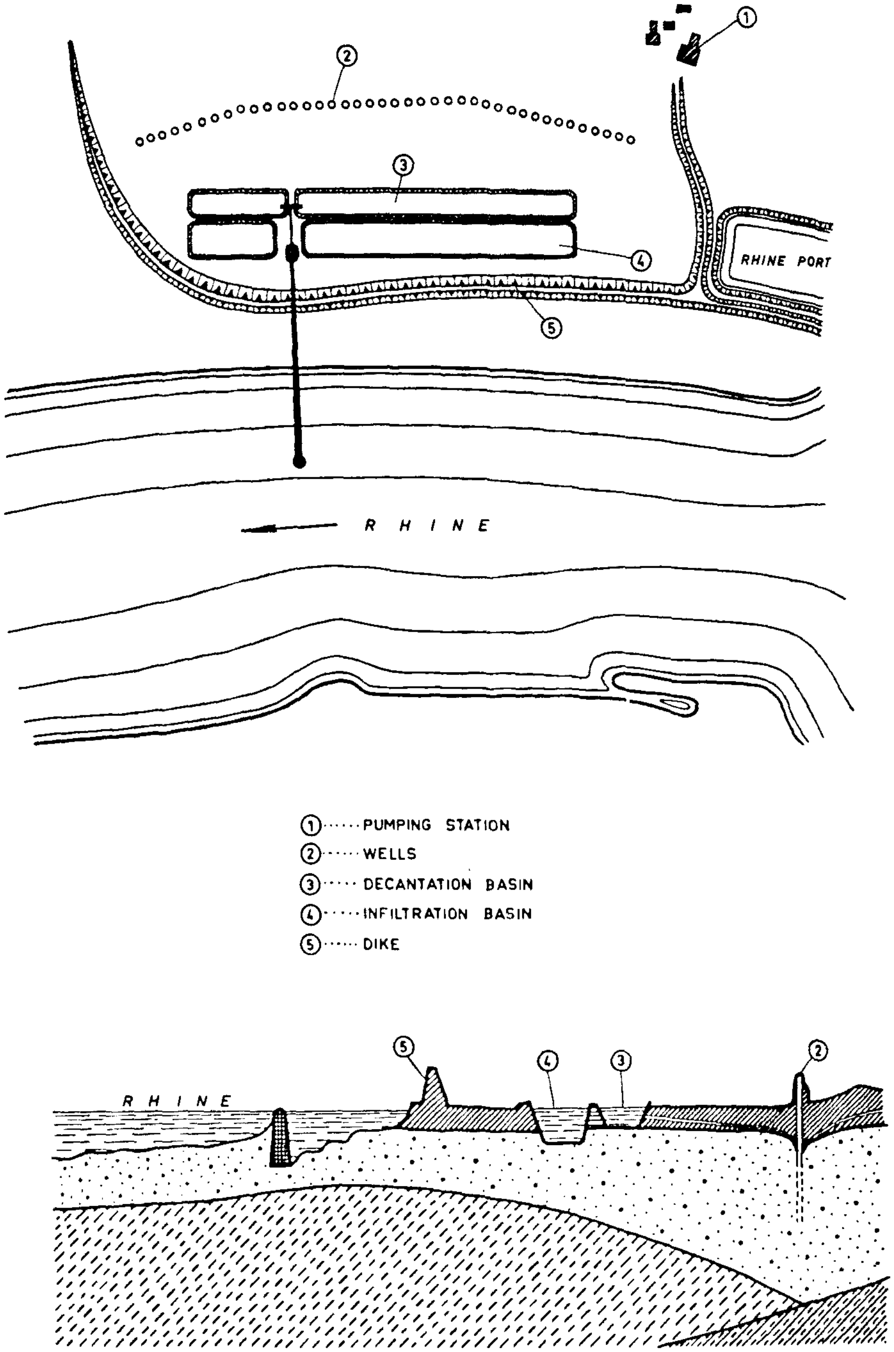
* Case study No. 23 prepared by G. Castany (France).

FIGURE 33



## RHINE VALLEY, WIESBADEN,
## FEDERAL REPUBLIC OF GERMANY,

PUMPING OF ARTIFICIAL GROUND-WATER
AT SCHIERSTEIN – WIESBADEN

CASE STUDY N° 23

The circuit of water is complicated because a part of the raw water, which is sent into the infiltration basin, is treated in a station before being injected.

The injected waters undergo biological purification and thermal regulation during their passage through the aquifer (see table below). The distance between the infiltration basins and the pumping wells is 230 m and is covered by ground water in 60 days, at a speed of 3.85 m/day. During this time, the water temperature is stabilized at $8^{o}$-$12^{o}C$, the germs disappear and the organic matter diminishes; but during the time of the flow in the aquifer the geological factors intervene in an unfavourable way, causing an increase in iron and manganese, and a considerable enrichment in $CO_2$. Hardness also increases, and a second treatment is, therefore, necessary. A diminution of the infiltration rate has been observed, which implies a diminution of permeability, owing to the precipitation of iron and manganese in the formation:

| | Water from the Rhine | Water from the aquifer | |
|---|---|---|---|
| | | Artificial recharge | Induced recharge |
| Iron | 0.12 | 0.7 | 4 |
| Manganese | 0.06 | 0.4 | 1.5 |
| Total hardness (French degrees) | 10 | 19 | 18 |
| Carbonate hardness | 9 | 12 | 14 |

The ground water which is pumped has, therefore, a complex and mixed origin:

(a) Natural ground water (30 million $m^3$/year);

(b) Induced infiltration from the Rhine plus water from artificial recharge (100 million $m^3$/year).

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## RUHR VALLEY, DORTMUND, FEDERAL REPUBLIC OF GERMANY*

The background information for the Ruhr valley (Dortmund) project is:

(a) Region: alluvial valley of the Ruhr river; city of Dortmund - Gesecke;

(b) Geography: Ruhr valley; right bank tributary of the Rhine approximately 50 km up stream from their junction. This is the most industrialized region in the Republic. The population and industrial density are very high and water needs are considerable;

(c) Climate: temperate, humid, cold; average annual rainfall from 750 to 800 mm;

(d) Reservoir type: river alluvium.

### Ground-water reservoirs and utilization

Geological conditions: The geological log is as follows:

(a) Silts (low permeability), from 1 to 1.5 m; (b) Layer of gravel and sands, from 5 to 6 m; (c) Impervious substratum with a very irregular surface.

The geological conditions are of coarse river alluvium, heterogeneous, containing an unconfined aquifer. Horizontal hydraulic conductivity is from 100 to 1,000 m/day; effective porosity is good. Grains are 10 per cent fine gravel and coarse sands, and from 5 to 10 per cent fine sands. The estimated volume of water in storage is $10^6$ $m^3/km^2$.

The characteristics of the water of the Ruhr river utilized for artificial recharge are given in the following table. It is injected into the aquifer without any preliminary treatment.

|  | Absolute maximum | Average over 5 years | Absolute minimum |
|---|---|---|---|
|  |  | (parts per million) |  |
| Cl | 40 | 25.5 | 13 |
| $SO_4$ | 80.6 | 52.6 | 30.1 |
| $NO_3$ | 30.6 | 16.3 | 6.8 |
| $NH_4$ | 3.16 | 0.54 | 0.02 |
| Oxidizability | 22 | 8.2 | 3.4 |
| Hardness (French degrees) | 17 | 13 | 9.2 |

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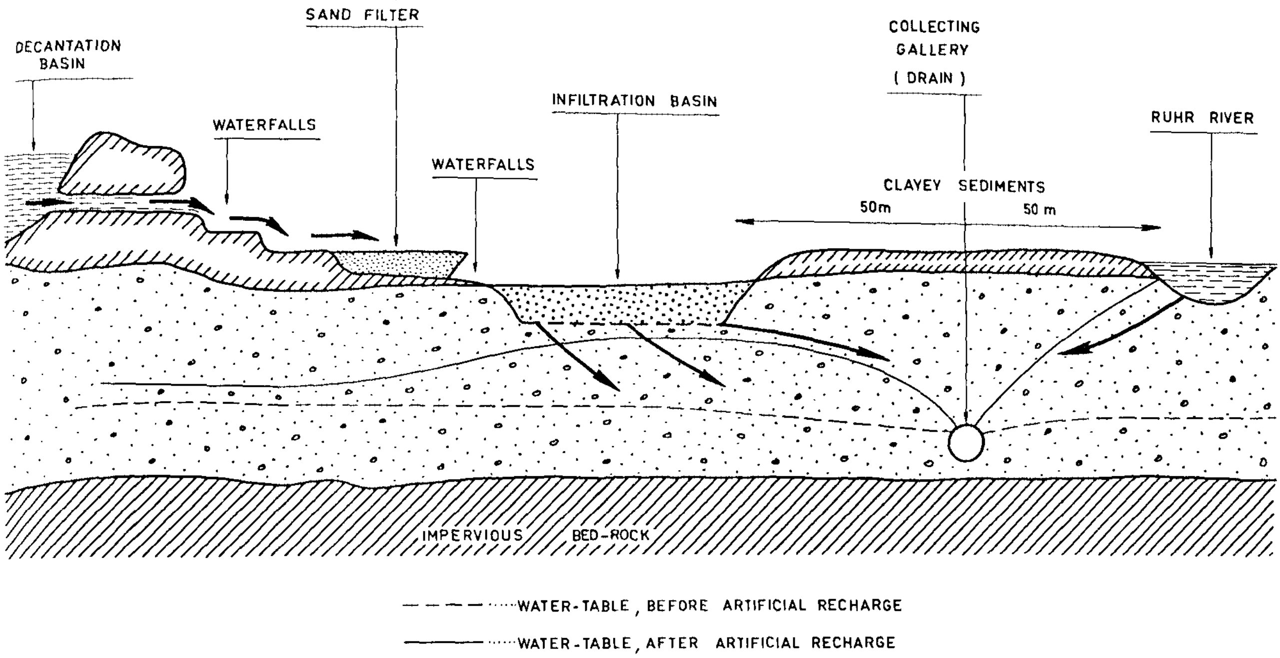
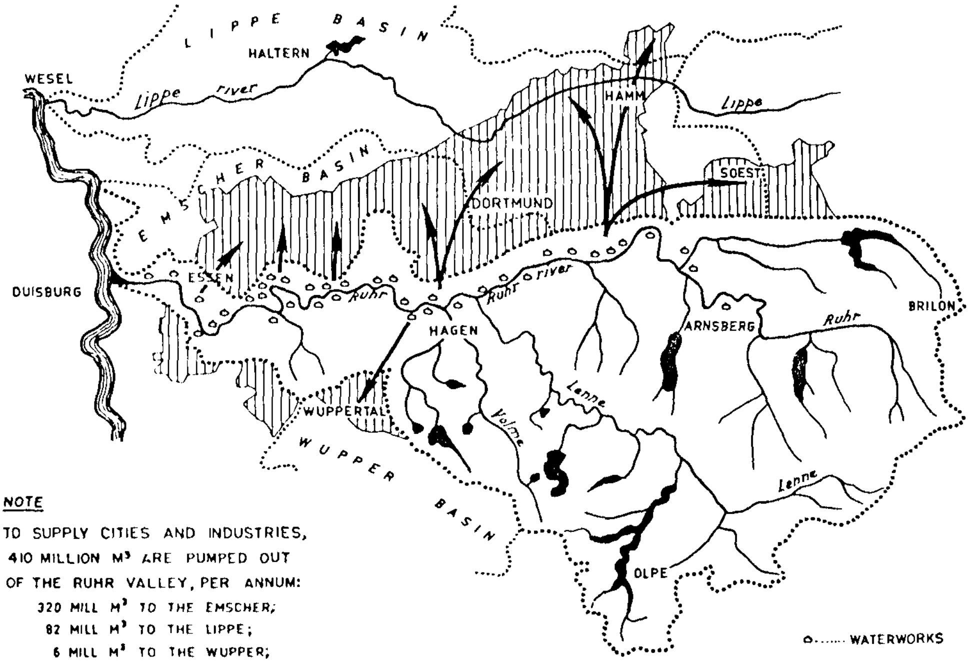
[*] Case study No. 24 prepared by G. Castany (France).

FIGURE 34





NOTE

TO SUPPLY CITIES AND INDUSTRIES, 410 MILLION M³ ARE PUMPED OUT OF THE RUHR VALLEY, PER ANNUM:

320 MILL M³ TO THE EMSCHER;
82 MILL M³ TO THE LIPPE;
6 MILL M³ TO THE WUPPER;
AND 2 MILL M³ TO THE EMS BASIN.

RUHR VALLEY, FEDERAL REPUBLIC OF GERMANY,

DORTMUND ARTIFICIAL RECHARGE SCHEME

CASE STUDY Nº 24

Recharge is through infiltration of rainfall. The rate of recharge is 10 l/sec/km$^2$. Outflow issues from adjacent ground-water bodies, in particular from the edges of the valley. The over-draught due to pumping since 1910 reversed the direction of the ground-water flow.

The ground water is utilized for the water supply of the urbanized area of Dortmund. The problem which existed in Dortmund and was solved is quite a general one in the Ruhr valley, and can be considered as typical, especially with respect to the scheme which was established. In the Ruhr river are to be found the main water resources of this large industrial region. The first installations of artificial recharge date back to 1887. Currently, more than 100 pumping and treatment plants yield 1,200 x 10$^6$ m$^3$/year.

The water exploitation in this area of northern Westphalia is as follows:

| | | |
|---|---|---|
| Surface water | 9 | per cent |
| Artificial recharge | 33.4 | per cent |
| Induced replenishment | 28.29 | per cent |
| Native ground water | 28.7 | per cent |

## Artificial recharge

From 1910 to 1935 the resources of the alluvial aquifer were over-exploited by pumping, creating a considerable depression in the piezometric surface, and an infiltration of river water. Therefore, a self-purifying process in the aquifer was created through induced replenishment. This system deteriorated owing to the clogging of the banks and the increase of the pollution in the Ruhr. In 1935, the artificial recharge installation of the alluvial aquifer was established. The effect sought is solely the improvement of water quality.

The waters of the Ruhr circulate as follows:

(a) A settling basin lowering the suspended solid contents to 10 ppm;

(b) A prefiltration basin of 33.3 m$^2$, including eight filters;

(c) Flow in cascade to oxygenate the water;

(d) Infiltration basins (200 x 25 m penetrating into the mud-silt layer), the bottom of which is in the alluvium, and which contains a sand layer 0.2-0.3 mm in diameter and 0.50 m thick.

The infiltration rate is 0.2 m$^3$/m$^2$/h. The water depth is from 0.3 to 0.4 m.

There are 24 infiltration basins, with a total surface of 126.7 m$^2$. They are in parallel with the pumping installations at a distance of 50 m in the direction of the foot-hills. The waters are collected by a drain laid upon the impervious substratum, parallel to the river bed at a distance of 50 m. The injection system is operated on a continual basis. The characteristics of the aquifer do not allow temporary storage. It is not thick enough, the sediments are too coarse and the permeability is high. The principle of induced replenishment is utilized here.

The pumping totals 100 million $m^3$/year; half from the artificial replenishment occurring through the infiltration basins, half from the infiltration of the waters from the river. The exploitation is carried out utilizing a drain 4,560 m long, with a diameter 1-1.20 m. The water is extracted from this drain by 163 wells. The clogging of the basins by suspended matter and algae requires complete periodic drainage and dredging of the upper section of the layer of filtering sands.

Present research is concerned with tests of intermittent injection to increase the time between cleaning operations. The cost of 1 $m^3$ of water is between $US 0.03 and $US 0.04, everything included.

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Bize, J. et L. Bourguet. Le prix de revient de l'eau dans trois aménagements d'alimentation artificielle. Techniques et sciences municipales (Paris), 3:113-120. 1968.

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# SEBIKOTANE AQUIFER, SENEGAL*

The background information for the Sebikotane aquifer (Senegal) is as follows:

(a) Region: East of Dakar, West Africa;

(b) Geography: Cap Vert peninsula, on the Atlantic shore lines. N'Diass, hilly structure rising some 60 m above sea level, oriented north-south and edged east and west by two depressed areas; no permanent surface-water flow; karstic morphology with typical thorn-bush vegetation of the savannah;

(c) Climate: defined as "subcanarian", with a dry season quite windy (nine months) and a short rainy season with sudden and intense showers. Average annual rainfall, 640 mm. During the period 1960-1966, there were three years with an average annual rainfall of only 600 mm. The amount of precipitation is extremely variable. Average annual temperature, 25°C; average annual evaporation on water-free surface, 1,750 mm; average annual real evapo-transpiration, 440 mm;

(d) Reservoir type: karstic carbonated rocks;

(e) Methods of investigation: detailed hydrogeological study; detailed inventory of ponds and wells; electrical geophysical prospection; reconnaissance drilling and exploitation wells, including pumping tests, geochemical study of ground water and detailed piezometric study. Control of the piezometric surface and study of its fluctuation; study of piezometric network. Climatological study and study of water balances.

## Ground-water reservoirs

The geological backbone of the region is the anticline horst of N'Diass oriented north-south, constituted of Maestrichtian sands and clays. Its western flank, faulted and built of Paleocene "Sebikotane" limestones, corresponds to the aquifer which is considered here. It outcrops as a narrow strip north-south, limited east and west by submeridian faults. The western accident brings into contact with the limestones a thick series of Eocene marls. The eastern accident brings into contact with the limestones the sandy clays and sands of Maestrichtian age of the N'Diass horst.

The shallow or almost outcropping Sebikotane limestones plunge southwards as far as Pantior and further north. There, the transverse fault of Pantior raises the limestones which outcrop in the Pantior ponds. Then the limestones again plunge south, being overlain with Eocene marls. Along the Sebikotane fault, a valley has been dug out during the Quaternary period, penetrating 65 m into the Paleocene limestone and the underlaying Maestrichtian sandstones. This valley has been filled with sands of diverse coarseness, containing some clays. This ancient valley is of a great hydrogeological importance.

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* Case study No. 25 prepared by G. Castany (France).

# SEBIKOTANE AQUIFER, SENEGAL

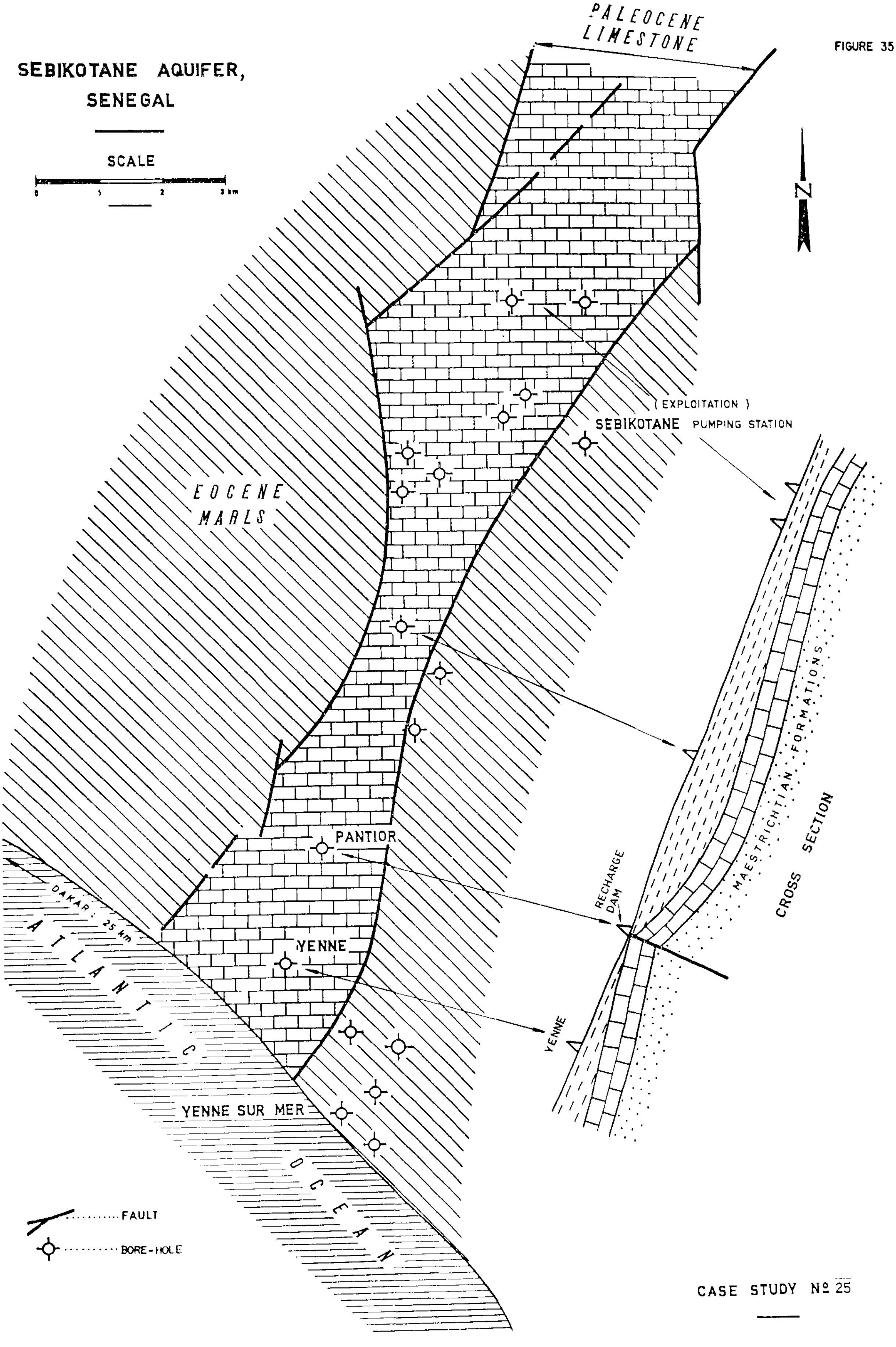

FIGURE 35

CASE STUDY Nº 25

The geological log is as follows:

(a) Dunar sands, well-developed on the northern and southern shores (quarternary);

(b) Transgressive marls (Eocene);

(i) Eocene transgression surface;

(ii) Lower Eocene emersion;

(c) Paleocene formations;

(i) Zoogenic and eroded limestones, Paleokarst, average thickness 100 m;

(ii) Marly limestones with interbedded clayey horizons;

(d) Maestrichtian formations;

(i) Sands, locally clayey;

(ii) Carbonated sandstones;

(iii) Clays and sand, sandstones (clays only, eastwards).

The limestones are found on a narrow strip oriented north-south, 60 km long; at the south the limestone is 15 km wide; it is 5 km wide at the northern end. The limestones provide an unconfined aquifer north of the Pantior fault. In the southern part the aquifer is confined under the Eocene marls. Effective porosity is 15-20 per cent; storage coefficient, under confinement, is $7 \times 10^{-4}$; average transmissivity is 3,000 $m^2$/day.

In the northern part of the aquifer, ground water is sweet and has a calcium bicarbonate chemical facies:

| | |
|---|---|
| Ca | 74-84 parts per million (ppm) |
| $HCO_3$ | 125-160 ppm |
| Total hardness | 20 French degrees. |

In the southern part, the ground water contains an increasing concentration of salts owing to sea-water intrusion. The total dissolved solids (TDS) contents, which was 1,760 ppm to the north, is as high as 92,824 ppm at Yen, owing to local concentration. The nearness of this salt water creates a danger for ground-water exploitation; the intrusion progressing as over-draught develops.

Recharge characteristics are as follows:

(a) Direct replenishment by rainfall, 45 per cent;

(b) Direct replenishment by run-off, small;

(c) Underground replenishment issued from other aquifers along the boundaries, 50 per cent;

(d) Ground water issued from the buried valley, 4 per cent.

A detailed study for 1958-1966 is given in table 17.

Table 17. Recharge and discharge of the ground-water reservoir of Sebikotane

| Years | 1960 | 1961 | 1962 | 1963 | 1964 | 1965 | 1966 |
|---|---|---|---|---|---|---|---|
| Average precipitation on the watershed (millimetres) | 590 | 510 | 620 | 575 | 640 | 607 | 515 |
| Piezometric level at Pantior before the rains (metres) | 1.2 | 2.4 | 3.9 | 4.45 | 4.8 | 4.95 | 5.75 |
| Increase of the piezometric level at Pantior (metres) | 1.78 | 2.10 | 3.80 | 3.75 | 5.50 | 5.60 | 5.80 |
| Volume of pumped water required to eliminate increased level at Pantior (million cubic metres) | 5.4 | 5.3 | 7.2 | 7.0 | 8.8 | 8.2 | 7.8 |
| Pumped quantities equivalent to a rainfall of 600 mm (million cubic metres) | 5.5 | 6.2 | 7.0 | 7.3 | 8.25 | 8.1 | 9.0 |
| Increase of water level equivalent to 600 mm rainfall (metres) | 1.8 | 2.5 | 3.67 | 3.9 | 5.1 | 5.53 | 5.59 |

Previously, the ground-water flow was oriented north-south; the buried valley had the effect of lateral drainage, carrying a certain amount of ground water to the ocean. This effect has been reversed since the exploitation began. The ground water is utilized for the urban water supply of Dakar and surrounding areas. Ground-water exploitation began in 1958. The rate of exploitation is shown in table 18.

Table 18. Rate of exploitation

| Period of exploitation | Extraction (cubic metres per hour) |
|---|---|
| Up to December 1958 | 180 |
| December 1958-April 1959 | 600 |
| April 1959-January 1960 | 1,400 |
| Up to April 1962 | 1,400 |
| April 1962-December 1966 | 1,150 |
| January 1967 | 1,000 |
| 15 January 1959-30 June 1967 | 83 million cubic metres |

This exploitation led to an over-draught having damaging effects upon the ground-water flow and water quality. In July 1959, the ground-water stream-flow reversed to the north, thus causing the drainage of N'Diass area (bringing sweet water) and a sea-water intrusion into the southern limestones "compartment". The piezometric surface was lowered by approximately 2 m in a large area. In 1962 a sudden increase of water salinity occurred in the Pantior water catchments.

## Artificial recharge

The purpose of the project was to restore the piezometric level in order to repel the sea-water instrusion in the south; to rehabilitate the water catchment; and the utilization, through artificial recharge of run-off waters, of the limestone aquifer of Sebikotane, with a view to the storage of ground water.

Early in 1964, a dam was built at Pantior. It is a simple clay dike compacted, with asphalt cover 4 m high and 100 m long. The artificial lake extends upon the Paleocene limestones outcropping in the Pantior ponds and upon the sands of the buried valley. Therefore, a double artificial recharge occurs: directly at the level of the Pantior faults; indirectly, through the buried valley. The total storage potential of the dam is 3.4 million $m^3$.

The utilization of the dam has, within a short time, stopped sea-water intrusion and raised the piezometric levels. The latter exceeds by 14-25 per cent increases resulting from natural recharge conditions (see table 18). Ground-water storage has increased by 7-15 per cent, and averaged 10 per cent.

The artificial recharge stopped salt-water intrusion in 1964, and the salt-water front retreated after 1965, which was a rainy year. This is owing to the infiltration of water stored behind the dam directly into the brackish aquifer of the southern compartment (an increase of 1 m) and to the generalized rise of the piezometric level.

At Damboussane, north of Pantior, the ground waters which were, through contamination, initially bicarbonated calcic, then sodium chloride, had recovered their initial chemical content by April 1965. The rapidity of this decontamination is owing to the permeability of the fissured limestones. On the other hand, in the sands of Santhia the decontamination is slower, and the waters have not yet recovered their initial chemical composition. However, their favourable evolution is certain.

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# SEINE RIVER GROUND-WATER BODY AT CROISSY, FRANCE*

The background information on the Seine River ground-water body at Croissy is as follows:

(a) Region: vicinity of Paris;

(b) Geography: valley of the Seine River, 11 km down-stream from Paris;

(c) Climate: temperate, humid; average annual rainfall of 740 mm;

(d) Reservoir type: fissured chalk overlaid by alluvium;

(e) Methods of investigation: detailed hydrogeological study; piezometric study; geochemical study of surface water and ground water. Observation of the fluctuation of the piezometric surface and of the water quality.

## Ground-water reservoirs

The geological log is of recent alluvium of the Seine River, from 8 to 15 m thick, averaging 13 m. There is also a body of Senonian chalk, of which the upper 10-25 m is fissured. This fissuring is due to the conjunction of tectonic and periglacial actions.

The aquifer is of the unconfined phreatic type, located in the fissured chalk and in the alluvium. The latter is hydraulically connected with the river Seine. Total thickness of the aquifer (chalk plus alluvium) is from 20 to 40 m; effective porosity is 2-5 per cent; total porosity is 30-35 per cent; hydraulic conductivity is 50 m/day. The volume of water storage ranges from 0.4 x $10^6$ to 2 x $10^6$ $m^3/km^2$.

The physico-chemical characteristics of the waters are given in the following table:

| | Seine | Infiltration basin | Exploitation bore-holes |
|---|---|---|---|
| Temperature (centigrade) | 2-25 | 3-27 | 8-16 |
| Turbidity | 0.35 m (disc) | 2-5 drops putty | 2-3 drops putty |
| Bio-chemical oxygen demand (BOD) (5-day) | 4-10 | 0.4-2 | - |
| Detergents | 0.25-1.5 | 0.1-0.6 | Less than 0.1 |
| Organic materials (in $O_2$) | 2-5 | 0.9-1.5 | 0.4 |
| Ammonia (as $NH_4$) | 0.4-9.6 | 0.15-4.5 | 0-0.45 |
| Colibacillus (per litre) | $10^5$-$10^6$ | 250-10,000 | - |

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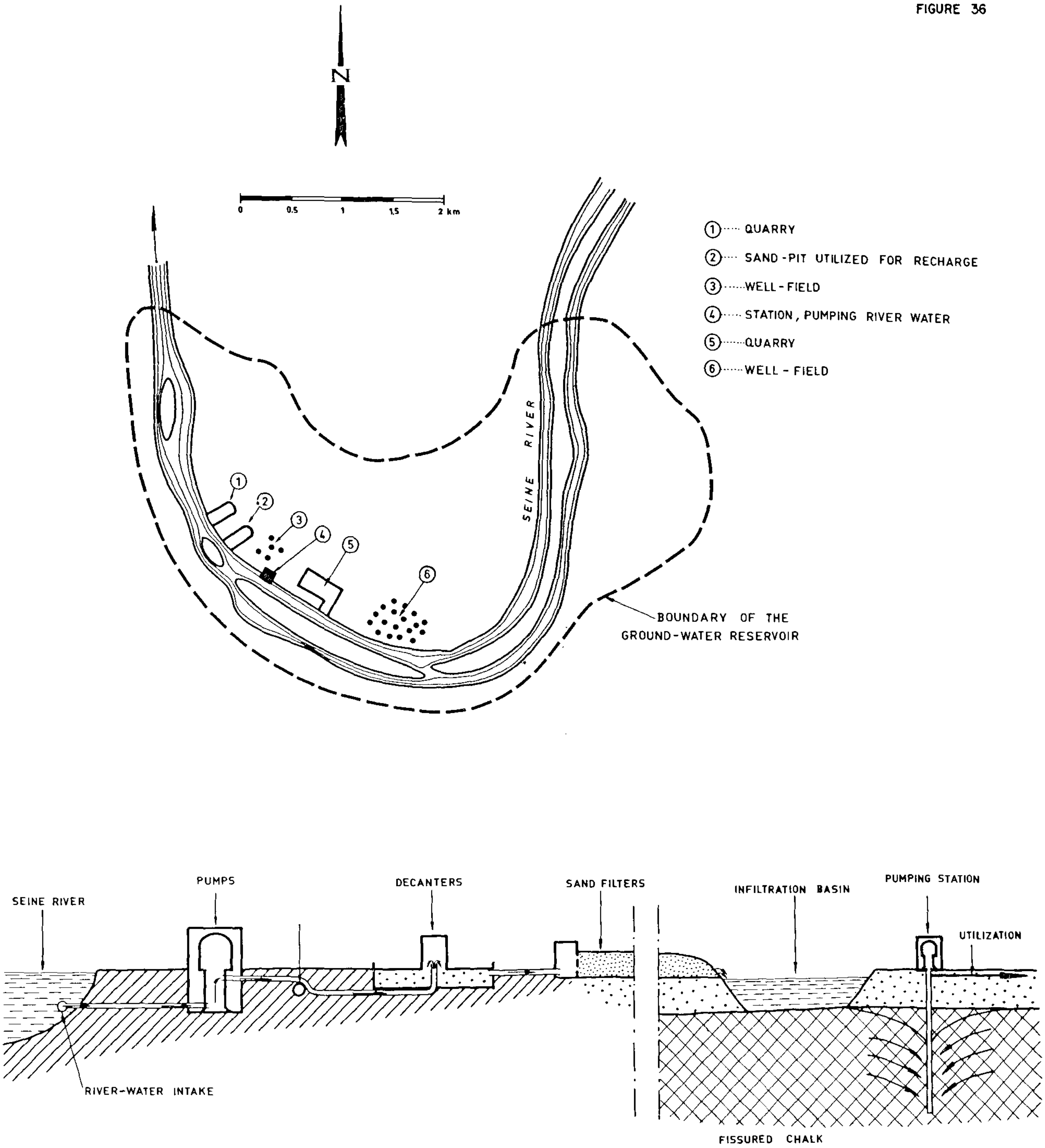
* Case study No. 26 prepared by G. Castany (France).

FIGURE 36



SEINE RIVER GROUND-WATER BODY AT CROISSY,

FRANCE

CASE STUDY Nº 26

In low-water periods, the Seine River includes 40 per cent sewer waters. Direct purification would be difficult and expensive, owing to the presence of industrial-waste water.

Recharge takes place by precipitation over the basin and from the Seine River, but weakly in normal periods because of clogging of the banks and the bottom. Drainage occurs from the valley slopes; from various interconnected aquifers; from Soisson sands and gravels; and from Lutetian limestone. Discharge occurs mainly through municipal pumping.

## Artificial recharge

The ground water is utilized for the urban water supply of the western part of the Paris area. Since 1959, the aquifer, which is over-pumped, has been artificially recharged in the pumping field itself, for the purpose of:

(a) Restoration of the reserves;

(b) Regulation and increase of the resources available by means of combined utilization of surface and ground water;

(c) Conservation of the quality of ground water and the improvement of the potability of the injected surface water;

(d) Thermal regulation.

The Croissy ground-water body has been exploited for nearly a century as the urban water-supply of the western suburbs of Paris. The over-draught which took place during recent years ($50 \times 10^6$ $m^3$ in 1959) has caused a depression of the piezometric surface in the area of pumping and a deterioration of the quality of ground water. As a matter of fact, the piezometric surface has been lowered to 6 or more beneath the level of the waters in the Seine River, causing an infiltration of polluted surface-water into the aquifer.

The recharge waters are pumped from the Seine River, as long as a certain pollution threshold is not reached. This threshold is usually exceeded between July and September, when the waters contain 40 per cent industrial- and urban-waste water.

The water is then given the following treatments:

(a) Passing through a turning grid;

(b) Injection of a coagulant and activated charcoal;

(c) Rapid filtration at a constant flow, to eliminate suspended matter, on two batteries of sand filters in parallel, having four compartments of 32.5 $m^2$ each, or a total of 260 $m^2$ of filtrating surface. The filters are regenerated by the means of infiltration of air and clean water. The water flows into former sand pits located in the centre of the pumping area. Their bottom is filled with sandy alluvium, 1-4 m thick. The pumped water is treated because infiltration of water from the Seine River into the aquifer has been demonstrated.

Results have shown that the dynamic levels in the bore-holes and the piezometric surface have been partly restored. The volume presently injected amounts to 12 x $10^6 m^3$/year, for a total of 35 x $10^6 m^3$ pumped (the difference being provided by the aquifer through natural replenishment). The injected volume will be increased to 20 x $10^6 m^3$ in the near future. Since the ground-water reserve has a regulating action, the injections can be operated outside the periods during which the pollution of the Seine is at its peak. The chemical and bacteriological purification of the injected waters is accomplished in the sand pits and the aquifers. The iron is removed, the $NH_4$ content is lowered, colibacillus are scarce and temperature is regulated.

The biological action in the water saturated with oxygen begins in the sand pits, where the water stays for about 10 days. During warm periods, a rapid development of various algae, including diatoms, can be observed. An important biological activity takes place through chlorophyllian action, in particular. Contents of 28 g/l of oxygen are recorded, although saturation content does not exceed 11 g/l. As a result, a heavy precipitation of carbonates and a lowering of the hardness of the water follow. The action of the oxidizing bacteria result in the destruction of the organic material. The disappearance of colibacillus has also been observed.

The purifying process continues in the sand and chalk, which present a remarkable bactericidal power that is probably due to agglutinating physical phenomena. As a result, the temperature is also regulated. This has considerable action upon the biological processes which, if they slow down or cease in the basin, continue within the aquifer.

The bottom of the sand pits becomes clogged by colloidal clay in suspension, dust brought by the wind and the earthy material from the banks. The algae also cover the bottom with a rather impervious layer during the spring period. To remove these materials, the sand pit is periodically drained in periods when the Seine waters are too polluted to be utilized. The algae cover disintegrates, the colloids coagulate and dredging by mechanical means is therefore rendered possible.

The cost of one injected $m^3$ of water is:

| | | |
|---|---|---|
| Maintenance costs | | \$0.02 |
| Financial costs | | \$0.04 |
| | Total | \$0.06 |

Equipment costs total \$3.6 million. It must be emphasized that the artificial recharge increases the value of previous pumping installations.

Future operations call for: improvement of the pre-treatment of raw water; selection of the periods of utilization of raw water; practical process of unclogging, including study of the algae and possible action against their growth; action to prevent thermal stratification of the water.

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# TANGIERS RECHARGE PROJECT, MOROCCO*

The background information on the Tangiers recharge project is as follows:

(a) Region: south-west of the city of Tangiers;

(b) Geography: coastal plain;

(c) Climate: Mediterranean; rainfall (autumn-winter), 600-700 mm;

(d) Reservoir type: sedimentary coastal basin.

## Ground-water reservoirs and utilization

The geological structure can be described as a synclinal basin. The formations of interest in the basin are Pliocene shell limestones and sandstones, 300 m thick, which overlie Cretaceous clays. The Pliocene limestones are karstic. The principal aquifers are the limestones and sandstones, which are unconfined. The syncline is considered as an isolated unit. Therefore, the boundaries of the syncline and the aquifer are the same. Hydraulic conductivity is 1-10 m/day. The surface area of the aquifer is 20 $km^2$; it is 300 m thick. Natural recharge occurs by means of infiltration of rainfall and run-off into the aquifer; total yearly recharge is in the range of $1 \times 10^6 m^3$. Natural discharge occurs through underflow towards the ocean. The aquifer is exploited by means of wells to provide a municipal water supply for Tangiers.

The exploitation of this reservoir has increased continuously. In 1953, the aquifer was over-exploited; in 1955, $3 \times 10^6 m^3$ was extracted, but there was only $1 \times 10^6 m^3$ of natural recharge. Storage was being depleted to the extent of a 15 m drop in the piezometric level in four years. With this, the problems of sea-water intrusion increased.

## Artificial recharge

The purpose of artificial recharge was to stop the instrusion of sea water into the aquifer and to maintain the available supply. In 1958, a low check-dam was constructed on the Mhardar River to provide temporary retention for winter flood-waters, permitting the waters to percolate into the aquifer. During the six-year period, 1958-1964, an average of 1 million $m^3$/year was recharged to the aquifer in this manner. Surface water is used exclusively during the winter, and the replenished aquifer is exploited in the summer. The artificial recharge technique has been effective in maintaining the water supply for Tangiers, and will be continued.

References:

Ambroggi, R. et R. Hazan. Alimentation artificicelle de nappe aquifère dans des grès fissurés. Tanger. Colloque de Dobrovnik. AIRS UNESCO, pp. 496-499. 1965.

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* Case study No. 27 prepared by G. Castany (France).

# COASTAL PLAINS, TOGO*

The background information on the Togo coastal plains is as follows:

(a) Region: Gulf of Guinea, West Africa;

(b) Geography: flat coastal plain with lagoons and small streams;

(c) Climate: tropical, humid;

(d) Reservoir type: sedimentary coastal aquifers;

(e) Methods of investigation: a survey of all the existing wells and bore-holes; a geophysical survey, including a resistivity survey for water quality. The drilling of bore-holes, pumping tests, preparation of maps and a survey of water needs in the area.

## Ground-water reservoirs

With respect to geological conditions, the coastal sedimentary formations overlie the crystalline and metamorphic rocks of the Pre-Cambrian Shield of West Africa. At the outcrop area in the north, the formations are in contact with crystalline rocks. The total thickness of the sedimentary deposits increases rapidly to the south. Near the shoreline, the total thickness is approximately 800 m. The following units, from oldest to youngest, are found in the sedimentary complex:

(a) Sands, sandstones and clays that have transgressed upon the basement rocks (Upper Cretaceous-Maestrichtian);

(b) Lama clays (Eocene);

(c) Sands and sandstones (Continental Terminal);

(d) Dune sands, in the vicinity of the shore, cap the Continental Terminal formations.

The principal aquifer is composed of the sands and sandstones of the "Continental Terminal" (late Cenozoic) which overlies the Lama clay. The aquifer is considered to be unconfined. The sedimentary coastal basin extends from Ghana to Nigeria; as an aquifer in Togo its dimensions are 70 km x 30-55 km. The thickness varies from 0-150 m. The total capacity of the reservoir overlying the Lama clays has been estimated at 650 x $10^6 m^3$ for the Agoueve depression only. The water quality varies as a function of sea-water encroachment.

Recharge takes place by the following methods: direct infiltration of rainfall (approximately 3 million $m^3$/year); direct infiltration of surface water

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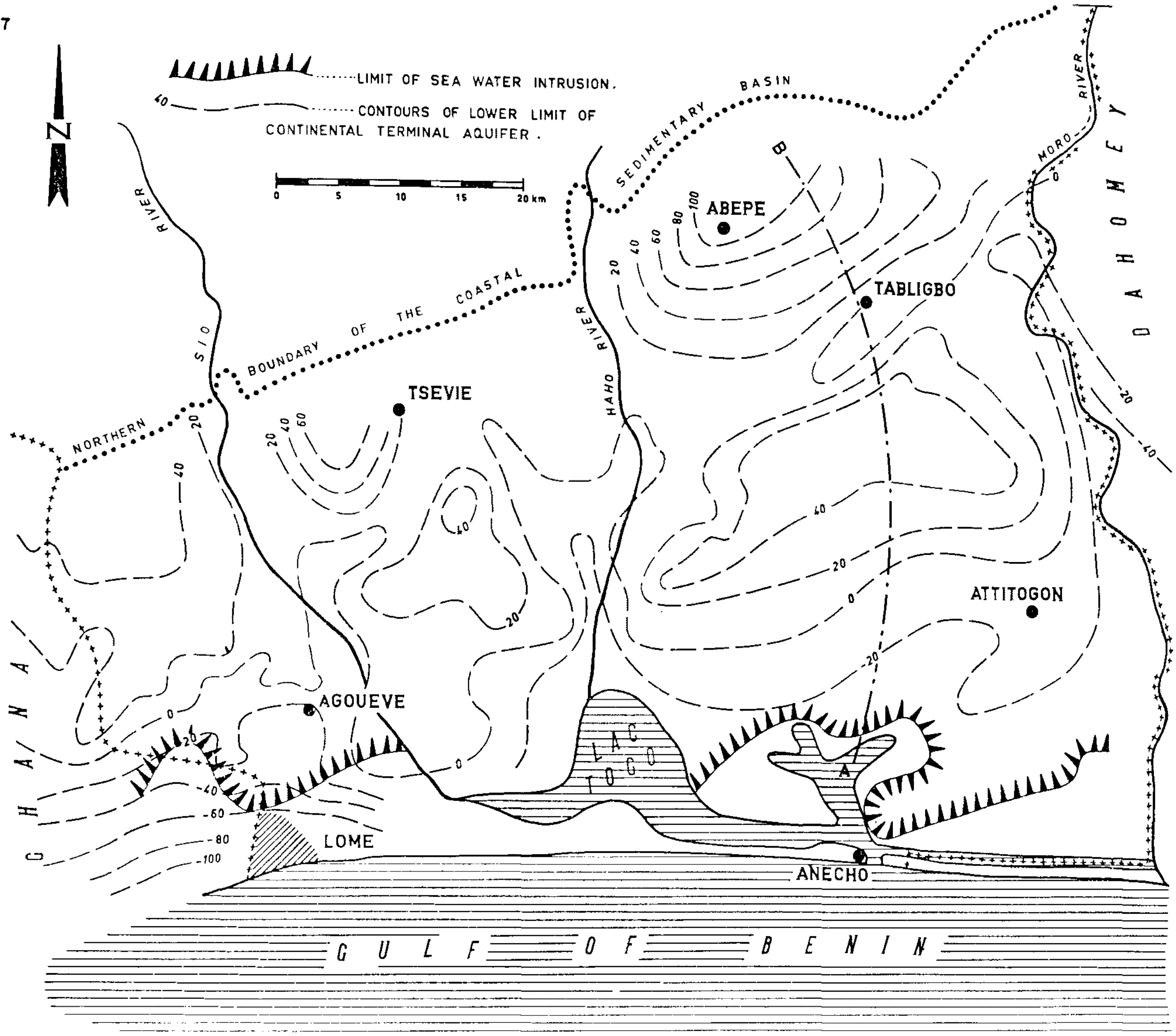
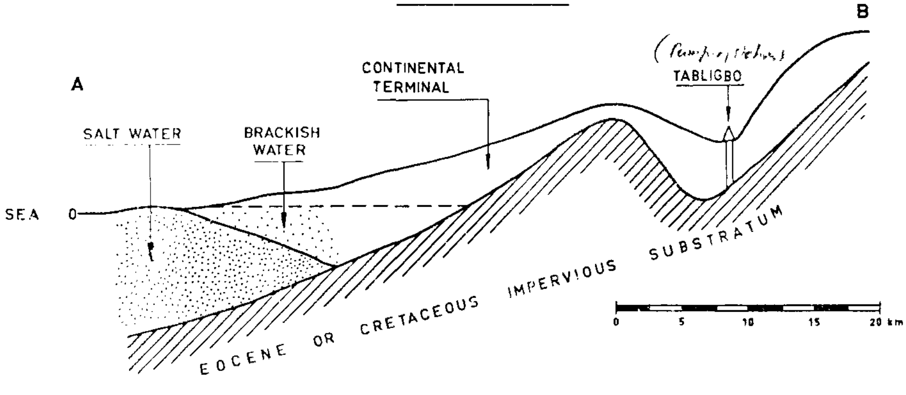
* Case study No. 28 prepared by G. Castany (France).

FIGURE 37



## CROSS SECTION



# TOGO COASTAL PLAINS,
# TOGO

CASE STUDY Nº 28

from coastal streams (less than 600,000 $m^3$/year); direct infiltration of run-off water in the areas of contact between the crystalline and sedimentary rocks in the northern part of the area. Discharge takes place by pumpage of approximately $2 \times 10^6$ $m^3$/year.

The effective porosity of the aquifer is 15 per cent. Transmissivity coefficient is $5-8 \times 10^{-3}$ $m^2$/sec, or 430-700 $m^2$/day. The hydraulic conductivity coefficient ($\underline{K}$) is $2-4 \times 10^{-4}$ m/sec, or 17-35 m/day. Specific capacity of the wells is from 25 to 30 $m^3$/h/m of drawdown.

## Utilization of ground water

Most of the pumpage occurs in the western part of the area, in the capital city of Lome, and is used as a water-supply for the city. Salt-water encroachment is occurring owing to the amount of pumping in the area of Lome.

The objectives of future utilization are to develop an optimum pumping pattern in order to prevent salt-water encroachment, and to meet the growing water needs of this area. It is likely that combined utilization of surface and ground-water resources, including artificial recharge of the aquifer, represents the most sensible approach for securing the water-supply of this area. Alternatives considered would be to drill to deeper formations, such as the Maestrichtian sands and sandstones, and desalination of sea water.

In the eastern part of the basin, the ground-water potential is greater and the needs are smaller. Therefore, if economically feasible, the ground water may be used for irrigation.

### References:

United Nations ground-water resources surveys and technical reports.

# TOKUSHIMA INJECTION PROJECT, JAPAN*

The background information on the Tokushima injection project is as follows:

(a) Region: Tokushima Prefecture, Shikoku Island, Japan;

(b) Geography: coastal plain, near mouth of the Yoshino River;

(c) Climate: humid, temperate zone; average rainfall about 1,000-1,500 mm per year;

(d) Reservoir type: alluvium and diluvium sedimentary rocks;

(e) Methods of investigations: hydrogeological investigations, including pumping tests and chemical analysis of ground water.

## Ground-water reservoirs and utilization

Geological conditions are characterized by alluvial and diluvial sedimentary rocks, composed of loose gravel, sand and clay, over crystalline schist of Palaeozoic age. The thickness of the sediments is unknown, but is over 70 m. The boundary of alluvium and diluvium has not been determined.

The principal aquifers are composed of alluvium and diluvium sand and gravel. The depth of the top of the aquifer is about 30 m; it is about 30 m thick. The estimated minimum volume of water in storage is $7 \times 10^6$ $m^3/km^2$. Hydraulic conductivity coefficient (K) is 1 m/day; specific capacity is about 1,000-18,200 $m^3$/day/metre drawdown.

Water quality is as follows:

| | Unit | Free ground water | Confined ground water |
|---|---|---|---|
| pH | - | 6.5-7.0 | 6.6-7.9 |
| Free $CO_2$ | milligramme per litre | 4-30 | 0.2-2.6 |
| Cl | " | 51-272 | 55-468 |
| $SO_4$ | " | 13.6-728 | 5-88 |
| $NO_3$ (as N) | " | 0.05-4.65 | 0.0-3.32 |
| $NH_3$ (as N) | " | 0-1.7 | 1.0-1.3 |
| $P_2O_5$ | " | 0.5-2.3 | 0.8-3.7 |
| $SiO_2$ | " | 1.1-19.2 | 1.8-20.0 |
| Ca + Mg | " | 0.5-30 | 0.8-13.0 |

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* Case study No. 29 prepared by T. Konishi (Japan).

|  | Unit | Free ground water | Confined ground water |
|---|---|---|---|
| $Fe_2O_3$ | milligramme per litre | Max. 0.28 | Max. 0.19 |
| Mn | " | 0.01-0.66 | 0.01-0.13 |
| Cu | " | 0.04-0.52 | trace-0.42 |
| $KMnO_4$ | " | 4.3-16.2 | 3.8-15.0 |
| Total hardness | French degrees | 1.7-15.2 | 1.9-5.7 |
| Total dissolved solids | milligramme per litre | 131-1,586 | 92-822 |
| Resistivity | ohm-centimetres | 1,100-9,500 | 1,000-11,500 |

Natural recharge occurs through infiltration by precipitation, and from the Imakiri River. The general movement of free ground water is toward the sea, while the movement of artesian ground water is unknown. Discharge is accomplished by pumping wells. The ground-water balance has been affected by over-pumping, with resultant salt-water encroachment.

The area of concern is in the industrial district of the north-eastern part of Shikoku Island, where there are many pumping wells. Salt-water encroachment has occurred, and its prevention is the most important problem of this area.

Cost of water per cubic metre in Tokushima Prefecture is as follows:

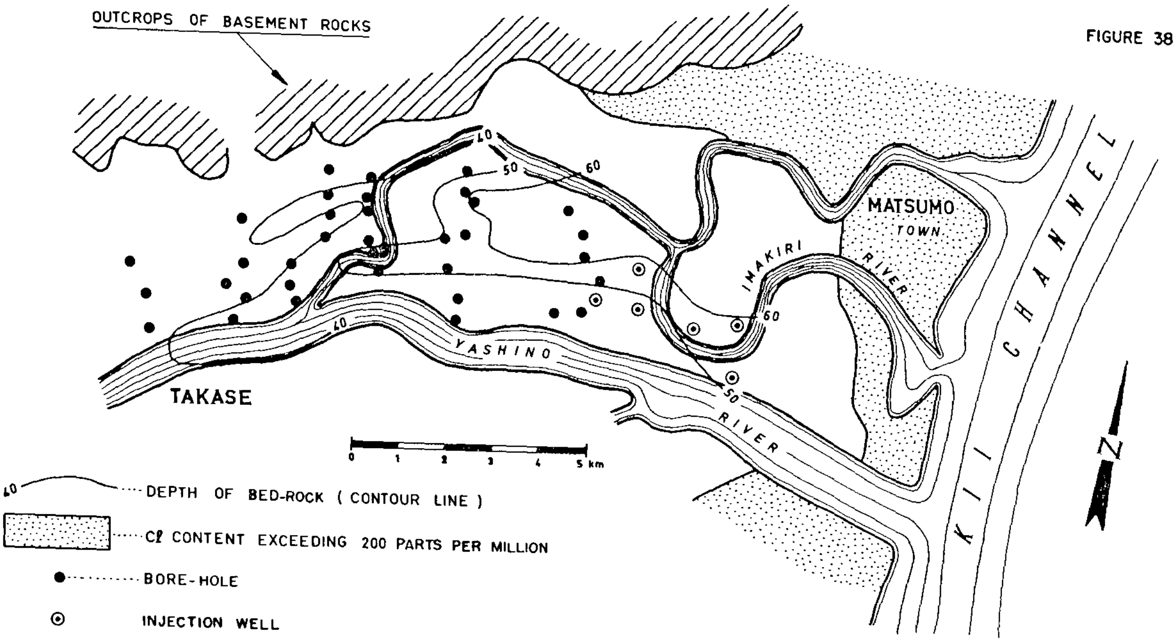
|  | Dollars |
|---|---|
| City water | 0.0582 |
| Surface water | 0.015 |
| Underflow | 0.0055 |
| Pumping ground water | 0.0028 |
| Average | 0.00758 |

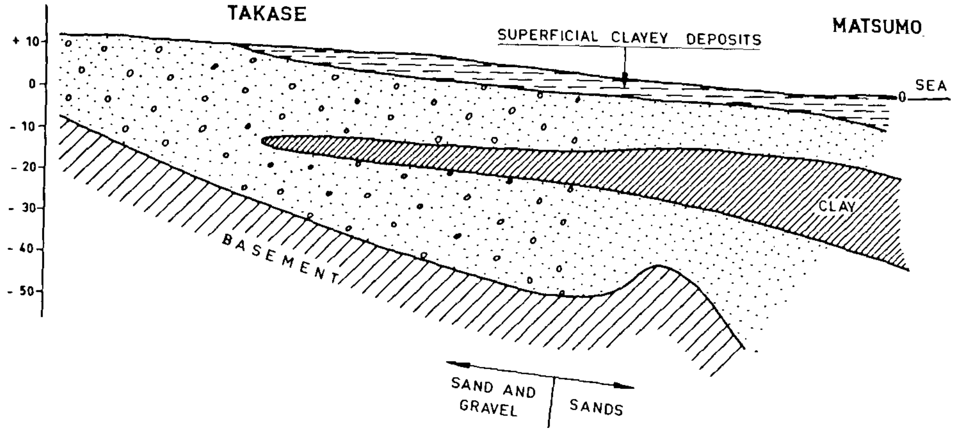
The trend of water costs is that it increases with demand. The service area includes chemical, textile and other industries, which tend to grow within the area, thus requiring an ever-increasing supply of water.

## Artificial recharge

The purpose of this injection project was the prevention of salt-water encroachment. The injection well was 350 mm in diameter and 46 m in depth; a slotted screen was set at 30-46 m. Surface water from the Imakiri River was used for injection. The first test was at a rate of 20-25 $m^3/h$, but it was stopped after several days because of the overflow of water around the outer side of the cement between the well-pipe and the bore-hole. Cement grouting was applied around the pipe down to 7-15 m. The second test was conducted under 0.5-0.9 $kg/cm^2$ pressure, with injection rates of 40-60 $m^3/h$, and the pressure was later increased to 0.9-1.1 $kg/cm^2$. The maximum injection rate was 90 $m^3/h$, and the pressure rose to 1.4 $kg/cm^2$.

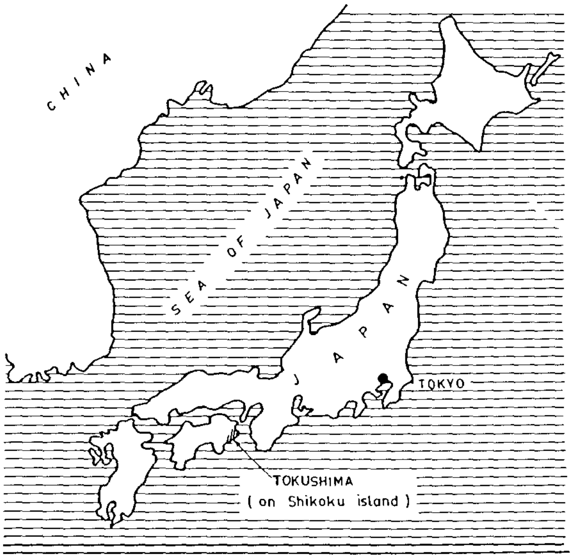
FIGURE 38





# TOKUSHIMA INJECTION PROJECT, JAPAN

CASE STUDY Nº 29



Water overflowed even at small injection rates, and the experiment was discontinued. The reason for the overflow was the injection of untreated water, so the problem is how to treat the surface water.

Pressurized injection was undertaken from 6 December 1960 until the end of March 1961, the total injection amounting to 60,000/$m^3$. In March, water overflowed even at a rate of 30 $m^3/h$ and the experiment was stopped. There was little variation in chloride in the water of No. 5 well, which is at a distance of only 100 m; but variations were clearly observed in the waters of wells Nos. 2, 5 and 6, which are located at more than 140 m from the injection well. This is believed to be caused by the conditions and distribution of the water-bearing formations.

References:

Hydrogeological map of Tokushima Prefecture, Tokushima Ken, 1960.

Takahashi, S. Preliminary report on the artificial ground-water recharge No. 2. Bulletin of the geological survey of Japan, 13:2, 1962.

## UZBEKISTAN RIVERS, UZBEK SOVIET SOCIALIST REPUBLIC*

The background information on the Uzbekistan rivers project is as follows:

(a) Region: eastern part of Uzbekistan;

(b) Geography: Chirchik river valley, near Tashkent;

(c) Climate: Continental type; average air temperature, 11°-13°C; maximum summer temperature (July-August), 42°-45°C; the minimum temperature observed in January is from 25° to 32°C below zero. Average yearly rainfall is 380 mm (mostly in autumn and winter);

(d) Reservoir type: alluvium.

### Ground-water reservoirs

The aquifers are composed of gravel (Late Quaternary and modern formations); gravel with conglomerates (Upper Quaternary); underlain by compact impervious conglomerates (Mid-Quaternary). The gravels are covered with loam and sandy loam 0.8-2 m thick.

The area includes a flood plain 750-1,400 m wide, overlooked by a terrace, from 250-300 to 700-2,000 m wide. The terrace is composed of a gravel deposit 50 m thick (40 m saturated with water) underlain by the Quaternary conglomerates. The reservoir contains about 23 million $m^3$ of water.

The hydraulic conductivity coefficient is 30-35 m/day. The non-saturated zone of the gravel, 10-13 m thick, has a filtration coefficient of about 10-20 m/day (after 40 experimental injection experiments). Hydrogeological conditions in the area are favourable to artificial recharge schemes. Recharge water from rivers and channels is available throughout the year.

### Artificial recharge

Hydrogeological conditions were examined to solve the main problems of water conservation: (a) To limit the water-well area as greatly as possible; (b) To increase the ground-water resources for utilization and improve their chemical composition; (c) To reduce to a minimum the land necessary for construction; (d) To improve technical and economic performances of water wells.

With the objective of selecting the most efficient type of installation, a ground-water replenishment scheme has been carried out on an experimental plot

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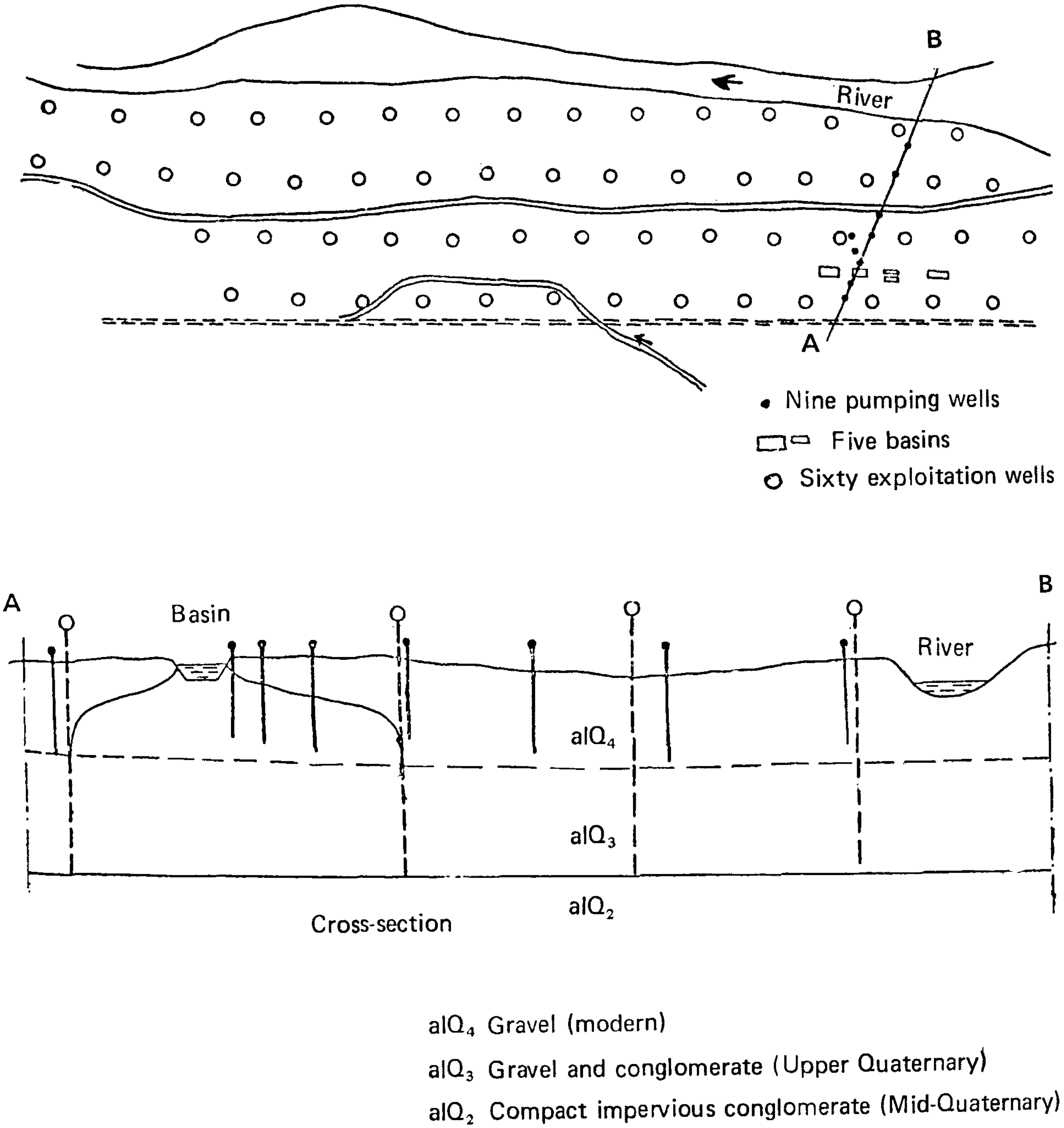
* Case study No. 30 prepared by V. Kunin, S. Mirzayev and A. Akromov (Union of Soviet Socialist Republics).

Figure 39. Uzbekistan rivers project, Uzbek Soviet Socialist Republic



since 1971. The experimental plot includes nine pumping wells, 45-47 m deep, with filters 400 mm in diameter; 23 observation wells, 18-22 m deep; and five recharge basins, 3-3.5 m deep. Both the wells and the reservoirs are provided with instruments and devices for measuring and controlling the level of the water-table and discharge. The wells are situated on both sides of the reservoirs. The distance between a well and a reservoir varies from 84 to 224 m.

The ground-water replenishment experiment was conducted during the period September 1971-March 1972. In an earlier period (September 1970-March 1971) the test wells were pumped periodically, because of a shortage of ground-water reserves, at a discharge rate of 25-45 l/sec. The total discharge of the well in the last three months of 1970 was 1.9 million $m^3$.

Due to the effect of artificial-water recharge from October-December 1971 the wells were pumped for the entire period at a discharge of 35-105 l/sec. This discharge represented a 35-94 per cent increase compared with that of the previous year, and an average increase of 60-70 per cent. The total discharge of the well at that period exceeded 5 million $m^3$, that is 2.65 times as large as the initial discharge.

In addition to the experiments, some other measures were recommended for the entire water-well area to recharge the ground-water reservoirs. In June 1971, after reconstructing and cleaning, the bed, the old channel, 2 km long and 10-12 m wide was again put into operation, conveying the waters into three reservoirs having a total area of 3.5 ha. Depth of the water was 2-3 m. The measures taken permitted use of only one half of all the pumping wells (28-30 wells), and total well discharge increased by 50-70 per cent.

The results of the experiments led to the following conclusions:

(a) Owing to the artificial recharge scheme, the total discharge of the 60 projected wells (there are 40 at present) will increase from 2,525 to 6,000 l/sec;

(b) The areal extent of the valuable and fertile land utilized for construction could be reduced by 2,000 ha;

(c) Due to artificial ground-water recharge, the chemical composition of water and the régime of operating wells will change for the better.

At present, various studies are being carried out on the subject of water-infiltration, self-purification of recharge water, clogging of filtration beds, selection of the most efficient type of installation and availability of recharge waters from various sources. Similar experiments are envisaged for other river-basins of Uzbekistan.

## References:

Mirzayev, S. Sh. and A. A. Akramov. Ibragimov ya khodgizadayev t. (in Russian) Tashkent. Proceedings of the HYDROENGEO Institute, Experience, results and methods for studying ground-water resources in Central Asia. 1972.

# YARKON SPRING, ISRAEL*

The background information on Yarkon spring is as follows:

(a) Region: the Yarkon spring rises at the foot of the mountains north-east of Tel Aviv, at a distance of 15 km from the coast. It is a typical large karst spring;

(b) Geography: the spring is replenished by rainfall on an area of about 1,200 km$^2$ in the Judean mountains. These mountains form a chain running from south to north, with peaks of about 1,000 m elevation above sea level at a distance of about 50 km from the coast. Towards the west the mountains are succeeded by a belt of foot-hills and by the coastal plain. In the east, the mountains are limited sharply and abruptly by the deep Jordan depression;

(c) Climate: semi-arid, Mediterranean, with seasonal winter rainfall of about 600 mm/year;

(d) Reservoir type: folded carbonate rocks;

(e) Methods of investigation: geology is known in detail from outcrops and bore-holes; yield of spring and discharge of bore-holes are precisely gauged. Theoretical investigations conducted with the aid of decay-curve analysis and an electrical analogue model.

## Ground-water reservoirs and utilization

The mountains of Judea are composed of folded Cretaceous limestones and dolomites underlain by shales, with strikes running generally north-north-east to south-south-west. The folds dip steeply towards the west and disappear below chalky and marly impervious rocks of Senonian-Eocene age and, finally, beneath Quaternary sediments of the coastal plain. A north-south line limits the reservoir on the east at the edge of the Jordan Depression.

The Cretaceous rocks composing the aquifer are subdivided into two major parts:

(1) An upper zone, consisting mainly of limestone with dolomitic limestone and a thick band of marl at the base;

(2) A lower zone, predominantly dolomitic, underlain by shales.

The upper zone of the reservoir is 370 m thick; the lower zone is 300 m thick. The outcrop area is about 1,200 km$^2$.

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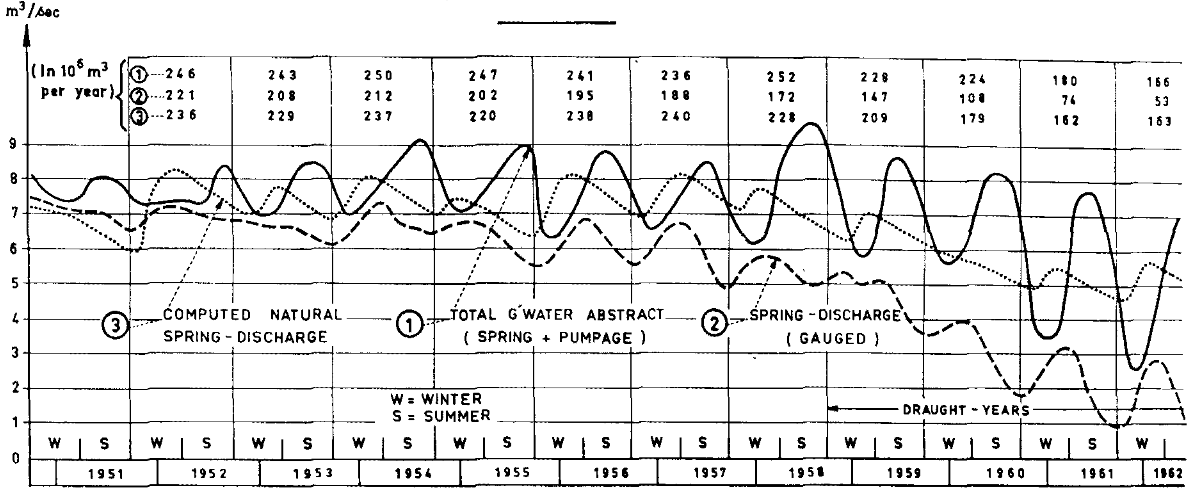
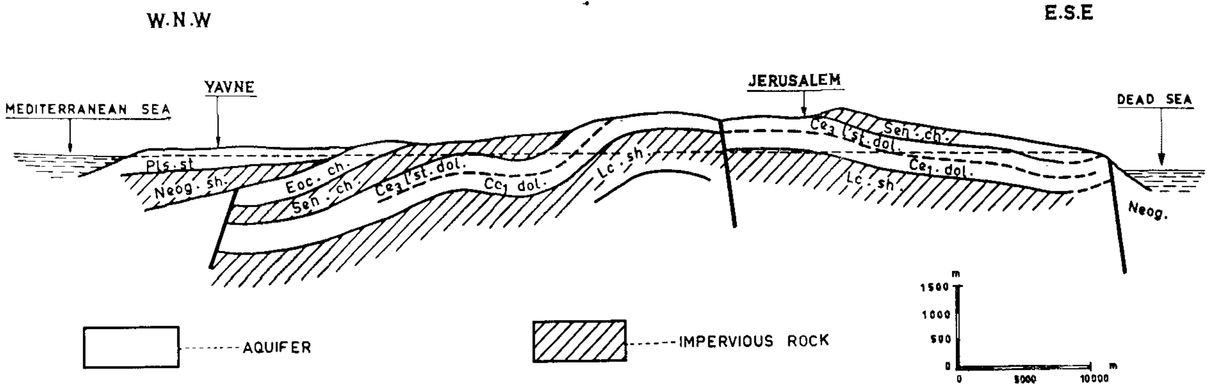
* Case study No. 31 prepared by S. Mandel (Israel).

FIGURE 40

## EXPLOITATION OF THE AQUIFER FEEDING THE YARKON-SPRING



## CROSS-SECTION THROUGH JUDEAN MOUNTAINS



▭ AQUIFER

▨ IMPERVIOUS ROCK

| | |
|---|---|
| Pls. st | PLEISTOCENE<br>SANDSTONE |
| Neog. sh. | NEOGENE<br>SHALES |
| Eoc. ch. | EOCENE CHALKS<br>SEMI - PERVIOUS |
| Sen. ch | SENONIAN<br>CHALKY MARLS |
| $Ce_3$ l'st. dol. | TURONIAN - CENOMANIAN<br>LIMESTONE AND DOLOMITE |
| $Ce_1$. dol. | LOWER CENOMANIAN<br>DOLOMITE |
| Lc. sh. | LOWER CRETACEOUS<br>SHALES |

## YARKON SPRING, ISRAEL

CASE STUDY Nº 31

The natural regulative reserves have been determined with the aid of the hydrograph-analysis method to average 900 x $10^6$ $m^3$ at the end of the rainy season, under natural conditions. Approximately 31 per cent of the rainfall on the replenishment area is discharged by the Yarkon spring under natural conditions.

The Yarkon spring is the only major outlet of the regional ground-water reservoir. A thick layer of impervious shales (probably Neogene) separates the Cretaceous strata from the overlying Pleistocene sandstone in the coastal plain. At the shoreline, the top of the Cretaceous is more than 1,000 m below sea level; and at the prevailing hydraulic heads (maximum + 20 m under natural conditions), no outflow into the sea is possible.

Ground water in the carbonate rocks is separated from the overlying Pleistocene sediments by thick impervious strata. For these reasons, movement and discharge is, under natural conditions, to the Yarkon spring. The spring is situated at the lowest outcrop of the carbonate formations in the region, at about + 16 m elevation and, under natural conditions, the Yarkon spring yields on the average 220 x $10^6$ $m^3$/year. Discharge varies from 5 to 8 $m^3$/sec, according to season.

Exploitation of ground water started in the early 1950s by holes drilled into the confined part of the aquifer all along the foot-hills of the Judean mountains. The number of bore-holes and exploitation of the aquifer increased rapidly. By 1959-1960 it reached 120 x $10^6$ $m^3$, and it has now reached about 220 x $10^6$ $m^3$, equal to the natural discharge of the spring. Until 1957, the aquifer was managed so that the total water supply by pumpage, plus residual spring flow, coincided with the demand curve. In 1957-1958 a series of dry years began and pumpage was increased. The dry years continued until 1963, during which period water supply was kept at a tolerable level by pumpage from bore-holes, but spring discharge declined and in 1963 stopped completely.

The Jordan River pipeline was put into operation in 1963. It would then have been possible to let the spring recover and revert to the mode of operation practised in 1958, i.e., pumpage for the seasonal modification of water-supply. However, it was found more advantageous to keep the water level in the reservoir low and to utilize the storage space thus created for seasonal and long-term ground-water storage from the Jordan River pipeline. These operations are now controlled with the aid of an electric analogue model.

## Artificial recharge

The purpose of the project was to provide seasonal and long-term storage for the water of the Jordan River, in addition to the limited storage capacity of Lake Tiberias. Existing exploitation bore-holes are used for recharge, and they are connected to the National Water Carrier by a system of pipelines. Injection rates are between 500-1,000 $m^3$/h. During 1968-1969, injection was carried out in 12 bore-holes and a total of 31 x $10^6$ $m^3$ of water from the Jordan River was injected.

During the first few years, 1965-1967, difficulties were encountered at high rates of injection because of air entrainment. These difficulties have now been eliminated by more careful supervision and improvements in the installations. Clogging by bacterial slimes considerably reduces injection capacities after about two months of continuous operation. Pumping for 2-4 hours quickly cleans the well-face and restores the capacity of the well. The foul water pumped during this period has to be rejected.

The cost of injecting water is about $0.015. This mainly reflects energy requirements and energy losses, since only small, inexpensive installations had to be installed for this purpose. The scheme is operated in conjunction with the National Water Carrier by Mekoroth Water Co., Ltd., under the water laws of Israel. Future operations are to continue.

References:

Mero, F. Application of groundwater depletion curves etc. International Association of Scientific Hydrology, publication 63, 1:107-117, August 1963.

Schneider, R. Geologic and hydrologic factors related to artificial recharge etc. International Association of Scientific Hydrology, publication 72, pp. 37-45, March 1967.

Harpaz, Y. and J. Schwarz. Operating a limestone aquifer as reservoir, etc. Bulletin of the International Association of Scientific Hydrology, year XIII, 1:78-89, 1967.

Sternau, R. Artificial recharge of water through wells. International Association of Scientific Hydrology, publication 72, pp. 81-100, March 1967.

# YONNE RIVER GROUND-WATER BODY AT APPOIGNY, FRANCE*

The background information of the Yonne River ground-water body at Appoigny is as follows:

(a) Region: basin south-east of Paris;

(b) Geography: broad alluvial valley of the Yonne River, a tributary of the Seine;

(c) Climate: temperate, humid; average annual precipitation, 720 mm; average annual temperature, 10°C; average annual evapo-transpiration, 480 mm;

(d) Type of reservoir: river alluvium;

(e) Methods of investigation: detailed hydrogeological study, including piezometric map and piezometric study (1965-1969); geophysical electrical prospecting, reconnaissance drilling and pumping tests. Geochemical study of surface water and ground water; observation of the evolution of geochemical characteristics; laboratory testing of the influence of decanting time upon the clogging of the filters and the bacteriological evolution of filtered waters.

## Ground-water reservoirs

The geology of the area may be described as a lens of river alluvium overlaying a clayey substratum. The substratum presents an irregular surface with a depression in the area of the exploitation well, owing to erosion by the river. The average thickness of the aquifer is 3.50 m, with a maximum of 5-6 m in the areas of the substratum, which are eroded. Effective porosity is 15 per cent; average horizontal hydraulic conductivity is 900 m/day. The surface of the aquifer is 60,000 $m^2$. The estimated volume of water in storage totals 9,000 $m^3$. This is 18 days of utilization and corresponds to an acceptable lowering of the water-table not exceeding 1 m. Water quality of the Yonne River is shown in table 19.

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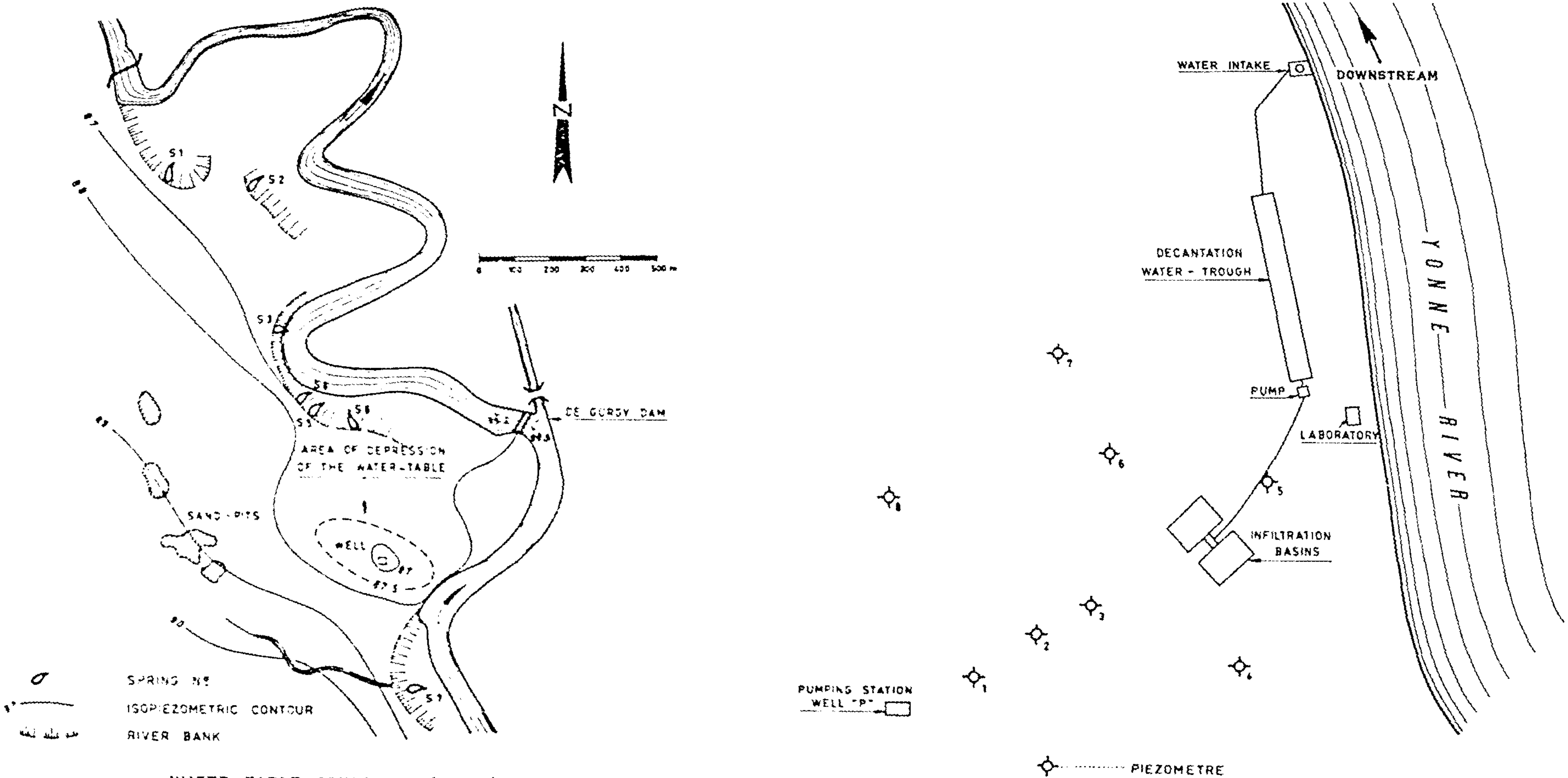
* Case study No. 32 prepared by G. Castany (France).



WATER-TABLE CONTOURS (1957)

YONNE RIVER GROUND-WATER BODY AT APPOIGNY, FRANCE

CASE STUDY Nº 32

Table 19. Water quality of the Yonne River
(sampled 26 March 1968)

| | | | |
|---|---|---|---|
| Temperature | 11.1°C | Total hardness (French units) | 15.1 |
| Clogging potential | 3.3 | Total alkalinity | 13.2 |
| Resistivity at 20°C (ohms per centimetre) | 3,555 | Silica (parts per million $SiO_2$) | 6.5 |
| pH at 20°C | 7.9 | $CO_2$ (parts per million) | 2.6 |
| Dissolved oxygen (parts per million) | 11.7 | | |

| Anions (Parts per million) | | Cations (Parts per million) | |
|---|---|---|---|
| $HCO_3$ | 161.3 | Ca | 57 |
| Cl | 7.5 | Mg | 2 |
| $SO_4$ | 10 | $NH_4$ | trace |
| $NO_2$ | trace | Na | 4.1 |
| $NO_3$ | 6.6 | K | 1.6 |
| | | Fe | 0.05 |

The water is lightly mineralized and low in undissolved solids.

Water quality of ground water is shown in table 20.

Table 20. Water quality of ground water, Yonne River
(sampled 3 September 1968)
(Parts per million)

| | Anions | Cations |
|---|---|---|
| Turbidity (putty) | 1 drop | |
| Resistivity (ohms per centimetre) | 2,500 | |
| $p^H$ | 7.5 | |
| $NH_4$ | - | |
| $NO_2$ | - | |
| $NO_3$ | | 1 |
| Cl | | 12.4 |
| O yielded by $KMnO_4$ | | 0.9 |
| Total hardness (French degrees) | | 14.3 |
| Fe | | - |

Recharge occurs through precipitation on the area; discharge occurs mainly through pumping. Before exploitation began in 1965, the natural ground-water flow was from the area towards the river. In 1965 a pumping well was installed, and after two years of exploitation the piezometric surface became substantially depressed and the direction of the flow was reversed. A dam built for navigation purposes raised the water level in the river and maintained this level at a fixed elevation.

## Artificial recharge

The ground water is used to supply the village of Appoigny (3,000 inhabitants) with a required total of 500 $m^3$ per day. This is a rare example of artificial recharge applied to a village water-supply. The purpose was to employ artificial recharge, using river water, to re-establish the piezometric level of the aquifer and to maintain it during the period of exploitation. The recharge is continuous because the storage capacity of the aquifer is small and permits very little natural regulating effect to take place.

The water is pumped from the river after passing through a screen. The output of the pump is 60 $m^3/h$, and it is operated automatically in order to maintain a certain water level in the basins. The water flows into a settling tank of 500 $m^3$. It then flows into two filtering basins which are used alternately. The bottom of the basins are filled with a layer of sand 0.50 m thick. The distance of the exploitation well from the river is approximately 250 m, and the infiltration basins are located between the well and the river at a distance of 100 m from the well.

The artificial recharge restored the initial piezometric level. The recharge first exceeded, then was equal to 500 $m^3$/day during the dry season, then was lowered to 15 $m^3/h$, owing to the natural replenishment from rainfall. The yield of the installation is 90 per cent.

In future, the settling process will be improved and a smaller tank will be installed, as the optimum settling time is 10 hours. The laboratory experiments with respect to the filtration in the sand of the basins will be continued.

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L'alimentation artificielle experimentale de la nappe alluviale d'Appoigny (Yonne). J. Bruno *et autres*. *Techniques et sciences municipales* (Paris), 3:97-106, 1969.

# ZAGHOUAN LIMESTONES, TUNISIA[*]

The background information on the Zaghouan limestones is as follows:

(a) Region: Tunis region, eastern Tunisia, North Africa;

(b) Geography: mountain massifs south-east of the city;

(c) Climate: Mediterranean; rainfall, 463 mm; rainy season, November to April;

(d) Reservoir type: karstic and fractured limestones and dolomitic limestones.

## Ground-water reservoirs and utilization

Geologically, the area may be described as a limestone massif bounded on the east by the Zaghouan faults. Limestones are Jurassic in age and dip generally to the north-west, where they finally disappear under marls of the lower Cretaceous. The massif is cut by many longitudinal and transverse faults. The best aquifers are karstified dolomitic limestones and zoogenic limestones of the lower Jurassic, and karstified zoogenic limestone of the upper Jurassic. The lower Jurassic karstified zone is 1,000 m thick; the upper Jurassic karstified zone is 400-500 m thick. These limestones are separated by a zone of lower and middle Jurassic of limestone and marl, 50 m thick.

The surface water and ground-water basins have the same boundaries and area of about 20 $km^2$.

The surface- and ground-water basins have the same boundaries and area, about 20 $km^2$. The average storage coefficient is equal to specific yield, which is 5-7 per cent (aquifers are unconfined). The specific yield decreases with increasing depth and is high in the upper 10 m. Fissures are closed as depth increases and specific yield drops between 0.5 and 1 per cent. Total water stored annually is $3.2 \times 10^6 m^3$. Ground-water movement is towards the north-west. Waters are of calcium carbonate type. Total dissolved solids (TDS) do not exceed 380 parts per million (ppm).

Recharge is by infiltration of rainfall throughout the entire surface area and averages 166 mm/yr. Recharge occurs readily because of karstification of limestone at the surface. In addition, recharge has been increased, beginning in the days of ancient Carthage, by the construction of small dry-stone dams in mountain ravines.

Natural discharge is through two principal springs, Ain Ayed and source de la Nymphée. The latter occurs on a transverse fault and has been utilized since the Roman period for the water-supply of Carthage. At present the springs do not flow, except during very rainy years. Artificial discharge is through two drainage galleries which have been driven 15-30 m below the level of springs.

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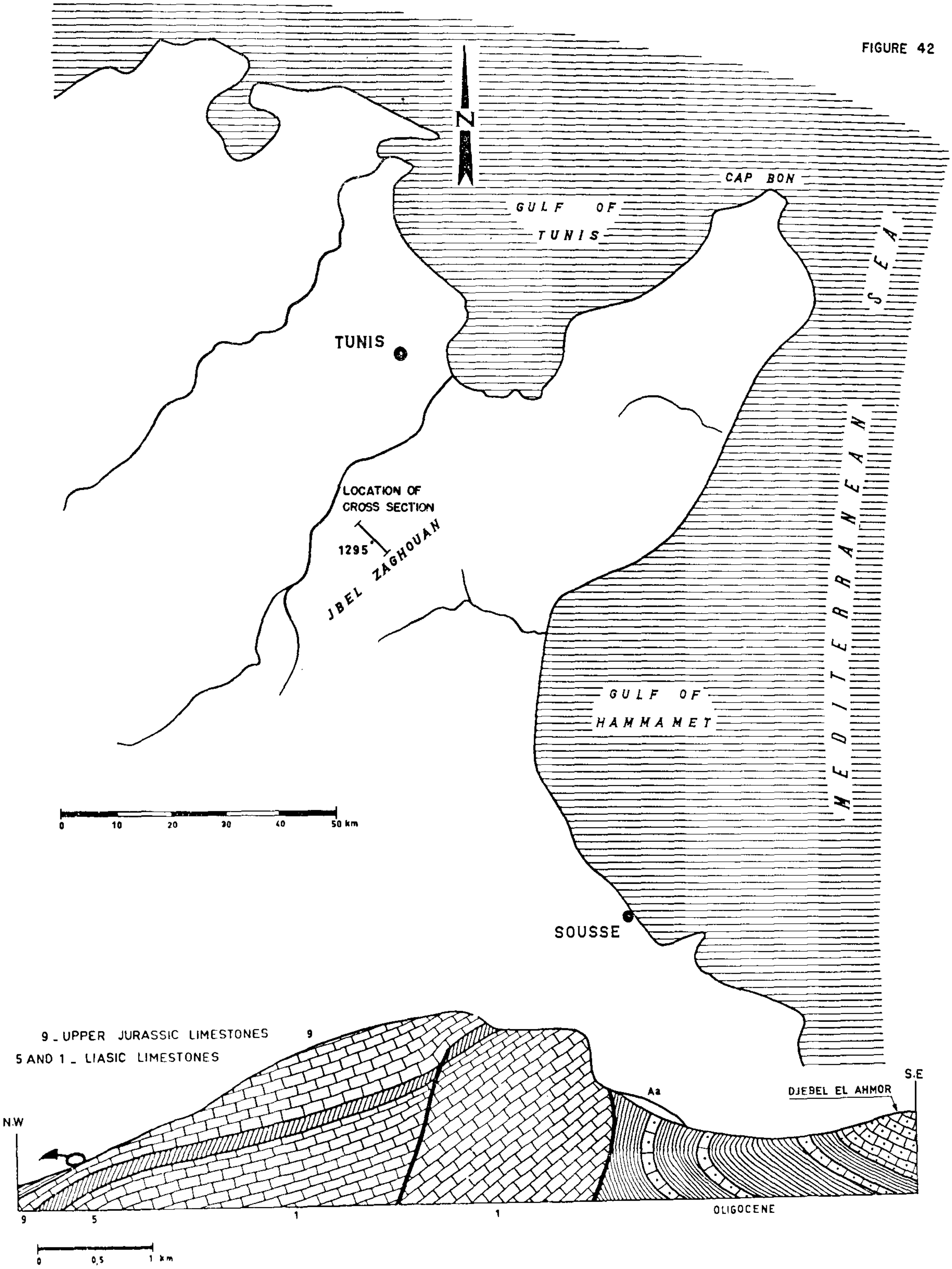
[*] Case study No. 33 prepared by G. Castany (France).

FIGURE 42



ZAGHOUAN LIMESTONES,
TUNISIA

CASE STUDY Nº 33

The over-all water balance is summarized as follows:

Rainfall = Evapo-transpiration + infiltration + run-off
463 mm = 297 mm + 166 mm + negligible

The ground-water reservoir is managed by controlling the discharge from the galleries. The discharge is gradually shut off during the rainy season, thus filling the ground-water reservoir. The rise in the level of the reservoir is about 30 m. The reserves are then tapped during the period from June to November. The lowering of ground-water levels in the reservoirs contributes to the increase in infiltration. Annual outflow from the galleries is approximately 3 x $10^6$ $m^3$.

References:

Castany, G. Exploitation des eaux souterraines et bilan hydrique dans les calcaires de Tunisie. Colloque de Dubrovnik, pp. 518-525. 1965.

________. Structures hydrogéologiques et régularisation des resources en eaux. Symposium de Haifa, pp. 413-425. 1966.

## ZANDVOORT, THE NETHERLANDS*

The background information on Zandvoort is as follows:

(a) Region: Amsterdam area; dune area between Zandvoort and Noordwijk;

(b) Geography: coastal plains and sand dunes of the North Sea coast;

(c) Climate: humid; yearly rainfall approximately 800 mm;

(d) Reservoir type: clastic sedimentary deposits and sand dunes.

### Ground-water reservoirs and utilization

The geological formations in this area are Quaternary clastic sediments about 200 m thick. Holocene sands are at 5-13 m; a clay horizon is at 13-20 m; coarse Pleistocene sands are at 20-160 m; and thin-bedded marine sands and silts are found at 160 m. This latter material is saturated with salt water.

The principal aquifer can be divided into two units. One consists of unconfined sand layers with interbedded lenses of clay; the second, deeper unit, consists of coarse sand and is confined. The whole aquifer system can be described as a large fresh-water lens floating on salt water.

The aquifer is 120 m thick with an exploited surface area of 3,650 ha.

With respect to water quality, natural ground water has 40 parts per million (ppm) chloride; injection water from the Rhine River has 60-250 ppm chloride. The infiltration rate is maintained within appropriate limits in order to keep the chloride content of exploited waters below the 200 ppm limit.

Natural recharge occurs from direct infiltration of rainwater at a rate of 425 mm/year or 12 x $10^6 m^3$/year. Artificial recharge of the waters of the Rhine River into the aquifer amounts to approximately 70 x $10^6 m^3$/year. Natural discharge occurs as outflow to the sea.

The shallow aquifer has a permeability coefficient ($k$) of 120 m/day. The specific yield is approximately 30 per cent. The estimated volume of water in storage in the exploited area is 1,300 x $10^6 m^3$.

The ground water is exploited by tube-wells and is used for the municipal water-supply of Amsterdam. Prior to the artificial recharge scheme, sea-water intrusion was a problem. Future utilization will presumably continue at present levels.

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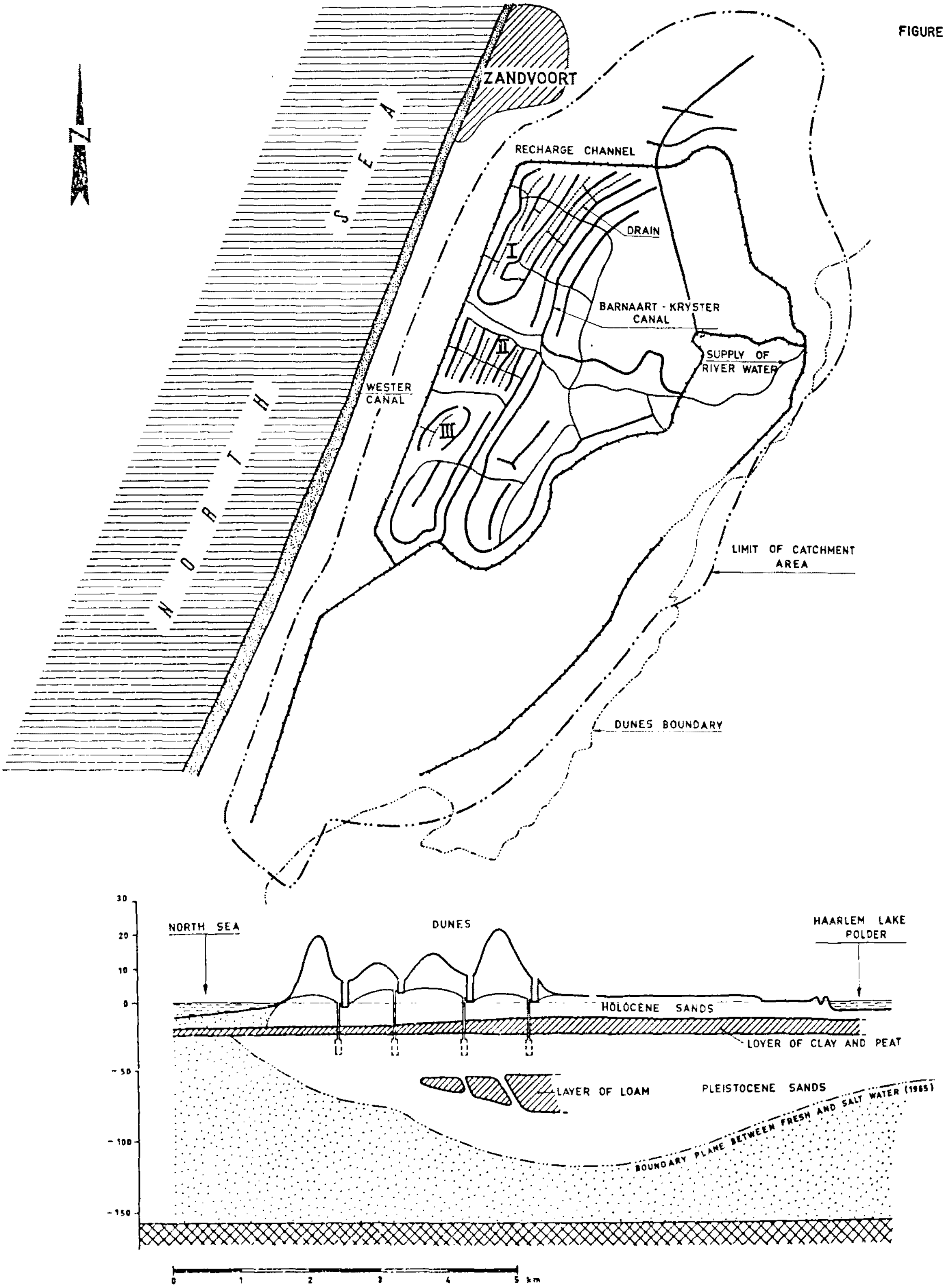
* Case study No. 34 prepared by G. Castany (France).

FIGURE 43



## ZANDVOORT,
## NETHERLANDS

CASE STUDY Nº 34

## Artificial recharge

The purpose of the project was to restore piezometric levels to a point where the intrusion of sea water would be halted, and ultimately reversed. Beginning in 1957, an artificial recharge scheme was developed using prefiltered waters pumped from the Rhine River at Jutfass, south of Utrecht, 53 km distant. The scheme permits the infiltration of some 70 million $m^3$/year into an open-ditch network of about 430 ha, operating approximately two months per year. The infiltration canal is 37 km long and has been dug in the shallow sand formation overlying the clay. The deeper unit of the aquifer is exploited by bore-holes equipped with screens, up to a length of 25-30 m. Storage of water in the dune sands is considerably less expensive than the use of surface storage in this flat, low area, where the construction of a retaining dam would present almost insurmountable difficulties.

The artificial recharge scheme has achieved its objective of reversing sea-water intrusion, and has also made available additional water from the Rhine that would otherwise be lost into the sea. The scheme will be continued.

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