DEVELOPMENT AND MANAGEMENT OF GROUNDWATER RESOURCES:

GENERAL PRINCIPLES AND THE CASE OF ISRAEL[1]

by

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ABSTRACT

This paper deals with conjunctive use of surface and ground waters, and then deals with Israel's water resources system as a demonstration. The introduction discusses the characteristics of the two types of sources, emphasizing the differences between them which should be exploited when a water resource system has the two types of sources.

The water resources of Israel are described, with emphasis on the two main groundwater sources: the Coastal Aquifer and the Mountain Aquifer. The third main source is Lake Kinneret, the Sea of Galilee. The National Water Carrier is the main backbone of an integrated national system connecting these and additional sources. It starts in the Kinneret and goes all the way to the South of the country. It is the linking element which allows conjunctive development and operation of surface and groundwater sources.

Reclaimed sewage is discussed as a source for agricultural water, supplied to replace potable waters which are needed in increasing quantities as the population increases and the standard of living rises. Desalination can be an additional source, where conditions warrant it.

The role of water in peace agreements in the Middle East is mentioned. Finally, some research needs in groundwater hydrology are listed.

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Introduction: Surface and Ground Waters

The purpose of this paper is to promote the case for conjunctive use of surface and groundwater, and to demonstrate how this is done in Israel. The concept and practice of "conjunctive use" exists for a long time. Still, we find in many places that it is not fully appreciated nor exercised. The paper will present general principles, and then elaborate them in the context of the Israeli water system. This will provide the opportunity to describe in some detail the Israeli water situation, the problems and issues facing it today, and the approaches taken to address them.

To begin, we discuss some characteristics of surface and ground waters, stressing differences between them which are important when one is planning the development and operation of a water resources system which contains both surface and ground waters. Groundwater is found in abundance in many parts of me world. Its importance increases in arid and semi-arid regions, where surface water is less abundant and its yield highly variable. The following characteristics are important when one considers conjunctive development and use.

Geographic Distribution. Surface waters appear in well defined bodies — rivers, lakes and reservoirs - which cover a relatively small part of the total area. This means that facilities must be constructed to convey the water from the sources all the way to the consumers. Groundwater, on the other hand, appears in aquifers which extend over a large area. This provides considerable flexibility in deciding where to extract the water.

Storage. Aquifers usually have a much larger storage than surface reservoirs.

Conveyance. Water flows in the aquifer under natural and induced gradients. It is therefore possible to use the aquifer as a conveyor of water from one location to another, thereby reducing the cost of constructing canals or pipes. The use of aquifer conveyance does not come free, however, since energy is required to create the desired gradients.

Losses. The losses from an aquifer are different from those we find in surface systems. There is no appreciable evaporation, but on the other hand there are flows which leave the aquifer and become unusable, such as flows to the sea.

Staged Development. Surface systems are constructed in large increments, whereas an aquifer can be developed in a staged manner, a few wells at a time, located where needed. This results in a more flexible and feasible capital investment program.

Response to Hydrological Variability. Aquifers respond more slowly to variations in hydrological inputs. When surface systems suffer from the results of a drought, the groundwater reservoir may still be full, providing a reserve. The different response of the two systems adds flexibility and reliability.

Vulnerability. Both surface and ground waters are subject to pollution from various sources. However, it is more difficult to protect the aquifer, since it is distributed over a wide area, and frequently there is considerable human activity on its surface which cannot be moved away. Aquifers are also vulnerable to encroachment of low quality waters from adjacent water bodies or flows through mineral formations.

Remediation. It is difficult to clean up a surface reservoir which has been polluted. It is much more difficult — if possible at all — to remediate a polluted aquifer.

Mixing. The aquifer provides an opportunity to mix waters of different qualities, then pump out water of some desired intermediate quality. Surface reservoirs may be heterogeneous in quality in the volume (for example sediment load, or temperature) but it is more difficult to extract from them selectively at intermediate qualities. Surface reservoirs can, however, serve as total mixers.

Self Purification. Flow through porous media is a form of treatment. For example, reclaimed sewage may be injected into the aquifer as a final stage in the treatment process. Similarly, organic load can be eliminated by infiltration into the aquifer.

These characteristics, and particularly the differences between surface and ground waters, make it very attractive to use the two conjunctively. This is true for the development as well as the operation of the two types of sources.

With this as background, let us look at Israel's water system, and emphasize the aspect of conjunctive use.

Israel's Water Resources and Their Management

Table 1 summarizes the supply and demand balance of Israel's water system, in recent years, and that recommended for the year 2000 in the national water plan (Tahal, 1988).

The data in Table 1 show that over 50 % of the water in the National Water Carrier comes from groundwater, primarily from the Coastal and the Yarqon-Taninim Aquifers. Groundwater accounts for over 40 % of all fresh water supplied, and a good part of the brackish water also comes from groundwater. It is mostly supplied directly to agriculture, and some of it to desalination.

Geography and Climate

There are three longitudinal geographic units into which Israel is divided (Figure 1): the Coastal Plain, which rises to about 200 m, the Mountain Range, which reaches 1000 M, then the Jordan Valley, which starts in the north well above sea level, then drops to 400 M below sea level at the Dead Sea, and rises back to sea level at Eilat on the Red Sea.

Table 1: ISRAEL'S NATIONAL WATER BALANCE (MCM/YEAR)

	Current From	Current To	Year 2000
Kinneret to the National Carrier	180	460	450
Local Supply from the Kinneret	150	200	200
Mountain Aquifer	330	410	300
Coastal Aquifer (net)	310	360	250
Western Galilee Aquifer	90	110	120
Reduction for Reliability			40
Total National Carrier	1020	1410	1280
Other Fresh Waters	280	300	360
Dan Region Reclaimed Sewage	80	180	330
Brackish and Floods	170	210	210
Total Supply	1650	1980	2180
Losses	60	70	60
Judea and Samaria	110	110	140
Total Allocation	1480	1800	1980
Domestic and Industrial	540	600	880
Agricultural (the residual)	940	1200	1100

Annual rainfall reaches above 1000 MM in the North, about 500-700 MM in the center, 100 MM in the Jordan Valley, and down to practically zero in the far South.

Main Water Resources

The Kinneret (Sea of Galilee), Coastal Aquifer, and Mountain Aquifer are the main water sources of Israel, as can be seen from Table 1.

Over the last 20 years the ground water resources have been depleted at a rate greater than the average annual replenishment, primarily in the Coastal Aquifer. As a consequence, quantity and quality problems arose.

1986/87 to 1989/90 were drought years, which brought this situation to crisis proportions. Agricultural allocations were curtailed severely. 1991/92 was unusually wet, and 1992/93 is also well above average. This has alleviated the immediate situation, but one must bear in mind that the long range problem of water shortage remains.

Israel uses practically its entire natural water resources, and there is almost no reserve for dry years. This raises the need of to produce more water from non-conventional sources, to further improve efficiency of use in all sectors, and to have an allocation procedure for irrigation water which is flexible and responsive to hydrological variations.

Note the way in which Table 1 is presented. After the natural sources are listed, reclaimed sewage is added. Actually, there are more reclamation projects beside the Dan Region, and the eventual potential of reclaimed sewage is probably about 400 MCM/Y, about 20 % of the total supply. From the total amount for allocation we subtract the domestic and industrial portion, and the residual is for agriculture. This is a reflection of the policy which states that domestic and industrial come first. Agriculture receives the residual, which should be allowed to vary from one year to the next in response to the hydrological condition. It is obviously necessary to adjust the way agriculture is structured and managed in light of this policy.

This latter aspect, probably the most essential policy issue in Israel's water sector, is beyond the scope of this paper.

The Coastal Aquifer

The Coastal Aquifer is a strip 10 to 30 KM wide along 120 KM of the Mediterranean Coast with a total surface area of 1800 KM^2. It is a Pleistocene aquifer, with a thickness ranging from zero in the East to some 200 M + at the coast line. The sand layers are interspersed by clay lenses, which divide the aquifer into a number of sub-aquifers, some leaky, some separated completely from their neighbors. The top aquifer is phreatic.

Precipitation in this area averages 500 MM/Y. Total recharge from rainfall and return flows is about 370 MCM/Y. The long range water extraction potential of the Coastal Aquifer is 240 MCM/Y, while in the near future it can still supply somewhat over 300 MCM/Y. The difference is due to the expected reduction in irrigation over this area, and also to the need to allow more water to flow to the sea for flushing the aquifer.

Flow in this aquifer is essentially towards the coast line. In places a local flow pattern which deviates from this overall direction has been created by local pumping or recharge. The result is a series of depressions and some mounds. Still, the predominant direction of flow is perpendicular to the coast line.

Sea water intrudes some 500 to 1500 M into the aquifer, at certain places as far as 2200 M, and advances at rates ranging from 20 to 70 M/YEAR, as a result of high rates of pumping in recent decades. The sea water intrudes into several of the layers, in separate wedges.

The water used for irrigation in this region and for recharge has higher salinity than that of the native water in the aquifer. Also, reclaimed sewage has considerable salinity, so that when it is used for irrigation salt accumulates. Furthermore, as extraction increases, sea water intrudes, adding to the problem. We therefore witness an increase in salinity of the waters in the Coastal Aquifer. To stop this trend it is necessary to allow more water to flow to the sea, keeping the balance with sea water and taking with it some of the salt brought to the area by the imported water and reclaimed sewage.

Pumping from the aquifer began in the early years of this century, and reached some 250 MCM/Y in 1948. In 1948-1955 it rose to 400 MCM/Y, with a maximum of 493 MCM in 1958. The pumping was reduced with the operation of the National Water Carrier in 1964, but it then rose again to about 400 MCM/Y. This resulted in a decline of water levels: as low as 4 m below sea level at some locations, and 2-3 M below the desired level at distances of 1500 M from the coastline.

All water extractions are strictly controlled in Israel, and the Water Commissioner has the power to modify the license for pumping from one year to the next, in response to variations in the hydrology.

Water quality in the Coastal Aquifer is a major concern. Chlorides concentration in about half the waters is below 170 MG/L, while in places it reaches 250 to 400 MG/L and even more. Nitrate concentrations are below 45 MG/L (the standard) in about half the waters only, while in rest they are between 45 and 90 MG/L, and sometimes even more. The rate of increase in Chloride concentration is 1-3 MG/L/Y, and that of Nitrates 0.5 to 1.3 MG/L/Y. These rates are of great concern, since more wells will have to be put out of service, or their waters treated (by desalination?) before they can be used.

Most importantly, the Coastal Aquifer is Israel's only long term reservoir. Each meter of change in its water surface amounts to about 450 MCM (effective storativity 0.25). The Kinneret is an annual reservoir, and the Mountain Aquifer operates over a one to two year period. This leaves the Coastal Aquifer as the only means for balancing supplies over several years, bridging drought periods.

The Mountain Aquifer

This is a limestone aquifer, much more porous and conducting than the Coastal Aquifer. This aquifer (Figure 3) is fed from rain falling on its feeding area, which then flows West and East. In Judea and Samaria the depth to water is quite large, up to 600 M and more, only small parts of the area are suitable for agriculture, and the population is not dense. Therefore the quantities of water extracted from the aquifer in the mountain area are relatively small. As the water flows West and East, the aquifer becomes confined, by an impervious layer which is the base in the West for the Coastal Aquifer (Figure 2).

Under natural historical conditions, a major part of the waters of the Mountain Aquifer flowed out through natural outlets, primarily the Yarqon and Taninim springs (hence its other name: the Yarqon-Taninim Aquifer).

Along the foot of the mountain range in the West the depth to water is smaller than in the higher areas, and so production wells are located primarily in this region.

Water quality in the Mountain Aquifer is considerably better than that in the Coastal Aquifer, and it therefore serves primarily for supply of domestic water. This aquifer is vulnerable to pollution from increased surface activity due to housing, industry, sewage disposal, solid waste management, and any other human activity which has a pollution potential. Great care must therefore be exercised in managing the activities on the surface of the recharge areas.

Lake Kinneret — The Sea of Galilee

The lake lies in the Jordan Valley, and has a surface area of 167 KM^2 It is fed from the Jordan and the surrounding areas. Its natural inflow was about 900 MCM/Y, part of which is now used before it reaches the lake. The watershed is heavily used, by agriculture, some industry, and tourism. Flows, lake levels and water quality are monitored, and a special agency is charged with managing the lake and the watershed.

The Kinneret supplies over one third of the water to the National Water Carrier. The quality is usually good, although at times the organic load is a problem, due primarily to the bloom of an algae specific to this lake. As water quality standards are raised, the water from the Kinneret -- averaging 400 MCM/Y — will have to be treated. This will constitute a very large cost, and studies are under way to determine the best strategy and technologies for treatment. Of particular importance is the question whether all the water, a substantial part of which goes to irrigation, will be treated at one central location, or whether only the water entering the municipalities will be treated there.

Studies of water quality in the watershed and the lake continue. Models for determining its operation are being developed and used: monthly operation over the entire season in normal times, and short range operation during times of high levels and inflows.

An Integrated National Water System

The National Water Carrier starts at Lake Kinneret, lifts the water from -210 M to + 145 M, from where it flows by further pumping and gravity all the way to the South of Israel. The top of the system is a 34 KM canal, then the water is treated at the Eshkol Reservoir, and put into a 108" pipeline. At Tel Aviv the line splits into two parallel pipes, which were the first part of the system to be constructed. They delivered at that time the waters from the Yarqon springs to the Negev, the Southern arid region. In the 1960s the Northern part of the Carrier was completed, and the system has been operating very successfully since then.

It integrates along the way over 25 regional water systems, which have surface and ground water sources. These systems exchange water with the National Carrier — they take water from it and provide water to it, depending on the location and the time of year. Thus the National Carrier integrates surface and ground waters, and enables conjunctive use.

When it was designed and completed, the National Carrier was also to be used for mixing waters from the Kinneret and the aquifers, to achieve the desired water salinity. The Kinneret had at that time a salinity of about 380 MG/L, too high for direct use. The native waters in the aquifers were much less saline. It was therefore planned to take Kinneret water via the National Carrier, inject it into the ground at certain locations, and pump water out at other locations, so that the mixing provided exactly the desired salinity.

This was indeed the case from 1964 to 1968. 1968/69 was a very wet year. In the same year the "Saline Conveyor" was also completed: a canal which takes some 20 MCM/Y of water and 60,000 tons of salt from saline springs at the North-West corner of the Lake, and diverts it around the Lake into the Jordan below the outlet. The Lake was flushed by the large floods of that year, and the saline springs were diverted at the same time. The result was a drop in salinity to about 230 MG/L, where it has remained since. The result is that the mixing of Kinneret and ground waters is much less important than it was considered during the planning and design phases.

Still, the salinity of the Kinneret is a major concern. Its waters bring a large amount of salt to the irrigated areas. Because irrigation is so efficient, and there is little return flow, flushing of the ground occurs mostly by rainfall, and this is not sufficient to prevent an increase in salinity of the Coastal Aquifer.

Work therefore continues on ways to reduce the salinity of Lake Kinneret, without losing too much water. Also, the organic and pollution loads on the Lake are a major source of concern, and therefore activities in the watershed and on the Lake are carefully monitored and controlled.

Sewage Treatment and Reuse

As the domestic consumption increases, more potable water has to be directed to the cities. This follows the increase in population and the rise in living standards. The consequence is a reduction in the quantities available for agriculture, which, as we saw, are the residual from the natural potential after the domestic and industrial consumption is fulfilled. To compensate for this reduction, reclaimed sewage is provided for irrigation.

As the domestic consumption increases, there is more sewage available for reclamation. The policy in Israel is that sewage must be treated to a level of quality which enables disposal without damage to health or the environment, and that the reclaimed sewage must be used to replace the potable water taken from irrigation to meet the increasing needs of the population. This may seem sufficient conditions for guiding national and local plans for sewage treatment and reuse.

Still, there remains an open discussion whether sewage is primarily a nuisance which must be removed, and only then a resource, or whether it is an integral part of the overall water resource, which happens to be polluted. The answer to this question is quite important: it determines the responsibility of the producer of the sewage. In the first case, the producer has full responsibility for bringing the effluent to a level of quality where it does not pose a threat to health, to the environment, and to the water sources. If the latter policy is adopted, and sewage is water in another form, then the municipalities may try to avoid their responsibility for proper treatment. The tendency is towards the former view: municipal and industrial producers of sewage have the responsibility to bring the effluent to a level of quality where it can be discharged into the environment with no appreciable harm, and they must bear the full cost. Reuse is the preferred way to dispose of the treated effluents. If a consumer is found who is interested in using the effluents, then the planning, design, operation, and economics of the project are adjusted to take advantage of this.

The Dan Region Sewage Project collects the sewage from the central metropolitan area of Israel, around Tel Aviv, brings it to a plant in the dunes, treats it by a combination of biological and mechanical processes, then infiltrates the water into the Coastal Aquifer. The water is pumped from a ring of wells around the infiltration ponds, after a residence time of years. The water pumped meets all present potable water quality standards. Still, it is conveyed in a separate system (called "The Third Line", in parallel with the two original lines of the National Water System) to agricultural consumers in the South. This water will cause no harm due to accidental drinking, but it was decided to keep it separate — as "tagged water" — since anyhow there is a large portion of the water that goes to irrigation, and one might as well use these waters separately, not mix them with the potable waters in the other systems.

Two other major sewage treatment and reuse systems exist. One takes about 20 MCM/Y from

Haifa some 20 KM to the Izrael Valley, where it goes through a large reservoir (whether this reservoir aids in the final stages of the treatment process is still under investigation), and is then distributed regionally through a system of smaller reservoirs to irrigation systems. The other system takes the sewage of Jerusalem which flows West, and uses it for irrigation in the foothills and Coastal Plain.

Desalination

Desalination of sea water and of brackish groundwater is accomplished by heat based and membrane processes. Selection of the most suitable method depends on the quality of source water, the capacity of the plant, disposal opportunities for concentrated brine, and consumers for whom the water is produced. Membrane processes are economic for desalination of brackish groundwaters, but they are already becoming competitive also for sea water.

Even advanced agriculture, possibly with the exception of very high value closely controlled production systems, cannot pay the cost of desalinated water. The cost of desalination is not expected to drop in the foreseeable future to a point where this will change. On the other hand, there are many places where domestic consumers can bear the cost of desalinated water, and where desalination is the most attractive alternative for fulfilling the demands.

Thus in Israel, desalination remains an option for local systems, where the following conditions are satisfied: there is a consumer able and willing to pay the price, there is a source of brackish water which has no better alternative use (for example irrigation of special crops), and disposal of the brine is adequately solved, desalination is sown to be the best and most economic solution. Desalination of sea water only requires a consumer willing to pay the price.

Desalination at the national level can be justified only if agriculture can afford it, or where it is part of a Middle East regional peace project.

Water and Peace in the Middle East

A discussion of this complex issue is beyond the scope of this presentation, but it is quite clear that water is a very important aspect of the peace negotiations.

There are many points of contact between the water resources and systems of Israel, its neighbors, and the Palestinians. On the one hand, these threaten to be points of disagreement and conflict in the peace negotiations. On the other hand, water provides opportunities for cooperation, where both sides can benefit from managing their water resources and water systems in a coordinated or cooperative manner. Joint management of the existing sources already can benefit all sides concerned. Joint production of new water can further alleviate real or potential conflicts.

Research and Development Needs in Groundwater Hydrology

Research and development aimed at providing effective solutions to some practical problems is required in a number of areas. Among them are the following.

Remediation. Remediation of polluted groundwaters is probably the most urgent research and development topic. Very large sums of money are devoted by many countries to remediate aquifers which have been polluted by hydrocarbons and by industrial wastes. The methods commonly used include: containment by gradient control; pump-and-treat; in situ treatment by flow, chemical, and biological means; combinations of these. There is considerable doubt whether the existing methods and techniques are effective in returning the aquifer itself to usable quality. Evidence is mounting that many of the projects are eventually found to have failed, in the sense that residual pollution in the aquifer requires treatment of the water extracted long after the main plume of pollution has been removed.

Prevention of Pollution. It is better to prevent pollution than to treat the aquifer or the pumped water. Cost effective techniques have to be devised, to prevent pollution from all types of activities over the aquifer, including: sewerage systems; landfills; storage and conveyance of fuels; storage of hazardous materials.

Exploration Techniques. With time, ground water has to be extracted from deeper and more problematic aquifers. Geophysical and other exploration techniques, some quite standard in oil exploration, should be used.

Extraction Techniques. The conventional method is a drilled well, a motor driving the pump from above, a long shaft, and an impeller down below. As depths exceed 500-700 M one should consider the possibility of different approaches. For example, a vertical shaft of wide diameter (say, 5 M) extending to below the water table, and tunnels extending from it, with the pumps located at the bottom of the shaft, pushing the water up to the surface.

There are still gaps in our basic understanding of several components of the hydrological cycle, and phenomena in porous media. Some of the important areas which call further work include the following.

Multicomponent Flows. The basic physical and chemical processes of multicomponent flow in porous media deserve further development. Solutions for practical field problems must be based on a solid understanding of these phenomena and on analytical and numerical models developed to describe the phenomena and describe what happens in a given field situation as a result of actions taken.

Scale in Groundwater Hydrology. Scale is receiving considerable attention in all fields of hydrology. The integration of surface hydrology with Global Circulation Models (GCMs) is a hot topic. Scale in groundwater hydrology is equally important. Several approaches contribute in this respect. First, there is the stochastic approach to groundwater hydrology, where the fields of porosity, conductivity, dispersivity, forcing functions, and other properties are considered random fields. As a consequence, the dependent variables, for example the head or concentration of a pollutant, are also a random field, whose description is sought. Often, moments of the resultant variables is what is computed. Fractals and chaos are two additional approaches.

Vertical Integration in Hydrology. Above ground, the integration goes from the atmosphere, through the vegetation canopy, to the surface, and possibly just below it. The unsaturated zone is then considered to be the lower boundary of the region of interest. Consideration should be given to a fuller integration, all the way to include the saturated zone. Disaggregation into separate components is a convenient and often necessary means, but with the advance in modelling capabilities, vertical integration should become more feasible, and its benefits may justify the extra effort.

Field Scale Studies. For many years there has been a strong move to numerical modelling, and there is not enough field work. More recently there are a more field studies, and this is to be commended and encouraged. It has been found time and again that the coefficients in our models are almost always not adequate for field conditions. The scale of field heterogeneities cannot be captured by simple laboratory tests or even point tests in the field.

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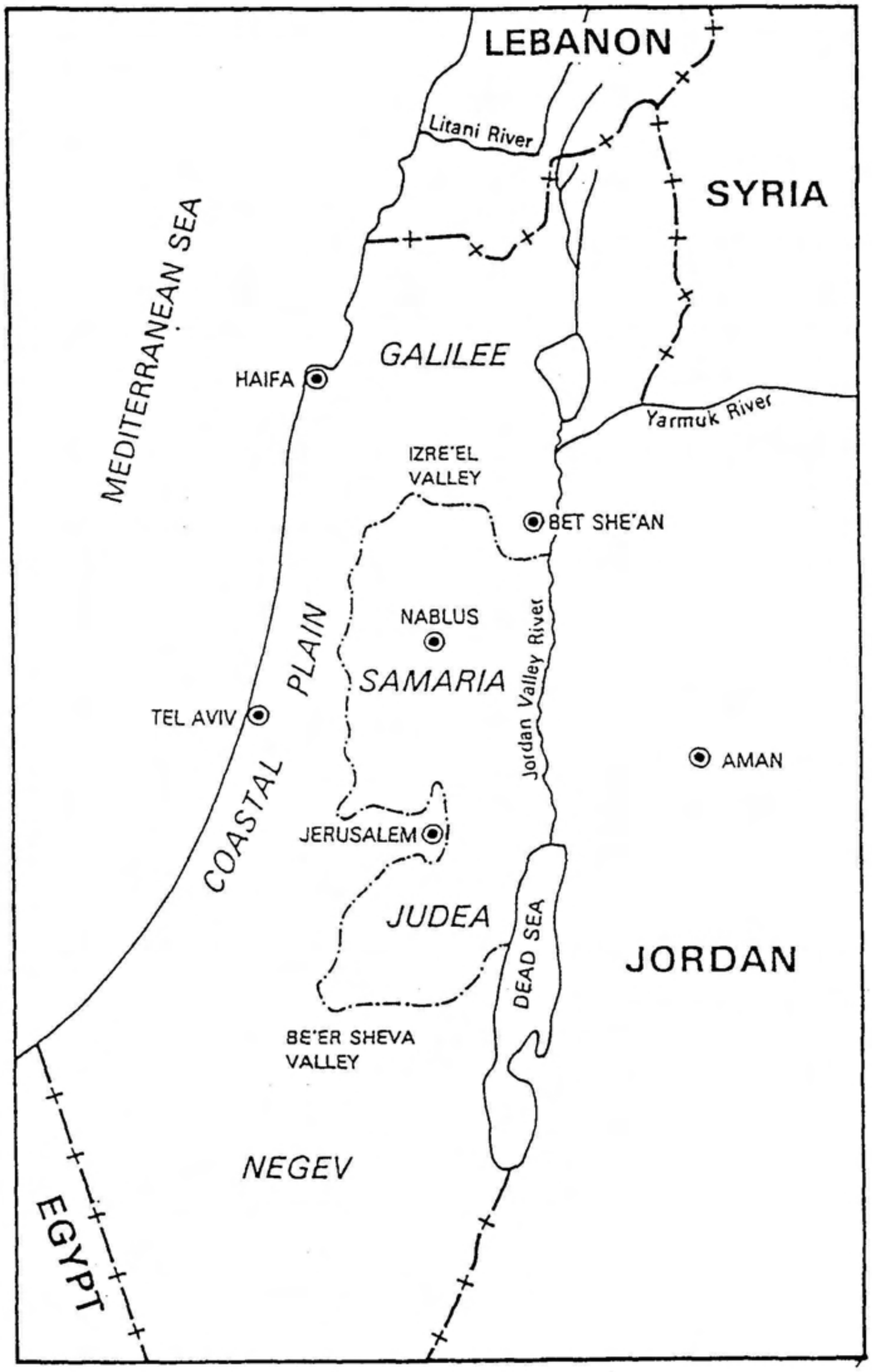

Figure 1. Geographic location map.

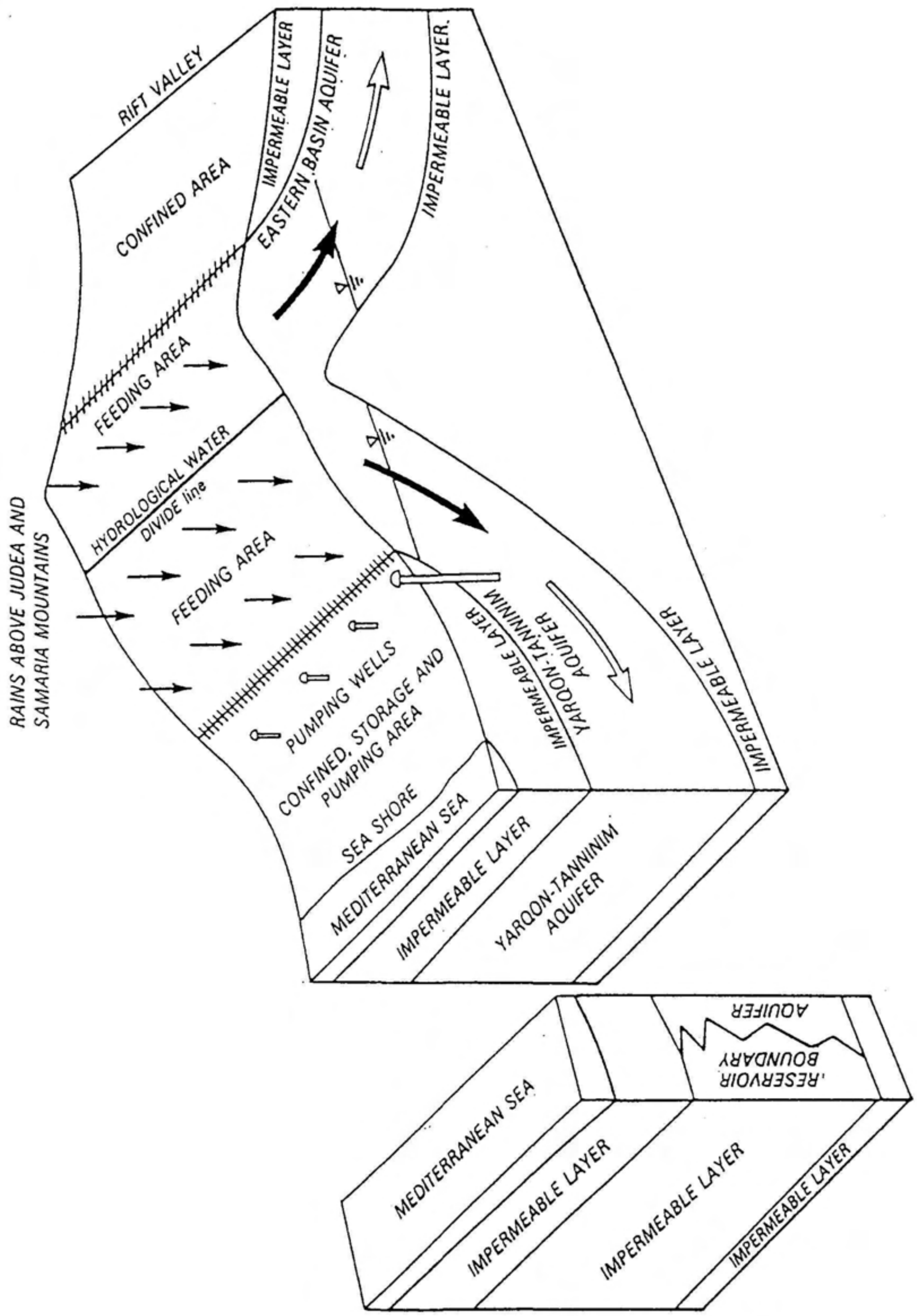

Figure 2. Block diagram of the Mountain Aquifer

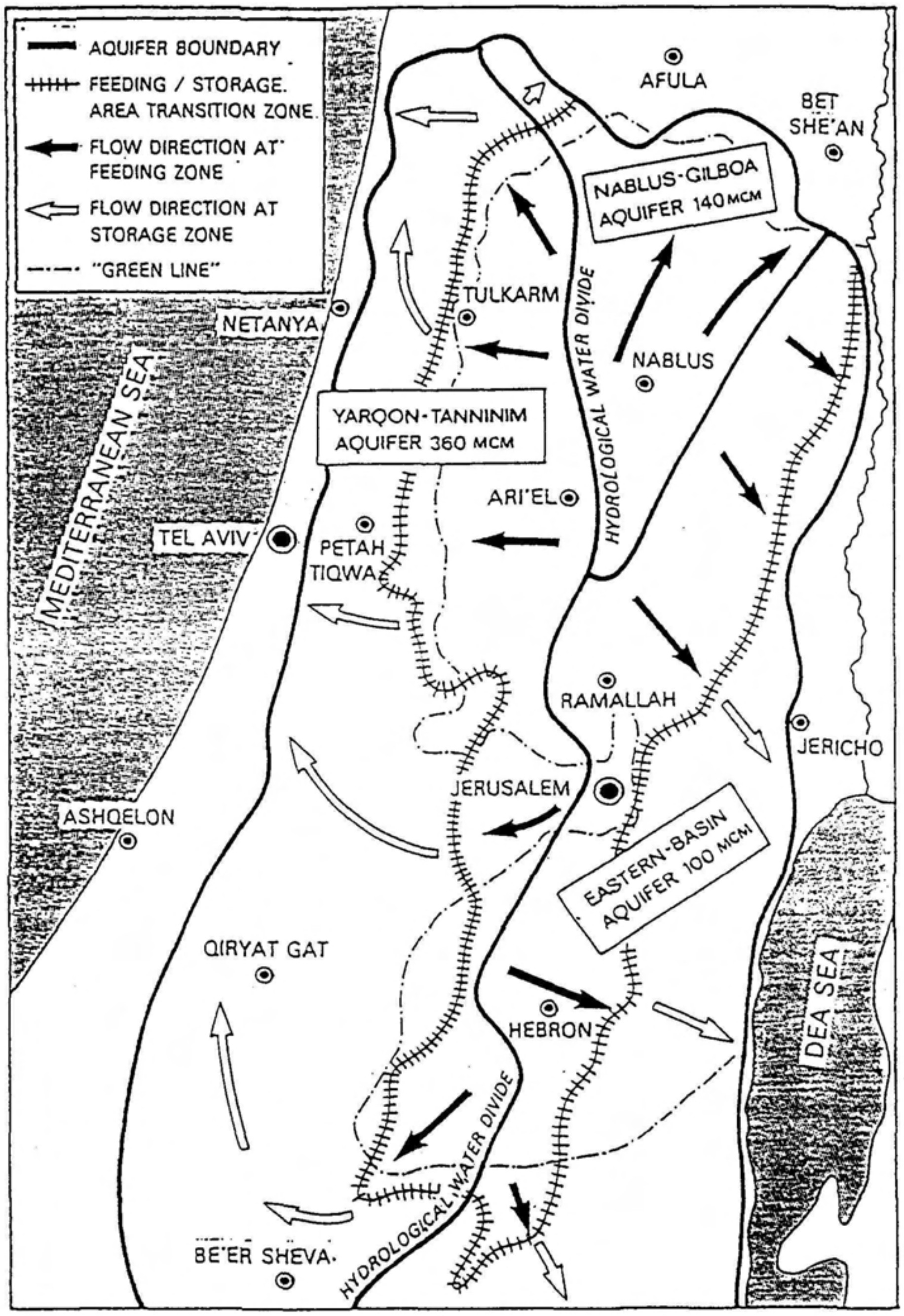

Figure 3. Hydrogeological map of the Mountain Aquifer