Cenomanian-Turonian Aquifer of Central Israel— Its Development and Possible Use as a Storage Reservoir

GEOLOGICAL SURVEY WATER-SUPPLY PAPER 1608-F

Prepared in cooperation with Water Planning for Israel, Ltd. (TAHAL), under the auspices of the U.S. Agency for International Development

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By ROBERT SCHNEIDER

CONTRIBUTIONS TO THE HYDROLOGY OF ASIA AND OCEANIA

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CENOMANIAN-TURONIAN AQUIFER OF CENTRAL ISRAEL— ITS DEVELOPMENT AND POSSIBLE USE AS A STORAGE RESERVOIR

By Robert Schneider

ABSTRACT

The Cenomanian-Turonian formations constitute a highly permeable dolomite and limestone aquifer in central Israel. The aquifer is on the west limb of an anticlinorium that trends north-northeast. In places it may be as much as 800 meters thick, but in the report area, largely the foothills of the Judean-Ephraim Mountains where the water development is most intensive, its thickness is generally considerably less. In some places the aquifer occurs at or near the land surface, or it is covered by sandy and gravelly coastal-plain deposits. However, in a large part of the area, it is overlain by as much as 400 meters of relatively impermeable strata, and it is probably underlain by less permeable Lower Cretaceous strata.

In general the aquifer water is under artesian pressure. The porosity of the aquifer is characterized mainly by solution channels and cavities produced by jointing and faulting. In addition to the generally high permeability of the aquifer, some regions, which probably coincide with ancient drainage patterns and (or) fault zones, have exceptionally high permeabilities.

The source of most of the water in the aquifer is believed to be rain that falls on the foothills area. The westward movement of ground water from the mountainous outcrop areas appears to be impeded by a zone of low permeability which is related to structural and stratigraphic conditions along the western side of the mountains.

Gradients of the piezometric surface are small, and the net direction of water movement is westward and northwestward under natural conditions. Locally, however, the flow pattern may be in other directions owing to spatial variations in permeability in the aquifer, the location of natural discharge outlets, and the relation of the aquifer to adjacent geologic formations. There probably is also a large vertical component of flow.

Pumping has modified the flow pattern by producing several irregularly shaped shallow depressions in the piezometric surface although, to date, no unwatering of the aquifer has occurred. In the central part of the area, pumping has induced some infiltration from overlying coastal-plain formations.

Injecting and storing surplus water seasonally in the aquifer should be feasible at almost any place. However, the movement and recovery of the injected water probably could be controlled most easily if the water were injected where depressions have been formed in the piezometric surface.

INTRODUCTION

Israel is a semiarid to arid country that extends from the eastern Mediterranean Sea to the Gulf of Aqaba, an arm of the Red Sea. It covers an area of 7,984 square miles, about the size of New Jersey. Recently Israel has been experiencing rapid economic growth; in the 10-year period ending 1961, its population expanded from 1,200,000 to 2,150,000 (Wiener and Wolman, 1962, p. 257).

The economy of the country depends almost entirely on its water resources, which are used largely for irrigation. Wiener and Wolman (1962) have outlined the prevailing nationwide comprehensive water policy or master plan for managing all the water resources. The plan, which was adopted in 1950, includes the development of considerably more ground water in the future. The full implementation of the plan also includes underground storage of surplus water which is available seasonally in certain places in the northern part of the country. In order to obtain ultimately an annual yield of about 1,700 million cubic meters, a storage capacity of about 1,500 to 2,000 million cubic meters would have to be developed (Y. Harpaz, written commun., December 1961). Owing to the scarcity of suitable sites for surface storage, about one-third to one-half of this amount would have to be stored in aquifers.

The Cenomanian-Turonian aquifer is one of the most important sources of ground water in Israel, but numerous technical problems are involved in its exploitation, Adequate solution of these problems will depend on accurate interpretation of the geologic history and hydrology of the aquifer.

I made a brief study in 1962 of the available information on the portion of the aquifer in central Israel where water development has been most intensive. The purpose of this report is to interpret some of the geologic and hydrologic characteristics of the aquifer and to discuss their relation to the problems involved in developing additional water and storing excess water. The study was made at the request of the State of Israel through the government water-planning agency, Water Planning for Israel, Ltd., known also as TAHAL, an abbreviated form of its Hebrew name. It was made under the auspices of the U.S. Agency for International Development.

I thank the following people for their guidance and for the stimulating discussions that they provided: Dr. Aaron Wiener, director general, TAHAL, and various members of his staff, including Dr. Samuel Mandel, chief of the Hydrological Research Section, Mr. Y. Harpaz, Mr. F. Mero, Mr. Y. Greitzer, Mr. M. Fink, Mr. E. Wakshal, and Mr. A. Galai, and also Professor Leo Picard, Department of Geology, Hebrew University, Jerusalem, and Mr. M. J. Goldschmidt, former director, Israel Hydrological Service.

GEOLOGIC ENVIRONMENT OF THE AQUIFER

The dominant structural feature of central Israel is the Judean-Ephraim anticlinorium. The axis of this structural complex trends north-northeast, and in the report area (pl. 1.) it extends through a point near 160/130 [1] about 10 kilometers west of Jerusalem (Bentor and Vroman, 1954). The Judean and Ephraim Mountains are the topographic expression of the anticlinorium and, consequently, except for the land corridor to Jerusalem, the report area consists of foothills and coastal plain. The general structural and stratigraphic relationships are shown diagrammatically in a geologic section (fig. 1). The location of the section is shown on plate 2.

The Cenomanian-Turonian formations (Upper Cretaceous) dip westward as steeply as 50° in a narrow north-south belt near grid line 152 East in the Jerusalem Corridor. West of this belt, in the foothills of the Judean Mountains, the westward dip is very low, and east of the belt, toward the crest of the anticlinorium, the strata are almost flat lying.

The Cenomanian-Turonian formations are the most commonly exposed rocks in the country. According to Picard (1959, p. 14), their total thickness may be as much as 800 meters, and they consist largely of dolomite and limestone but include some "marl" (clay) and chalk strata. In the Judean foothills, they are usually considerably thinner. The formations are regarded as one highly permeable aquifer system whose porosity is characterized mainly by solution channels and by cavities produced by jointing or faulting. The Lower Cretaceous section is composed, in descending order, of (1) dolomite and limestone with chalk and shale strata, (2) sandstone, and (3) a shale-limestone complex (Picard, 1959, p. 10–11). Little information is available on the hydrologic properties of the Lower Cretaceous formations, but presumably they are considerably less permeable than the Cenomanian-Turonian formations and act as a lower confining layer. Except in some places between the Lod and Yarkon Springs areas, where the Cenomanian-Turonian aquifer is overlain by sandy and gravelly coastal-plain deposits, the aquifer is generally overlain by Senonian, Eocene, Neogene, and Quaternary formations which serve to confine the aquifer hydraulically. In the area where most of the wells are located (pl. 2), the maximum thickness of the overlying confining strata is about 400 meters. Except for Neogene-Quaternary sandy and gravelly strata which are thin (pl. 1; fig. 1), they consist largely of relatively impermeable chalk

[1] Maps of Israel in this report bear a standard rectangular grid with 10-kilometer subdivisions. Locations are given east and north of the origin of the grid; for example, 155/210 is 155 East and 210 North.

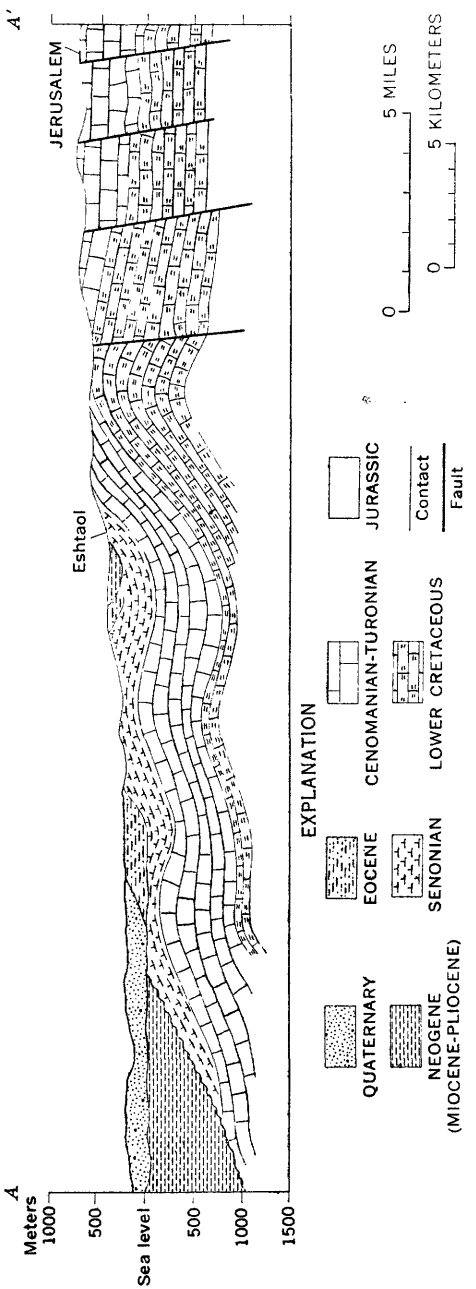

FIGURE 1.—Diagrammatic geologic section in southern part of report area.

and clay. Inasmuch as wells have been developed in a few places in Eocene carbonate-rock aquifers, the overlying formations may be capable of transmitting appreciable quantities of water even though they consist largely of chalk and clay.

The structure contour map of the top of the Turonian formations and the accompanying geologic cross section (pl. 1) indicate that some gentle warping, folding, and faulting has occurred locally. These features will be discussed later, particularly as they relate to the occurrence and movement of ground water. Toward the west, where the aquifer is beneath coastal-plain formations, it has been downwarped and downfaulted to a great depth. In the subsurface of the coastal region, where it was eroded during Tertiary time, the aquifer is covered in most of the area by a thick wedge of relatively impermeable clayey and shaley strata known as the Sakia Formation, principally of Miocene and partly of Pliocene age, according to Picard (1959, p. 20).

HISTORY OF PERMEABILITY DEVELOPMENT

In many places the aquifer is highly permeable; numerous wells yield hundreds and even thousands of cubic meters per hour with very small drawdowns. However, the yields of wells and the quality of the water are known to vary somewhat from place to place. The geologic factors that controlled the development of porosity and permeability are responsible for these variations, and they are a means of interpreting the natural flow regime, the way in which the present development has altered that regime, and how the future use of the aquifer will affect it.

According to Picard (1943, p. 41, 42), the sea retreated from Israel near the end of Eocene or in Oligocene time. Although the land was low, the circulation of ground water started to dilute and flush sea water from the rocks and, at the same time, enlarge joints, fractures, and bedding planes by chemical solution. Many of the general porosity characteristics of the aquifer probably were developed in Oligocene and Miocene time. During Miocene time, the rocks were subjected to intense tectonic activity which further fractured and jointed them. In addition to the folding and faulting, the land was uplifted, and, in places, erosion removed some of the Turonian formations. Where relatively impermeable formations were removed, as in the larger drainage systems, circulation of ground water was facilitated and the rate of chemical solution was accelerated. As a result, the porosity as well as the permeability of the Cenomanian-Turonian formations was increased, especially in the areas where the Turonian rocks were uncovered by erosion. The areal distribution of the sections

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of highest porosity and permeability is probably related to the major drainage pattern that was developed during Oligocene and Miocene time. The drainage pattern was controlled, to a certain extent, by the surface expression of faults and folds; thus the configuration of the sections of highest permeability is linear, sinuous, or branching. An example of the local pattern of such a drainage system is available from Neev's study (1960) of a pre-Neogene (late Oligocene or early Miocene) channel system in the Beersheba area, about 70 kilometers southwest of Jerusalem. The main channel trends northwest, and four short tributary channels trend generally northeast.

Several aspects of the piezometric surface south of grid line 180 North (pl. 2) are believed to reflect the manner in which the permeability distribution is related to the geologic structure. The crests of several short northeast-trending piezometric ridges or spurs occur at the following locations: 142/142, 143/151, 143/157, 143/163, and 145/174. One short northwest-trending spur is located near 141.5/178.5. Each ridge coincides with either a downfaulted synclinal block, a simple downfaulted block, or a structural basin shown on Issar's (1959, geologic sections following p. 5) structure contour map and geologic sections. Hydrologically (See also pl. 1, this report.) these structural features may be regarded as more or less isolated masses of relatively impermeable Senonian and younger formations (chalk and clay) bounded laterally and below by pervious Cenomanian-Turonian rocks. A good example of these features is shown at the north end of the geologic section on plate 1. Near the center of the section is a similar feature, but piezometric data are sparse at this location. As mentioned previously, the geologic features originated during late Tertiary time as a result of tectonic activity, and may represent regions where the rocks covering the Cenomanian-Turonian formations were not removed by erosion and where ground-water circulation and accompanying solution were limited. Consequently, they are believed to coincide with parts of the aquifer that are less permeable than adjacent parts from which erosion removed the strata above the aquifer.

If the aquifer were uniformly permeable in all directions and the rate of water withdrawal were evenly distributed along the belt between Lod and the Yarkon Springs area, the general effect on the piezometric surface would have been a simple north-south trench. The map of the piezometric surface indicates several irregularly shaped shallow depressions, although in detail the surface surely is much more irregular than can be shown with the available data. The general shape is caused partly by the areal distribution of pumpage and partly by variations in the permeability of the aquifer. The coincidence of the ridges in the piezometric surface with the previously mentioned structural features (areas of low permeability) suggests that specific aspects of the shape of the depressions are controlled by variations in the permeability of the aquifer. It might be expected that depressions in the piezometric surface produced by pumping would be elongated in the direction of highest permeability. The depression north of Lod is elongated in a northeast direction between two piezometric ridges; similar directions of elongation are apparent in the depressions at 145/163 and 147/173. The axes of the folds and almost all the faults shown on the structure contour map trend northeast and suggest that a general relationship exists between this linear pattern and the distribution and orientation of the sections of highest permeability.

Although the essential porosity and permeability characteristics of the aquifer were developed during late Tertiary time, the constant circulation and solvent action of ground water during Quaternary time further enlarged the pore spaces. The rate of solution probably was greater during Pleistocene time than during Recent time owing to more humid climatic conditions.

One of the primary controls on the movement of ground water in a series of stratified sedimentary rocks is the difference between the vertical and horizontal permeability. Inasmuch as the Cenomanian-Turonian aquifer consists of interbedded massive and stratified dolomite and limestone and strata of clay and chalk, it is assumed that, where structural deformation has not influenced the permeability distribution and physical characteristics of the pore spaces, highly permeable zones essentially parallel the bedding planes and are separated by parallel zones of much lower permeability. Jointing and faulting would tend to facilitate the vertical circulation of water, particularly through the massive, brittle, competent strata. Unless they are breached by faults, the clay and chalk strata probably can be regarded as aquicludes because, in general, joints and cracks probably would not remain open in these rocks nor would they be enlarged significantly by chemical solution. The interbedding of carbonate rocks of relatively high permeability with the clays and chalks may result in the concentration of highly permeably zones near the contacts between the strata.

In outcrops of Cenomanian-Turonian rocks, several large cavelike openings were observed, some of which were several meters in diameter. Records and logs of wells mention depth intervals, extending for tens of meters, in which drilling circulation was lost. These intervals may be large cavities in the subsurface. However, these well logs may not all be accurate and it is difficult to determine which are reliable and which are not. Most of the larger solution channels are about half a meter in diameter or less. Some of the solution openings appear to be tubelike in form, though actually most of them probably are extensive laterally or vertically in two dimensions (sheetlike) as a result of solution enlargement along joints, faults, or bedding planes. Locally, some of the rocks, which probably were massive, have had so much material dissolved from them that they appear spongelike. However, where large cliff faces or quarry walls in the Cenomanian-Turonian rocks were examined, the apparent percentage of the total rock volume composed of large solution openings generally is very small, perhaps only a few percent or less. Mandel (1959) states that the effective porosity of carbonate rocks in northern Israel ranges from 1 percent in Turonian limestone of the Carmel Mountains to 3 to 5 percent in dolomite of the Cenomanian-Turonian aquifer of the western Galilee Mountains; in central Israel, in the foothills near Lod, it is as much as 12 percent in the Cenomanian-Turonian aquifer.

In summary, the known hydrologic characteristics of the aquifer and the geologic events that controlled the development of permeability indicate that on a regional scale the aquifer is highly permeable. In addition, some regions, probably coinciding with ancient drainage patterns, fault zones, or both, may have exceptionally high permeabilities.

NATURAL FUNCTIONING OF THE AQUIFER SYSTEM

Although the Cenomanian-Turonian aquifer is considered a hydrologic unit, it is connected hydraulically with adjacent water-bearing rocks that generally have a lower permeability. The aquifer is the direct source of water pumped from wells, but some ground water circulates in the associated rocks of lower permeability. The recharge, flow, and discharge characteristics of the aquifer are obviously related to the hydraulics of the entire system.

In general, water in the aquifer is under artesian pressure. A comparison of the structure contour map (pl. 1) with the piezometric map (pl. 2) indicates that the piezometric surface of the Cenomanian-Turonian aquifer is above the top of the Turonian strata over practically the entire area. Where the younger confining formations are absent, as near 144/147, or where the aquifer is covered by a thin mantle of sandy and gravelly strata, as near the Yarkon Springs area, water in the solution openings of the system is confined, presumably by Cenomanian-Turonian rocks of relatively low permeability.

HORIZONTAL FLOW AND DISCHARGE

The general pattern of horizontal ground-water movement in the part of the aquifer beneath the foothills and coastal plain can be interpreted from the piezometric map (pl. 2). The few water-level measurements shown on the map in the Jerusalem Corridor area, east of grid line 155 East, were made in wells completed in the lower Cenomanian formations. These measurements indicate that the piezometric surface in this mountainous area is about 500 meters above sea level. There appears to be a hydraulic gradient to the southwest down to about 270 meters. Between the well where the piezometric level is about 270 meters (loc. 157/128.2) and the 23.0–meter contour in the foothills, there is located, near grid lines 152 to 153 East, the north-south belt (see p. F3) in which the formations are dipping westward as much as 50°[2]. East and west of this belt the formations dip westward much more gently. Some clay and chalk strata intervene, at least locally, between the upper and lower Cenomanian formations. The belt of steeply dipping formations is probably a zone of low permeability that impedes the westward movement of ground water and has caused the difference in head of more than 200 meters in a horizontal distance of about 5 kilometers. Apparently this zone of low permeability is related to the intense structural deformation and the presence of the relatively impermeable strata.

It was not possible to study the western flanks of the mountains, other than in the Jerusalem Corridor, to determine if the geologic and hydraulic conditions observed in this area are representative of a larger region. Professor Leo Picard of Hebrew University was consulted about this matter because he has made extensive studies of the geology of Palestine and neighboring countries (1943). According to him (oral commun., June 14, 1962) the structural conditions in the Jerusalem Corridor, that is, the occurrence of a narrow north-south belt in which the Cenomanian-Turonian strata dip westward at a high angle, are probably more or less representative of the western flanks of the mountains in Jordan. If one makes this assumption, it means that, in general, the westward movement of ground water from the mountains to the foothills is impeded by a zone of low permeability and that much of the ground water in the report area has been derived from infiltration in the foothills and adjacent parts of the coastal plain.

South of grid line 150 North, the control for the piezometric map is so unevenly distributed that only a suggestion of the flow pattern can be obtained. The general direction of movement appears to be westerly. Pumping in a few localized areas has probably shifted the contours to form small troughlike depressions such as those at locations 147/134, 144/136, and 144/144.5.

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[2] In a written communication of May 3, 1963, Dr. Samuel Mandel states that the water-level altitude in a new test hole near the west edge of the belt of "sharp anticlinal dip" on the road to Jerusalem is about the same as that in a well a few hundred meters to the west (shown on pl. 2 about 4 kilometers northeast of Eshtaol).

In the area between grid lines 150 and 170 North, the ground-water development is most intense and the natural configuration of the piezometric surface has been modified considerably by pumping. Assuming the crests of the piezometric ridges to be closest to the original surface and disregarding local undulations, there is a gentle northward or northwestward regional gradient of about 2 meters in 20 kilometers between the ridge east of Lod and the vicinity of the Yarkon Springs.

In the area bounded approximately by grid lines 180 and 205 North, a regional flow pattern that is northwest and piezometric contours that are comparatively regular in form suggest a uniform gradient. Toward the west, however, contours that appear to curve in a more westerly direction suggest a stronger northerly component of flow in this area. Locally, the regional flow pattern has been changed near centers of intensive pumping such as near 144/180, at Tulkarm in Jordan, and near 151/207. The shape of the north-south piezometric trough or valley produced by pumping at this last location may, in part, be controlled by a fault zone at approximately the same location (pl. 1). The fault is shown on an unpublished structure contour map of Israel.[3]

An extremely sharp northwestward gradient of the piezometric surface near location 155/210, from about 16.0 meters to 13.5 meters in a distance of about 1 kilometer, is probably related to a large syncline, the axis of which trends southwest and extends through a point near 160/220. Only part of the southeast flank of the structure is shown on plate 1, but on the unpublished structure contour map referred to in the previous paragraph, the top of the Turonian formations is shown at an altitude of more than 800 meters below sea level along the axis of the structure. The structural trough is filled largely with Senonian-Paleocene and Eocene formations (Picard, 1947), and the steep gradient of the piezometric surface is probably caused by the loss in head resulting from the northwesterly movement of water through the relatively impermeable rocks of the syncline.

The lowest piezometric level in the northwestern part of the report area is about 6.5 meters above sea level (loc. 145.5/215.5), in the vicinity of the Tanninim River. There also is a southwesterly component of flow toward this area, along the axis of the large syncline. The fact that in the extreme northeast corner of the map area the piezometric level is about 2 meters below sea level indicates a divide perhaps several kilometers southwest of this location.

The main discharge area for the aquifer under natural conditions is the Yarkon Springs, and a secondary one is through the springs

[3] Greenberg, Yaacov, 1959, Israel structural contour map on top Turonian, scale 1:250,000: The Israel National Oil Co., Ltd., Tel Aviv.

contributing to the Tanninim River (Goldschmidt and Jacobs, 1958, p. 3; Mandel, 1957, p. 7, 8). The map of the piezometric surface (pl. 2) appears to corroborate these statements although a northward component of flow could not be detected in the southern part of the area, south of grid line 150 North. Goldschmidt and Jacobs state that the average base flow of the Yarkon River, downstream from the spring area for the period 1944–54, is about 220 million cubic meters per year. The monthly discharges of the Yarkon Springs for the period 1950–58 are shown in figure 2. A pronounced difference exists in the chloride content of the ground water in the areas north and south of the springs. The apparent abruptness of this change in quality may be caused by the discharge of a large part of the northward or northwestward flow in this area. Mandel (1957, p. 7, 20) estimates the average flow of a Turonian limestone spring, discharging at the head of the Tanninim River, at 10 million cubic meters per year. On his map showing the direction of subsurface flow, this spring is a discharge point for water moving northwest.

The thick, extensive wedge of fine-grained Neogene rocks (Sakia Formation) that overlaps the eroded and downwarped seaward side of the aquifer apparently prevents any significant amount of discharge in that direction. However, oil wells and exploratory holes at 129.5/128 and southwest of the report area at 120.3/117.6, where the bottom of the Cenomanian formations is at a depth of about 1,200 meters, yielded water from the Cenomanian-Turonian aquifer that contained only 1,500 to 1,700 ppm (parts per million) chloride. This chloride content suggests that relatively fresh ground water is circulating in the aquifer at great depth or that it has circulated in these regions in the past. Owing to the absence of data on the head relationship between the aquifer and the overlying strata, it is impossible to state whether or not water is discharging westward through the Sakia Formation.

VERTICAL FLOW

Several features of the aquifer suggest that there is a significant vertical flow component in the system. The most obvious is the physical nature of the openings in the system—a complex network of solution cavities whose geometry appears to be related to lithologic-stratigraphic variations, structural deformation, and former drainage patterns.

The vertical temperature gradient in the aquifer and the areal distribution of chloride concentrations appear to substantiate this interpretation of the flow characteristics. In another study (Schneider, 1964), I found that, locally, the apparent vertical temperature gradient, which is based on water temperatures in wells, is very small,

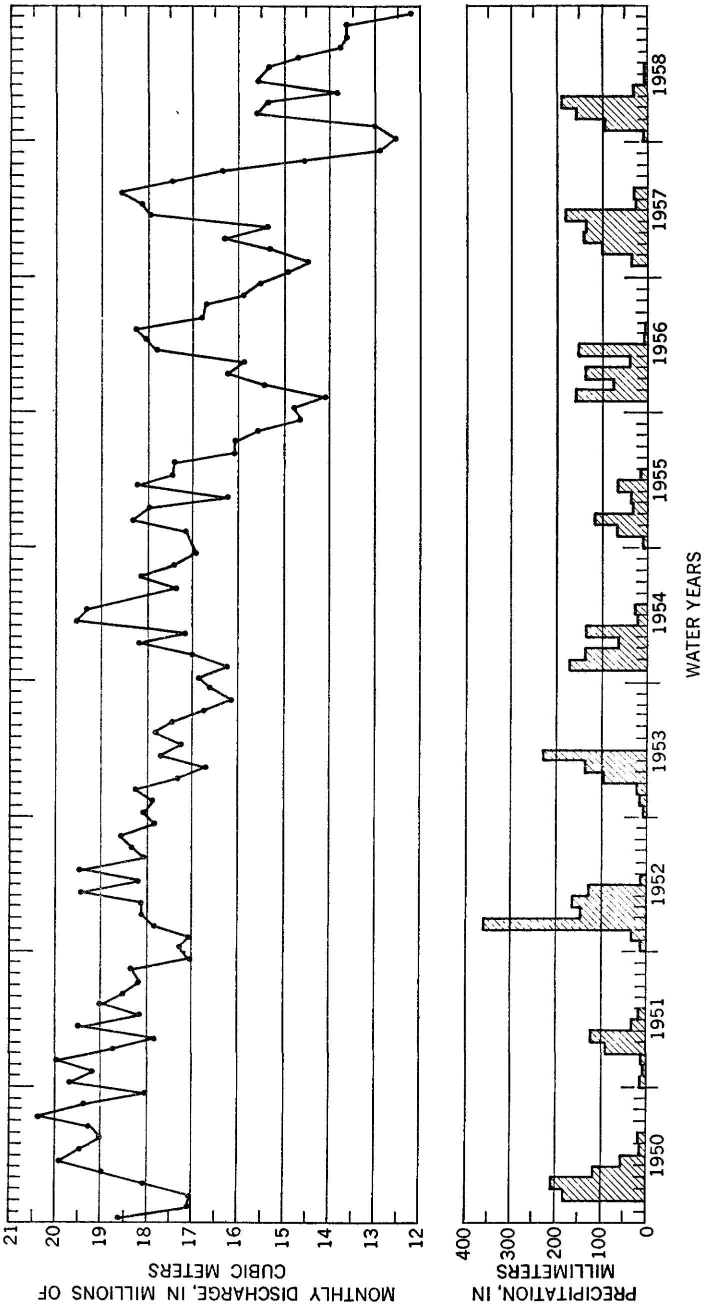

FIGURE 2.—Graph of discharge of Yarkon Springs and rainfall at Jerusalem.

owing apparently to a vertical component of flow that is large enough to reduce the prevailing regional geothermal gradient. The flow of heat from the earth would be disseminated throughout the aquifer by the upward movement of water. Infiltration and downward movement of cool water from the surface would also lower the vertical temperature gradient.

Data on the chloride content of the water in the fall of 1960 (Israel Hydrological Service, 1962) indicate that south of grid line 172 North the average concentration is about 200 ppm or more, and north of this line the average is about 60 to 70 ppm. A much more detailed study would have to be made to understand completely this pronounced difference in concentration; however, at least one important difference between the two areas can reasonably explain the difference in quality. Approximately south of grid line 152 North, the surficial formations in the foothills region are mostly Senonian and Eocene chalk and calcareous clay; north of this line the Cenomanian-Turonian rocks are at or near the surface (Picard, 1942, 1946). Water moving downward from the land surface toward the Cenomanian-Turonian formations may have dissolved mineral matter from the overlying chalk and clay in the south; this source of mineral matter is absent in the north. In a report on the salinity (chloride content) of water in the Cenomanian-Turonian aquifer of central Israel (south of grid line 140 North), Greitzer (1963, p. 9) states that the main sources of salinity in the upper part of the aquifer are the chalky-marly strata of post-Turonian age. He further observes that in the foothills of the Judean Mountains the salinity of the water in the upper part of the aquifer is higher than that in the lower part. On a schematic geologic cross section (following p. 1 of his report), he indicates that the water table in the overlying formations is higher than the piezometric surface of the aquifer and that water is moving downward from the Senonian formations into the aquifer.

Apparently the magnitude of vertical ground-water circulation is closely related to the recharge characteristics of the aquifer.

RECHARGE

The Cenomanian-Turonian aquifer could receive recharge in the foothills from two possible sources: One from ground water moving laterally westward from the mountainous outcrop areas, another from downward percolation of water derived from rain and streams in the foothills.

As previously mentioned the structural and stratigraphic conditions in the Jerusalem Corridor can be considered typical of those along the western flank of the mountains in Jordan. These conditions appear to be related to the occurrence of a zone of low permeability which impedes the lateral movement of water. The amount of ground water moving westward from the mountains to the foothills is probably small; however, several investigators have observed that significant quantities of surface runoff are lost in the mountainous areas, and some investigators have assumed that this lost runoff is the main source of recharge to the aquifer in the foothills. Pereira, Shachori, and others (1960, p. 3, 14) studied rainfall, runoff, and soil moisture for three seasons in a 34-square-kilometer area underlain by Cenomanian-Turonian rocks in the Carmel Mountains of northern Israel. They observed that surface runoff is very low, probably less than 3 percent of the annual rainfall. They also observed a substantial deficiency in soil moisture during the 2- to 4-week dry intervals which may occur between storms in the winter rainy season. In another project, Pereira, Downes, and others (1960, p. 2) analyzed a 20-year record of runoff and rainfall for a drainage area of about 75 square kilometers near Jerusalem. The runoff ranged from 0 to 17 percent of the annual rainfall, and the mean value was 6 percent. These authors state that a large proportion of the streamflow is lost to deep percolation which is intercepted by impermeable marl (clay) beds and delivered to springs; clay beds are an "unusually dominant feature" of this area.

Water percolating into the formations in the mountainous area of the Jerusalem Corridor must penetrate as much as 140 meters of unsaturated material above the water table. As noted earlier, this interval includes several clay and chalk horizons in addition to substantial thicknesses of carbonate rocks of low permeability. Because of the large thickness of the unsaturated zone and the presence of relatively impermeable strata above the water table, ample opportunity exists for the impedance and lateral diversion of downward percolating water to areas where significant amounts of ground water can discharge by evapotranspiration and through seeps and small springs.

Recharge by the downward percolation of water in the foothills area is possible if the artesian head in the Cenomanian-Turonian aquifer is lower than that in the overlying formations. On a schematic geologic cross section near grid line 110 North, Greitzer (1963, following p. 1) indicates such a relationship. The maximum difference, which occurs in the foothills region, is more than 300 meters. Specific data are lacking for most of the area of the present report, but, because the aquifer contains water under artesian pressure over practically the entire area, recharge from this source is characterized by more or less steady, slow seepage, derived primarily from rainfall.

SUMMARY

In general, water in the Cenomanian-Turonian aquifer is under artesian pressure, and hydraulic gradients are small. The net direction of movement is generally westward and northwestward, although locally the flow may be in other directions owing to spatial variations in permeability and the location of discharge areas. The permeability distribution appears to be related primarily to the orientation of faults and folds and former patterns of drainage. Discharge to the west is apparently restricted by the overlap of an extensive thick body of fine-grained deposits on the downwarped seaward side of the aquifer.

Several features of the aquifer suggest that in places there is a large vertical component of flow. Most of the water in the aquifer probably has come from infiltration in the foothills and adjacent parts of the coastal plain because structural and stratigraphic conditions along the western side of the mountains evidently impede the westward movement of ground water.

STORAGE CHARACTERISTICS AND SOURCES OF PUMPED WATER

In water-table aquifers, the water released from or taken into storage in response to a change in head can be attributed, for all practical purposes, to gravity drainage or refilling of the zone in which the water table fluctuates. However, in an artesian aquifer, a measured change in head represents a change in potential energy in the aquifer. No dewatering or refilling of the aquifer is involved, and the water released from or taken into storage can be attributed only to the deformation of the aquifer and overlying material and to the compressibility of the water.

A significant manifestation of the storage properties of the aquifer is the nature of water-level fluctuations. In general, the seasonal pattern of fluctuation is similar for the entire report area. The artesian head reaches a peak about March or April and a low about November. It is significant that little if any difference exists between the amplitude of fluctuation in areas of heavy pumping and the amplitude in areas where the pumping is light. In 1961, the average amplitude in the area south of grid line 180 North was about 2.2–2.3 meters, and north of this line it was about 2.6–2.8 meters. Because the bulk of the water is used for irrigation, pumpage decreases drastically after the earliest rainstorm in the fall. Shortly after the last rainstorm in the spring, intensive pumping commences and continues until fall. Consequently, one of the problems in analyzing the water-level records is to distinguish natural fluctuations from those caused by pumping. To study this problem, five areas of concentrated pumping were selected for which water-level records were available since about 1950. These areas are outlined on plate 2, and graphs of yearly pumpage and of the highest yearly water levels are shown on plate 3. A graph of the cumulative departure from an assumed normal value of 550 mm of precipitation is given for Jerusalem (unpublished data from Israel Meteorological Service). In general, except for area 5, all the hydrographs show a gradual net decline from about 1950 to 1958 and a more rapid decline from 1958 to about 1962. With the exception of area 5, the rates of water-level decline in all the wells are approximately the same for the entire period of record, and for the period 1958–62 the rates of decline are similar for all the areas.

The precipitation record can be correlated with the hydrographs. From 1950 to 1957, precipitation was slightly below normal most of the time; this deficiency is reflected in the gradual water-level decline. From 1957 to 1962, the cumulative departure dropped at a much increased rate and water levels also declined at an increased rate. The pronounced deficiency in precipitation in water years 1955–56 can be correlated with lowered piezometric levels in areas 1, 3, 4, and possibly 5; no record is available in area 2 for this period. The deficiency in 1951 is reflected only in the water-level records for areas 3 and 5; no record is available for this year in area 4. It should be noted that the discharge from the Yarkon Springs, which has been measured monthly for a number of years, fluctuates with the seasonal rainfall pattern with little time lag (fig. 2). Perhaps the fluctuations in spring discharge are caused by the same factors that produce seasonal fluctuations in water levels.

In a few instances, changes in the annual rate of pumping can be correlated with water-level fluctuations in the immediate area. In general, however, this correlation is not nearly as clear as the correlation with the precipitation record. A comparison of the pumpage records and hydrographs reveals certain anomalies that are difficult to explain. For example, one might expect that the pronounced increase in pumpage from 1956 to 1957 in area 5 would be reflected in lowered water levels. The more or less constant increase in pumpage in areas 2, 3, and 4 does not appear to be related to the distinct inflection in 1958 on all the hydrographs. There is a striking contrast between the generally similar shape of the hydrographs and the dissimilarity in the magnitude and pattern of change of the pumpage graphs. The total amounts of water pumped during the period of record varied considerably: about 124 million cubic meters in area 1, 42 million in area 2, 44 million in area 3, 64 million in area 4, and 87 million in area 5. Despite these large differences in the amounts of water pumped, the net declines in water levels for the period of record did not vary widely: 6.3 meters in area 1, 5.5 in area 2, 6.4 in area 3, 5.1 in area 4, and 4.4 in area 5.

The similarity of the main features of most of the hydrographs, the dissimilarity in the magnitude and pattern of pumping in the several areas studied, the near constancy in the amplitude of seasonal water-level fluctuations in the entire area, and the apparent close correlation between the long-term trend of the water level and the record of precipitation all suggest that changes in artesian pressure are caused mainly by the seasonal and long-term patterns of precipitation. Although the piezometric map shows that pumping has resulted in the formation of several depressions in the piezometric surface, pumping probably plays a relatively minor role in producing the widespread, uniform, seasonal fluctuations and the pattern of long-term changes in artesian pressure.

The mechanism by which the changes in artesian pressure occur must be explained because of the significance of the changes in interpreting the storage properties of the aquifer. The uniformity of the seasonal fluctuations in pressure over the entire area and their correlation with the precipitation pattern suggest that recharge changes the pressure rapidly in the aquifer. The application of a pressure change in a limited area (for example, the lowering of pressure in one of the areas of intensive pumping) apparently is localized to the extent that only a localized depression is produced in the piezometric surface. This localization suggests that the stresses responsible for widespread seasonal head changes in the aquifer are applied relatively uniformly over a large area. These stresses could be produced in two ways or in a combination of the two: (1) the stresses could be caused by fluctuations of the water table in the outcrop area resulting from natural recharge or discharge; and (2) the stresses may result from water-table fluctuations over the entire report area, which would increase or decrease the load on the artesian system. Matson and Sanford (1913, p. 238–239) discuss this phenomenon for limestone aquifers in Florida; they say that the results of this pressure are usually felt within a short time after a heavy rain and that the fluctuations in artesian pressure may be of either long or short duration. They mention further that the fluctuations may result as soon as water enters the soil and before it reaches the water table from the transmission of pressure by confined air.

The fact that the aquifer contains water under artesian pressure in the lowest parts of the depressions in the piezometric surface suggests that to date pumping has not unwatered the aquifer. However, the easterly extent of these depressions toward the outcrop areas is not known. Because the depressions are shallow and the hydraulic gradients are small, if they extend to the outcrop and if there is no appreciable change in transmissibility in that direction, the amount by which water levels in those areas would have been lowered is very small. If the average coefficient of transmissibility is high, appreciable quantities of water may be moving westward under a small gradient. As noted previously, however, the westward movement of ground water from the mountains may be impeded by a zone of relatively low permeability. Owing to the lack of specific information on the hydrology and geology in the outcrop areas, this apparently anomalous situation could not be resolved.

In addition to the water derived from artesian storage, some water in the area of most intensive pumping, between Lod and the vicinity of the Yarkon Springs, moves downward and eastward from the overlying sandy and gravelly coastal-plain formations. I (Schneider, 1964) found that the natural temperature distribution appeared to be modified significantly in this area, possibly by induced infiltration of cool water from the shallow formations.

USE OF THE AQUIFER AS A STORAGE RESERVOIR

One of the most important factors to be considered in using the aquifer as a storage reservoir for surplus water is the selection of storage areas from which most of the stored water can be recovered by wells during the immediately following irrigation season. In a good reservoir the amount of water that is discharged through natural outlets must be small. Most of the water to be stored in the aquifer probably will be injected through supply wells, and, in view of the large yields obtained, no problems should be involved in injecting large quantities of water. The wells will probably not be plugged by chemical precipitates because the wells are completed as open holes and the pore spaces in the aquifer are large.

Another aspect of the plan to use the aquifer as a storage reservoir is the injection of water of low mineral content in places where the aquifer water is excessively mineralized. The objective is to recover the water from one or more wells so as to mix the native water with the injected water during the pumping period in order to produce water with an intermediate level of mineral concentration. To accomplish this objective, the rate and direction of movement of the injected mass of water must be known.

The injection of large quantities of water anywhere in the aquifer will modify the head distribution to some extent and change the rate of movement. The only information available on the horizontal ground-water velocity is an order of magnitude suggested by Mandel (1960, p. 502) on the basis of injection tests using radioactive tracers in northern Israel; he suggested a velocity of 0.6 to 1 meter per day.

The piezometric map (pl. 2) is useful for evaluating the suitability of areas for the seasonal storage of water because it indicates general directions of ground-water movement. The most significant features of the piezometric surface are the spurs or ridges which were discussed earlier and which presumably indicate parts of the aquifer where the permeability is somewhat lower than in adjacent areas. Pumping probably has accentuated the height of the ridges in the piezometric surface by lowering the head in the intervening areas. These depressions may be regarded as local reservoirs insofar as the injection of water is concerned.

The area of the piezometric depression north of Lod appears a logical site for injection of water. If the piezometric surface were mapped as water is injected, the head distribution could be controlled, the depression could be preserved, and the outflow from this area could be minimized.

Another possible storage area is near Yarkon Springs. At least locally, water is moving toward the Yarkon Springs area from all directions, although pumping in the vicinity of the springs apparently has been a contributing factor in reducing the artesian head and the spring discharge. Pumping has produced a narrow irregular valley in the piezometric surface extending south from the spring area. The piezometric ridge at 145/174 divides the flow locally. Assuming that the velocity of ground-water flow is about 1 meter per day, water could be injected at the upgradient end of this valley and most of it could be recovered from wells during the irrigation season because the distance to the spring area is about 10 kilometers. As in the area north of Lod, the head distribution would have to be controlled to prevent the water from moving east or west toward areas where there are no wells. If the discharge from the springs could be stopped or reduced considerably by additional pumping, water possibly could be injected closer to the spring area.

Another localized depression in the piezometric surface where injection might be feasible is in the north-south valley east of Hadera. As in the valleylike depression south of the Yarkon Springs, water perhaps could be injected at the upgradient end of the valley and most of it could be recovered from wells because of the low velocity of ground-water flow.

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