SUSMAQ
Sustainable Management of the West Bank and Gaza Aquifers

A brief summary of the hydrogeology of the West Bank

Management Options Study Working Note

Important: This note is an output from the Management Options Study, part of the SUSMAQ project. Working reports are designed to communicate the results of work on the SUSMAQ project with the least possible delay. The findings, interpretations and conclusions expressed are those of the author(s), and should not be attributed to the Palestinian Water Authority or any other Palestinian organisation.

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The SUSMAQ Project

The aim of the project is to increase understanding of the sustainable yield of the West Bank and Gaza aquifers under a range of future economic, demographic and land use scenarios, and evaluate alternative groundwater management options. The project is interdisciplinary, bringing together hydrogeologists and groundwater modellers with economists and policy experts. In this way, hydrogeological understanding can inform, and be informed by, insights from the social sciences. The results of the study will provide support to decision-making at all levels in relation to the sustainable management of the West Bank and Gaza Aquifers.

The project runs from November 1999 to December 2003, and is a partnership between the Palestinian Water Authority, University of Newcastle and British Geological Survey. The project is funded by the United Kingdom's Department for International Development (DFID).

Management Options Study

The Management Options (MO) Study is part of the SUSMAQ project.

The MO Study focuses on changing water demands, the use and allocation of water as both an economic and a social good, and the policy and institutional arrangements that can support sustainable water use and sustainable livelihoods.

The MO Study has two main objectives. Firstly, it aims to identify alternative groundwater management options and evaluate them against a range of performance and feasibility criteria. These include cost and economic efficiency; equity; technical, political and institutional feasibility; public and political acceptability; and hydrogeological impact. Secondly, the study aims to develop economic, demographic and land use scenarios and evaluate possible abstraction/ pollution outcomes.

Bibliographical Reference

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Feedback!

The Management Options Team welcomes feedback, both positive and negative! Tell us what you think about the ideas and issues raised in this report by contacting the team at one of the addresses above. Thank you.

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1 Introduction

This working document forms part of the SUSMAQ project (the sustainable management of aquifers). The project is concerned with the transboundary aquifer of the West Bank of the Jordan which underlies the occupied Palestinian territories and Israel (see Figure 1). The SUSMAQ project is interdisciplinary. Economists and sociologists are working alongside groundwater modellers and hydrogeologists to help identify options for sustainable management of the groundwater resources. The project naturally splits into two components: the groundwater modelling and management options. This document is an output of the management options (MO) team and has been written to help successful communication across the project.

This report summarises the hydrogeology of the West Bank for non-specialists. The primary aim of the report is to act as the main hydrogeological source for the economists and sociologists which make up the Management Options team. However it could also act as an easy reference for all in the project, and help explain the hydrogeology to those outside. The report is illustrated with many schematic diagrams which attempt to aid understanding of the complex hydrogeology, rather than act as true geological maps or cross sections. Much of the information has been gathered from internal SUSMAQ reports with some references to external publications. A glossary is provided at the end of the report defining technical terms used in the report.

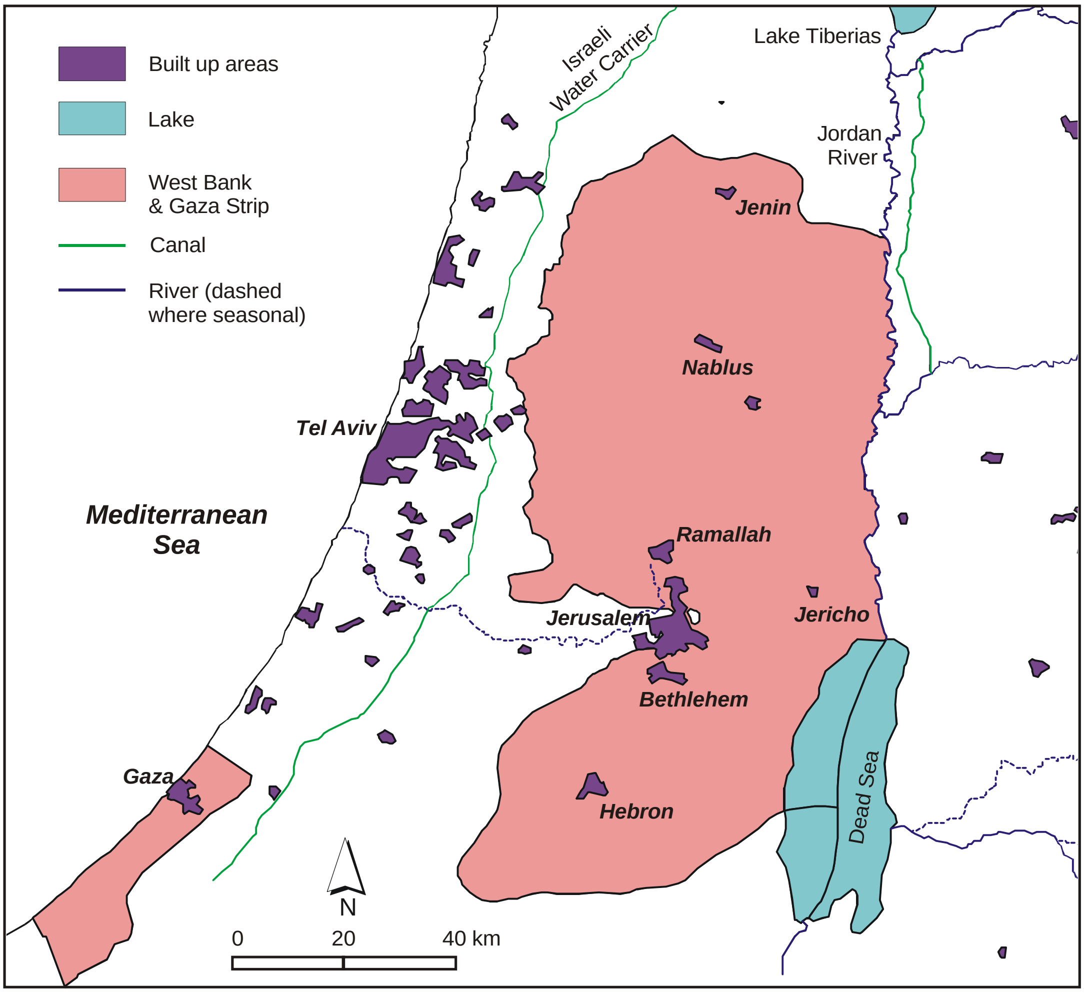

Figure 1 The West Bank and Gaza Strip.

2 General geology and hydrogeology

The West Bank is rugged. This topography is a result of the geology and has an important impact on groundwater in the area. A ridge of mountains extends from Nablus in the north to Hebron in the south; the mountains are generally greater than 700 m above sea level and rise to over 1000 m in some places. The Jordan valley to the east is the lowest place on the earth's surface, falling to 349 m below sea level at the Dead Sea. The West Bank is cut by numerous wadis.

The rocks in the West Bank comprise a complex sequence of limestone, dolomite, chalk, and marl. These rocks have been folded to form a major anticlinorium with its axis roughly coinciding with the mountains (Figure 2). This general structure is complicated locally by numerous faults and folds. The Jordan Valley comprises a rift valley. This is a strike-slip fault forming the northern extension of the Red Sea rift. There has been more than 100 km of horizontal movement and up to 3 km of vertical movement along the fault. This valley has been infilled with younger rocks. The geological succession of rocks on the West Bank and their hydrogeological significance is shown in Table 1.

The main aquifer on the West Bank is found within the Cretaceous rocks. This is often referred to as the Cretaceous Mountain aquifer. The aquifer comprises layers of limestones and dolomite separated by low permeability marls. The aquifer can be divided into the upper and lower aquifers.

The upper aquifer comprises limestones, dolomites and chalk of the Jerusalem, Bethlehem and Hebron Formations (see Table 1). The aquifer can be up to 400 m thick. The top of the aquifer comprises the Jerusalem Formation. This is a fine-grained limestone with chert nodules. The limestone is hard and uniform, but contains many joints. Limestone pavements are developed where the rock is at the surface. The Bethlehem Formation comprises hard well jointed limestone which becomes progressively more chalky towards the base. The chalk may impede groundwater flow. The bottom of the upper aquifer comprises the Hebron Formation. This is a well-jointed dolomite which has been karstified towards the top. Karst is where fractures and joints in rocks have been enlarged by dissolution to form conduits and sometimes caves. Groundwater in the upper aquifer is stored in the fractures and joints and large pore spaces of the limestone/dolomite. The water flows through the joints. This flow can be rapid through fractures that have been enlarged by dissolution.

The lower aquifer comprises limestone and dolomite of the Upper and Lower Beit Kahil Formation and can be more than 300 m thick (see Table 1). The Upper Beit Kahil Formation is a hard karstic limestone. The aquifer has marl layers up to 30 m thick within it. The Lower Beit Kahil Formation comprises dolomite and limestone. The top of the formation is probably

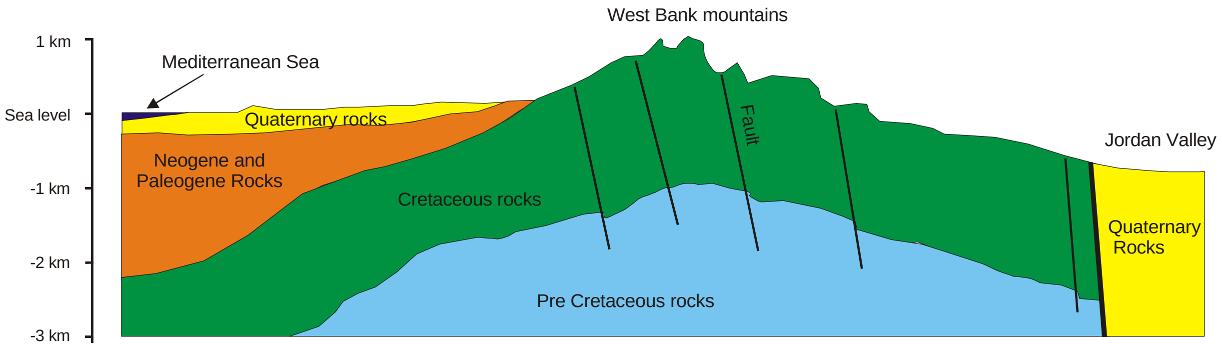

Figure 2 **Schematic cross section of the main rock units from the Mediterranean sea to the Jordan Valley.**

Table 1 Geological succession and hydrogeological significance for the West Bank. (Sources: SUSMAQ 2001; EXACT 1998).

Age		Typical Lithoogy	Formation (Palestinian)	Formation (Israeli)	Thickness (m)	Hydrogeology	Occurrence
Quaternary	Pleistocene	Alluvium, gravels and debris deposits	Recent	Alluvium	0-100	Valley aquifer	Eastern Basin
		Marl and gypsum	Lisan	Lisan	Unknown	Aquitard	Eastern Basin
Neogene	Pliocene Miocene	Conglomerate	Beida	Saqiye	200?	Beida aquifer	Eastern & NE Basin
Paleogene	Eocene	Limestone and Chalk (highly karstic)	Jenin	Avedat	300 - 600	Jenin aquifer	Eastern & NE Basin
Cretaceous	Senonian	Chalk with chert, some conglomerate	Abu Dis	Menuha	200 - 450	Aquitard	All Basins
	Turonian	Limestone/dolomite (karstic)	Jerusalem	Bina, Weradim	40 - 150	Upper Aquifer	All Basins
	Cenomanian	Limestone with dolomite and chalk	Bethlehem	Kefar Sh'ul	30 - 115		
		Limestone/dolomite (karstic)	Hebron	Aminadav	105 - 260		
	???	Clay/marl and limestone/dolomite	Yatta	Moza, Beit Meir	50 - 150	Aquitard	All Basins
	Albian	Limestone/dolomite with interbedded marl	Upper Beit Kahil	Kesalon, Soreq	60 - 190	Lower Aquifer	All Basins
		Limestone/dolomite (karstic)	Lower Beit Kahil	Giv'at Ye'rim, Kefira	110 - 210		
		Marl and clay	Qatana	Qatana	40 - 60	Aquitard	All Basins
		Marls and limestone	Ein Qinya	Ein Qinya	70 - 100		
	Aptian	Marl and clay	Tammun		50 - 90		
	Neocamian	Sandstone	Ramali		50 - 250	Ramali aquifer	Uncertain

karstified. Groundwater flow within the lower aquifer is through joints and fractures. The karstified layers at the top of the two formations will probably form rapid routes for groundwater flow.

The two aquifers are separated by the Yatta formation. This ranges from 50 to 150 m thick and comprises marls and clays with some chalk and limestone. The formation does not keep the two aquifers completely separate. There are many faults and fractures which cut through it. Sometimes the presence of these faults mean that the upper and lower aquifers are in direct contact.

Quaternary deposits, such as gravels in the Jordan valley and the coastal plain, are also important aquifers. In the north of the West Bank a thick chalk layer of Eocene age forms an important aquifer. Since these aquifers are not widespread, they are discussed separately in the sections describing the individual basins. Historically, the West Bank has been divided into three distinct groundwater provinces according to the direction of groundwater flow: the Western basin, Eastern Basin and NE Basin (Figure 3). Each basin is discussed individually in the next three sections.

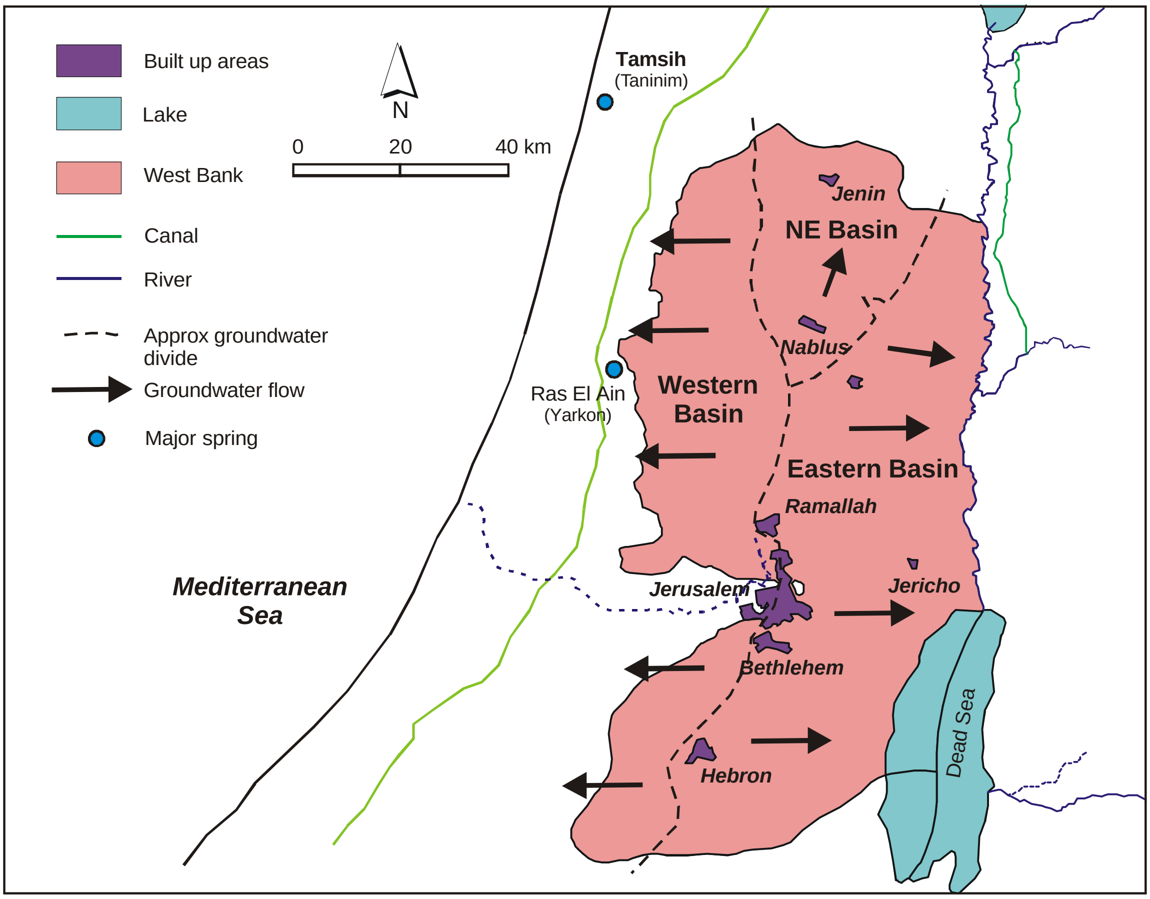

Figure 3 **Groundwater flow and basins in the West Bank.**

3 Western basin

Figure 4 shows a schematic cross section across the western basin. This basin is made up of the western part of the West Bank anticline. Groundwater in this area flows westward towards the Mediterranean. Prior to exploitation, most of the groundwater in this basin discharged through two major springs: the Ras El Ain (Yarkon) and Tamsih (Taninim). The two main aquifers in the Western Basin are the upper and lower aquifers of the Cretaceous mountain aquifer. Their characteristics are discussed in the previous section.

The upper and lower aquifers outcrop over the high ground of the West Bank (Figure 4). This is where the aquifers are recharged. Recharge occurs both through steady piston flow from the soil to the water-table, and also rapidly, through fractures in the limestones. Some studies suggest that water can reach the water-table within one year. In this area there may be downward leakage of groundwater from the upper to the lower aquifer.

Further west, the upper and lower aquifers are overlain by low permeability rocks which effectively confine the aquifers. The aquifers are therefore cut off from sources of recharge and contamination. In this region the groundwater is stored under pressure in the aquifers and will rise up and become artesian in some boreholes. Here groundwater is likely to move from the lower to the upper aquifer.

Further towards the Mediterranean, the upper and lower aquifers change to clay and chalks. The permeability of the aquifer is dramatically reduced and groundwater flow westward is limited. Much of the groundwater discharges through boreholes and major springs. The coastal aquifer is present at shallow depths on the fringes of the Mediterranean. This comprises gravels and shelly

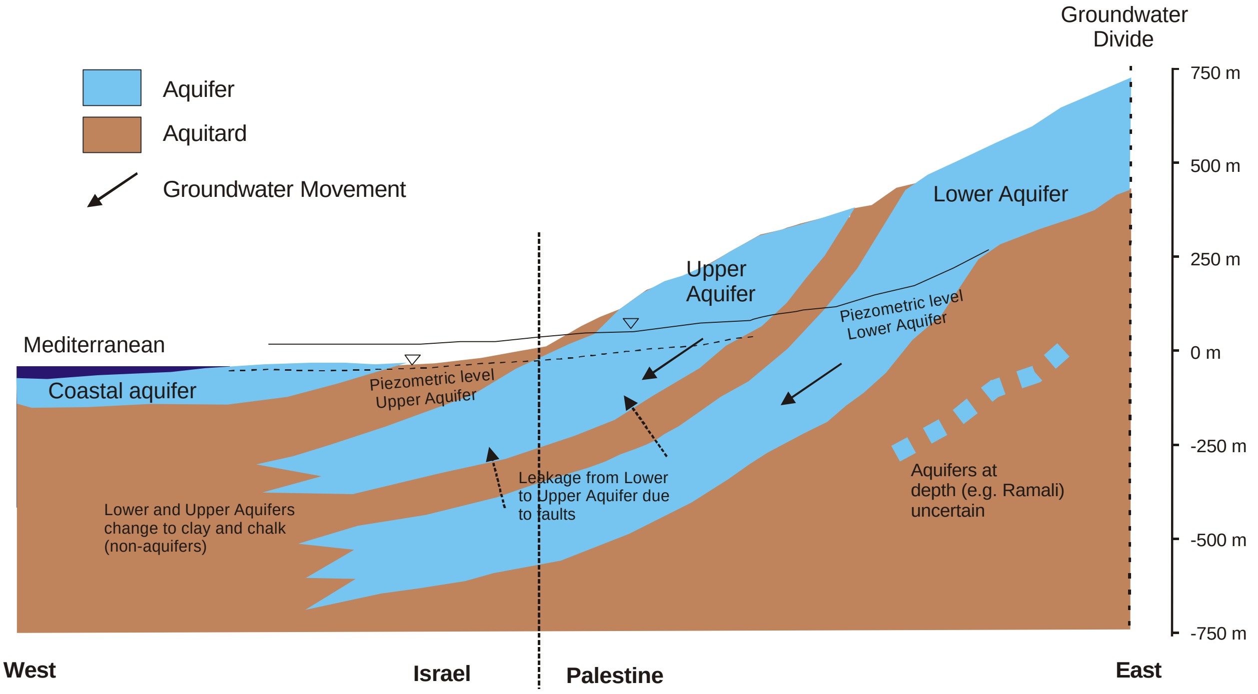

Figure 4 Schematic cross section of the Western Aquifer.

limestones and is used extensively as an aquifer in Israel and Gaza. The connection between the upper and lower mountain aquifer and coastal aquifer is unclear, but it is unlikely that it is significant.

There may be rocks below the lower aquifer that contain usable groundwater. Approximately 200 m below the Lower Aquifer is a thick band of sandstone, known as the Ramali Sandstone. This has not been utilised or investigated as an aquifer – it is so deep that even exploration is expensive. Therefore the extent, nature and quality of groundwater is uncertain.

The quality of the groundwater changes from the mountains to the coastal plain. In the mountains the water is fresh with chloride concentrations less than 100 mgl^{-1}. In the foothills region the chloride concentration is generally 100 – 250 mgl^{-1}, which increases towards the Mediterranean. In the foothills the lower aquifer is thought to have significantly lower salinity than the upper aquifer.

Most boreholes in the Western Basin have been drilled in the foothills on either side of the green line, although there are many more in Israel than Palestine. Pumping costs are lower here (since water-levels are shallow) and the supply is likely to be more reliable than in the mountain area where the aquifer is unconfined. There are two major springs in the basin, the Ras El Ain (Yarkon) and Tamsih (Taninim). Their flow is highly dependent on recharge and abstraction in the rest of the basin.

4 Eastern basin

Figure 5 shows a schematic cross section across the eastern aquifer. Groundwater in this basin flows eastward to the Jordan valley. The basin is separated from the western basin by a groundwater divide along the axis of the mountain. In some places the divide is a more definite physical boundary caused by the low permeability rocks pushing upwards in the core of the mountains (see Figure 5). The main aquifers in the Eastern Basin are again the upper and lower mountain aquifers; the valley aquifer in the Jordan valley is also an important source of water.

The upper and lower aquifers in the eastern basin are not as good aquifers as they are in the western basin. Recharge to the aquifers is lower and the aquifer properties (such as permeability and storage) are not as favourable. All of the recharge occurs in the mountains in the west of the basin and flows eastward. The upper aquifer is unconfined throughout much of the eastern Basin; water-levels can vary significantly throughout the year, and parts of the upper aquifer can be completely dry. Groundwater is more reliable in the lower aquifer. The two aquifers are connected by faults (see previous section) and groundwater flows from the upper to the lower aquifer. The upper and lower aquifers are cut off by a large fault in the Jordan valley. The presence of this fault forces groundwater to discharge as springs or leak into the shallow valley aquifer.

The quality of water from the upper and lower aquifers is the most important issue in the eastern basin. Although groundwater is fresh in the mountains, it rapidly becomes more saline towards the Jordan valley. In the Jordan valley, chloride concentrations are generally in excess of 200 mgl^{-1} and often in excess of 500 mgl^{-1}. Elevated nitrate concentrations and pathogen contamination may also be a problem around small springs.

The valley aquifer in the Jordan valley comprises gravels and alluvium. This is an important aquifer in the Jericho area and supports many boreholes. There is little direct recharge to this aquifer and the groundwater is replenished with flow from the upper and lower aquifers. Alluvium is also present in the main wadis and contains locally important groundwater resources.

There are many springs throughout the eastern basin. Freshwater springs are located in the mountains, for example around Hebron. There are also high yielding saline springs (chloride 500 – 2000 mgl^{-1}) towards the Dead Sea. Most of the boreholes in the basin are drilled into the lower aquifer. These are generally located in the south of the West Bank in the Jerusalem and Jericho areas. Small boreholes exploit the valley aquifer and also other alluvial deposits in the main wadis.

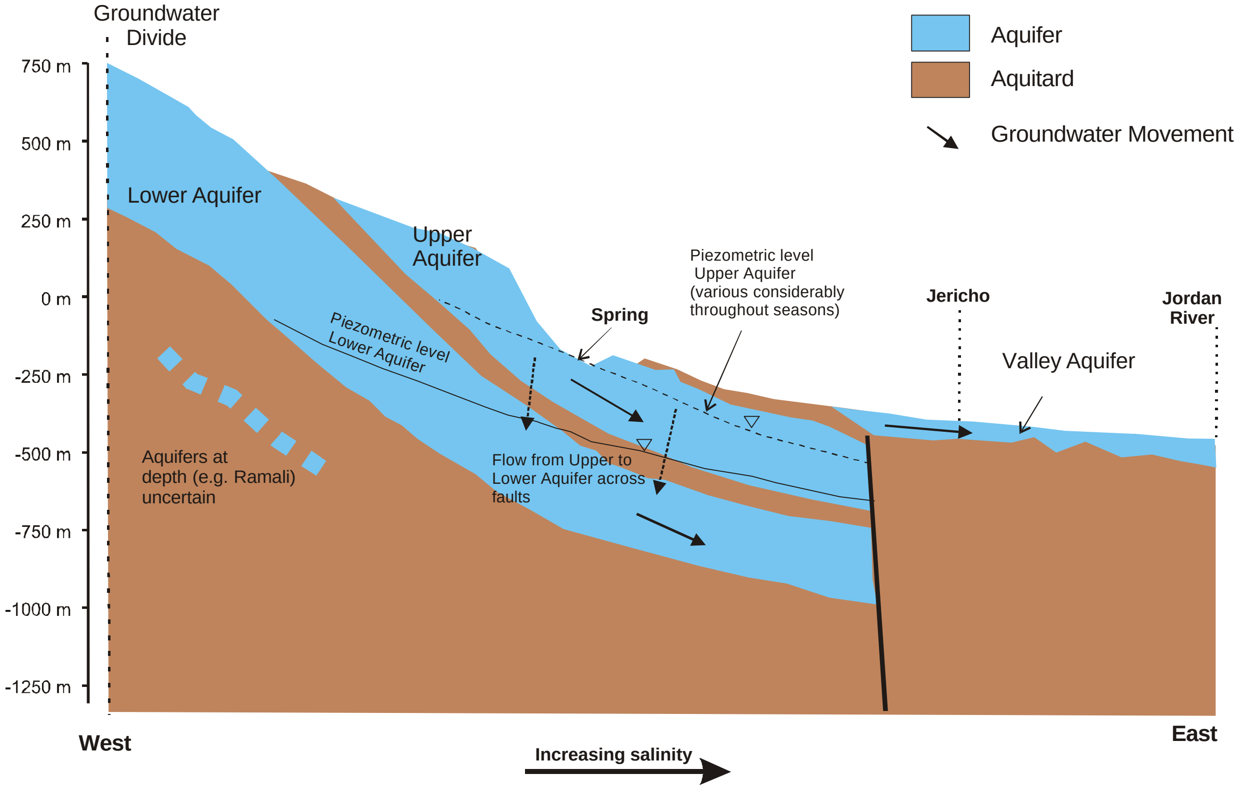

Figure 5 Schematic cross section of groundwater in the eastern basin.

5 North-eastern basin

Figure 6 shows a schematic cross section of the northeastern Basin. This is the smallest groundwater basin, and is sometimes included as part of the eastern Basin. Groundwater flows northward. There are two different aquifer systems: the Jenin aquifer and the upper and lower aquifers of the mountain aquifer.

The Jenin aquifer is shallow and unconfined. It comprises a multilayered series, with limestones and chalks and some highly karstified reef limestones. The aquifer is recharged from rainfall over its outcrop. The water-table can be shallow (10s of metres rather than 100s) and there are many springs – particularly in the foothills region. The aquifer properties are not consistently good. Although the karstic reef limestones can give high yields, borehole yields from the chalk layers can be low.

Irrigation boreholes have been drilled into the Jenin aquifer. Groundwater quality is generally good. In the mountain areas the salinity is low (chloride < 150 mgl^{-1}). Away from the mountains and foothills however, the salinity of the groundwater increases and has shown signs of worsening with time. Nitrate concentrations in excess of 50 mgl^{-1} NO_3 have also been recorded in some areas.

The upper and lower mountain aquifers in the northeastern basin are similar to that throughout the rest of the West Bank. The two aquifers are separated by an inconsistent aquitard, and groundwater flows from outcrops in the mountain area (not shown in the cross section) to the valleys. There may also be leakage from the Jenin aquifer.

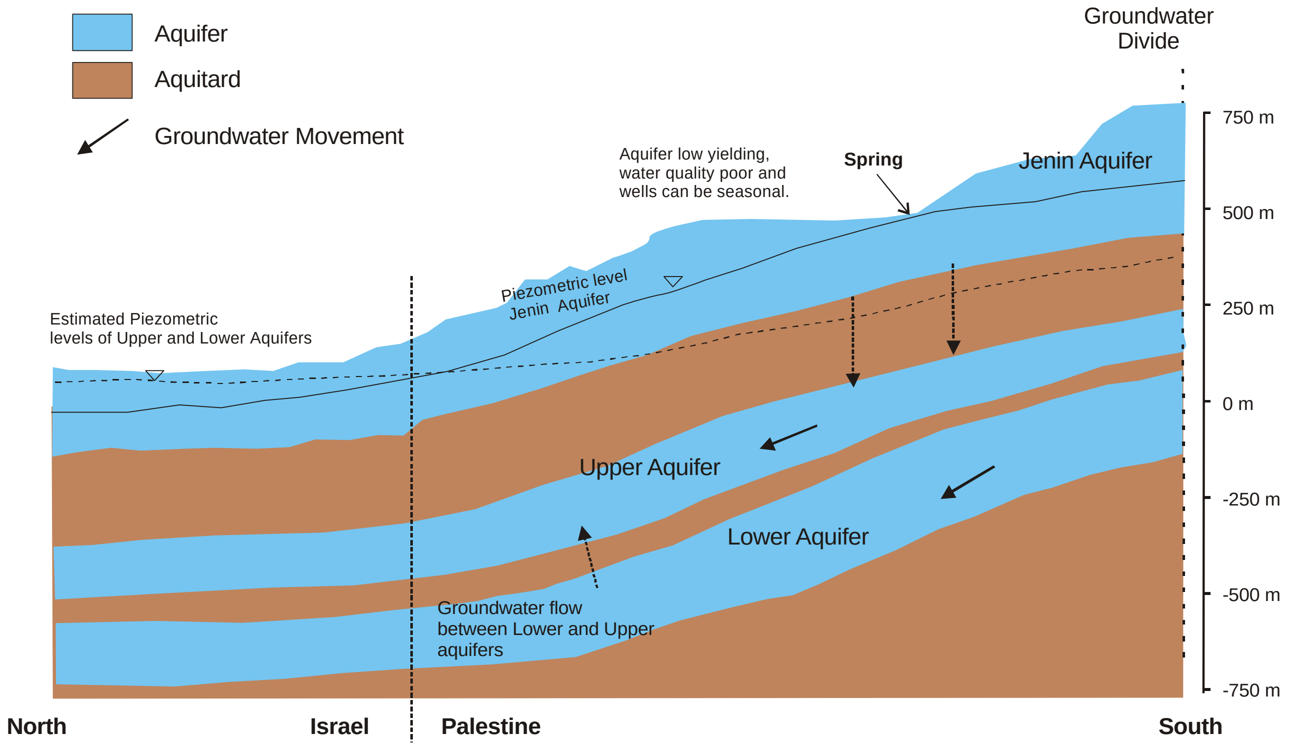

Figure 6 **Schematic cross section of the north-eastern basin.**

6 A rough water balance

Data on recharge and abstraction are being generated as part of this project, therefore any estimates at the present are preliminary and will be subject to revision. Table 2 gives an indication of water abstracted in each groundwater basin. The total abstraction has been given for each basin, not only that for within the West Bank. The Israeli abstraction has been separated from the Palestinian. Various data sources have been used including PWA databases and summaries from the Hydrological Service of Israel (1999). Recharge estimates are from various published sources and have not been made by this project. This project will eventually produce new, more reliable, recharge figures for the West Bank.

Abstraction has been taken as an average over 20 years (or the longest period available if the record is shorter than 20 years). This smoothes short term deviations and increases. For example, Israeli abstraction from the western aquifer has been estimated as 570 mcm for the hydrological year 1998/99.

Table 2 Long-term (generally 20 years) abstraction and recharge estimates for the West Bank aquifers.

Western Basin **(million cubic metres per annum)**

Recharge 318 - 366[e]

	PAL		*ISR in West Bank*		*ISR outside West Bank*		*Total*	
	Borehole	*Spring*	*Borehole*	*Spring*	*Borehole*	*Spring*	*Borehole*	*Spring*
Agriculture	15.5[a]							
Domestic	5.8[a]							
Total	21.3	2.4[b]	2.1[a]	0[b]	330[c]	5 (45)[c]	353.4	52.4
Total	**23.7**		**2.1**		**380**		**406**	

North-eastern **(million cubic metres per annum)**

Recharge 145[e]

	PAL		*ISR in West Bank*		*ISR outside West Bank*		*Total*	
	Borehole	*Spring*	*Borehole*	*Spring*	*Borehole*	*Spring*	*Borehole*	*Spring*
Agriculture	6.6[a]							
Domestic	9.2[a]							
Total	15.8	16.8[b]	10.4[a]	0[b]	53[d]	(81)[d]	79.2	97.8
Total	**32.6**		**10.4**		**134**		**177**	

proportion of fresh to saline unclear

Eastern Basin **(million cubic metres per annum)**

Recharge 118 - 197[e]

	PAL		*ISR in West Bank*		*ISR outside West Bank*		*Total*	
	Borehole	*Spring*	*Borehole*	*Spring*	*Borehole*	*Spring*	*Borehole*	*Spring*
Agriculture	12.3[a]							
Domestic	12.6[a]							
Total	24.9	44.8[b]	31.3[a]	(88)[d]		(9)[d]	56.2	141.8
Total	**69.7**		**119.3**		**9**		**198**	

Notes

[a] Data from PWA borehole database, average from 1980-1999

[b] Data from PWA spring database, average from 1980-1999

[c] Data from HSI summary 1999, average from 1980-1998

[d] Quoted in SUSMAQ (2001) data from HSI sources 1988-1999, monitoring and modelling

[e] From various sources, reviewed in McKenzie et al. (2001)

Figures in brackets denote saline water

Table 3 Abstraction from boreholes (million cubic metres per annum) in the West Bank according to aquifer. Average for 1980 – 1999. Data from PWA borehole database.

Aquifer	*Domestic*	*Agricultural*	*Israeli*
Valley Aquifer	0.2	7.4	0
Beida Aquifer	0	2.5	0
Jenin Aquifer	1.3	8.2	0.1
Upper Aquifer	15	16.3	12
Lower Aquifer	11.4	0.1	31.6
Total	**27.9**	**34.5**	**43.7**

Abstraction data has also been interpreted for the individual aquifers within the West Bank (Table 3). The data is only available for the outcrop of aquifers within the West Bank, so takes no account of abstraction from the same aquifer in Israel.

7 Summary of issues in the West Bank

The hydrogeology of the West Bank is complex. The specific groundwater conditions of the West Bank have implications for the management of the aquifer. The main issues are described below.

1. The aquifers are karstic. Groundwater flows through fractures within the aquifers and in some places can flow rapidly through conduits that have been enlarged by dissolution (see Figure 7). Water and contaminants can therefore move quickly from the ground surface to the aquifer and then to boreholes and springs.
2. The aquifers are deep throughout much of the West Bank. To penetrate the lower and upper mountain aquifers requires deep expensive boreholes, often to a depth of greater than 500 m.
3. Boreholes drilled away from the mountains (i.e. towards the greenline in the western basin) are likely to have shallower water-levels and more reliable supplies (since there are fewer fluctuations in water-table).
4. The aquifers may rely on relatively recent recharge. Since they are karstic, the storage within the aquifers is low. Reliable recharge is required to sustain the groundwater resources. This project is studying residence times of groundwater.
5. Groundwater abstracted from boreholes is often at the expense of spring flow. This is seen most dramatically in the yield of the two large springs, but is also important for smaller local springs.
6. Groundwater quality tends to deteriorate (mainly increased chloride) away from the central mountains. This is most marked in the Jordan valley, where the groundwater can be unusable.

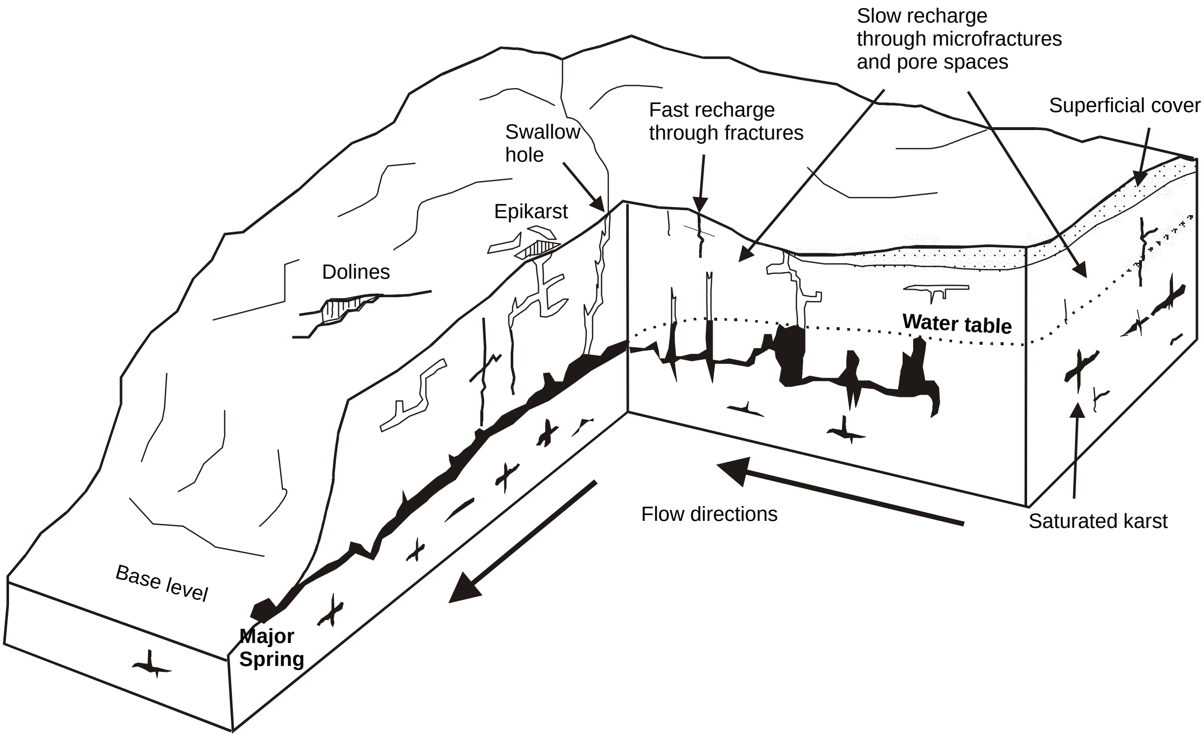

Figure 7 Some of the important features of karst environments.

Glossary

Alluvium	sand, gravels and clays deposited by river flow.
Anticline	A fold with strata sloping downward on both sides from a common crest (i.e. rocks that are folded into an “n” shape).
Anticlinorium	a composite fold structure of great extent consisting of a series of minor folds and having the form of an **anticline**.
Aquifer	a rock formation that contains sufficient groundwater to be useful for water supply.
Aquitard	a rock formation that has low **permeability** and hinders the movement of groundwater.
Artesian	when a borehole naturally overflows (i.e. the **piezometric level** is higher than the ground surface).
By-pass flow	water that rapidly flows to the **water-table** by flowing through fractures and by-passing pores.
Chalk	A type of **limestone** made up of skeletal debris of microscopic ocean plants and animals.
Chert	Micro crystalline silica deposits, very similar to flint. They can occur as nodules or sometimes in layers.
Confined aquifer	an **aquifer** where the water is stored under pressure. This occurs because the aquifer is overlain by an **aquitard**.
Dolomite	A sedimentary rock composed of calcium and magnesium carbonates ($Ca Mg[CO_3]$). Generally of organic origin.
Fault	A break or rupture in rock, along which there is movement
Gypsum	A common mineral in **limestones** and mudstones made up of calcium sulphate ($CaSO_4.2H_2O$). Can often make groundwater highly mineralised.
Joint	A break or rupture in rock along which there is no movement
Karst	The result of erosion on **limestone** which gives rise to dissolution enhanced channels and caves leading to rapid groundwater flow.
Limestone	a sedimentary rock composed largely of calcite ($CaCO_3$) generally from the remains of organic material.
Marl	A clay that has some calcareous material present, such as shell fragments etc.
Mudstone	A sedimentary rock made from particles of clay. This has low **permeability**.
Permeability	The ability of a rock to transmit fluids.
Piezometric level.	A way of expressing the pressure in a **confined aquifer**. It is the level that water would rise to in a borehole drilled into the confined aquifer.
Piston flow	The slow movement of water through pores in the soil and **unsaturated zone** to the **water-table**.
Rift valley	A valley associated with fracturing in which both sides of the valley are being pulled apart. Often accompanied by lava flows.

Sandstone	A sedimentary rock that is made of cemented sand grains – usually has high **permeability**.
Strike-Slip fault	A **fault** in which the movement is along the horizontal line (strike) of the **fault**.
Unconfined aquifer	an **aquifer** where water is not under pressure, generally because the aquifer is not overlain by an **aquitard.**
Unsaturated zone	The part of the aquifer above the **water-table** where the **aquifer** is not fully saturated.
Wadi	a steep sided valley in semi arid areas where stream flow is intermittent.
Water-table	The upper surface of the zone of saturated aquifer in an **unconfined aquifer**.

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