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Mapping groundwater development costs for the transboundary Western Aquifer Basin, Palestine/Israel

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Abstract

The costs of developing groundwater in the Western Aquifer Basin vary considerably across the West Bank and Israel. One of the main reasons for this variability is the diverse hydrogeological conditions within the aquifer. Using data from recent hydrogeological investigations, an estimate of the variation of both the drilling and pumping costs was calculated and then mapped across the Upper and Lower Aquifers within the Western Aquifer Basin. These *groundwater cost maps* proved helpful in analysing the impacts of hydrogeology on water supply, and also in communicating complex hydrogeological information to a broader audience. The maps clearly demonstrate that the most cost effective area to develop groundwater is along the Green Line – the 1949 armistice boundary between Israel and the Palestinian West Bank. Any migration of this boundary eastwards will increase the cost and feasibility of developing groundwater within Palestine, making abstraction from the Upper Aquifer impracticable, and increasing the cost of developing the Lower Aquifer. Therefore, the separation wall, which is being constructed to the east of the Armistice Line in Palestinian territory, will significantly reduce the ability of the Palestinians to develop groundwater resources.

Keywords: groundwater development, groundwater management, Israel, West Bank, socio-economic aspects

1. Introduction

The allocation of groundwater resources is a major source of contention between Israel and Palestine. The political situation has resulted in the hydrogeology of the region being discussed at the highest level in both countries. The Oslo Peace Process had recognised the difficulty of resolving water issues and left the discussions to be part of the final negotiations along with other issues, such as the status of Jerusalem. Further discussions of the role of water in the peace process are given by Shapland (1997), Allan (2001), Medzini and Wolf (2004), Aliewi and Assaf (2007), Zeitoun et al. (2009).

Most controversy surrounds the transboundary Western Aquifer Basin which straddles both the West Bank and Israel (see Figure 1). Groundwater is the main source of domestic, industrial and agricultural water in the West Bank. At present, groundwater abstraction is tightly controlled by the Israeli government, and relatively little water is abstracted by the Palestinians. As part of any lasting settlement, Palestine would hope to negotiate a more equitable share of the groundwater resources.

Given the high profile of groundwater issues in any negotiations, it is imperative that these resources are well understood and that this understanding is shared by those making key decisions on their management and allocation. In particular, decisions need to account for spatial variations in resource availability and access, as these conditions vary both between, and within, aquifers (PWA 2004).

One way of simplifying complex hydrogeological issues is to reduce the hydrogeological parameters to maps of the costs of developing and using groundwater – *groundwater cost maps*. Although groundwater is increasingly being considered and studied as an economic resource (e.g. Burke and Moench 2000; Koundouri 2004; Chermak et al. 2005) to the authors' knowledge, the approach of mapping groundwater costs has not been used elsewhere.

In this paper the relative costs of development across the transboundary Western Aquifer Basin have been estimated. The resulting maps of pumping costs, drilling and installation costs and annual development costs are not meant to be used as a detailed planning tool. Rather, the maps provide a way of illustrating information generated by groundwater models in a way that can highlight, for the non-specialist, the costs of different abstraction scenarios.

2. An introduction to the geology and hydrogeology of the Western Aquifer Basin

Groundwater, accessed either from springs or boreholes, is the primary source of freshwater available to people living in the West Bank. The water originates as rainfall falling on the mountains in the centre of the West Bank and then flows through the extensive aquifers away from the mountains. The groundwater is usually considered as occurring in three separate basins: the Western Basin, the Eastern Basin and the North-eastern Basin (Figure 1).

The rocks in the West Bank comprise a complex sequence of limestone, dolomite, chalk and marl. These rocks have been folded into a major anticline with its axis roughly coinciding with the mountains; numerous smaller faults and folds further complicate the structure. The Jordan Valley is a rift valley extending from the Red Sea and has been in-filled with up to 3 km of sediments. The main aquifers in the West Bank comprise limestones of Cretaceous age. These are often referred to collectively as the 'Mountain Aquifer' and subdivided into Upper and Lower Aquifers. The geology and hydrogeology of the system is discussed in more detail in PWA (2004) and in a series of reports from the SUSMAQ programme which examined the hydrogeology of the West Bank in considerable detail (SUSMAQ 2002; PWA 2004; Aliewi et al. 2005). A summary is given below.

Figure 2 shows a schematic cross section across the western part of the West Bank anticline. Groundwater in this area flows westward towards the Mediterranean Sea. Prior to exploitation, most of the groundwater in this basin discharged through two major springs, the Yarkon and Taninim. The three main aquifers are the Upper and Lower Aquifers of the Cretaceous Mountain Aquifer (which form the Western Aquifer Basin) and the Coastal Aquifer (which is usually treated separately as the Coastal Basin).

The Upper Aquifer comprises limestones, dolomites and chalk of the Jerusalem, Bethlehem and Hebron Formations. 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.

The Lower Aquifer comprises limestone and dolomite of the Upper and Lower Beit Kahil Formation and can be more than 300 m thick. 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 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 entirely hydraulically separate, due to the presence of many faults and fractures.

The Upper and Lower Aquifers crop out over the high ground of the West Bank where the aquifers are recharged (Figure 2). Recharge occurs by slow flow through pore spaces and micro fractures, and also rapidly, through fractures in the limestones. Some studies suggest that water can reach the water table within one year (Hughes et al. 2008).

Further west, the Upper and Lower Aquifers are overlain by low permeability rocks which effectively confine the aquifers. The aquifers are therefore protected from near surface sources of recharge and contamination. In this region the groundwater is artesian. Here groundwater is likely to move from the Lower to the Upper Aquifer.

Further towards the Mediterranean, the lithology of the Upper and Lower Aquifers changes to become more clay-rich and chalky. The permeability of both aquifers is dramatically reduced and westward groundwater flow 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 Sea. This comprises gravels and shelly limestones and is used extensively as a source of water in Israel and Gaza. The connection between the Upper and Lower Mountain Aquifers and Coastal Aquifer is unclear, but it is unlikely to be significant.

The chemistry of the groundwater is largely dominated by the geochemistry of the rocks and rainfall gradient across the West Bank. The waters are saturated with respect to calcite, and chloride concentrations increase from less than 100 mg/l in the mountains to between 100 and 250 mg/l in the coastal plain, related to decreasing rainfall. In the mountains the water is fresh with chloride concentrations less than 100 mg/l. Contamination of the Upper aquifer has occurred in the foothills due to poor sewerage coverage and intense agriculture.

3. Groundwater development in the Western Aquifer Basin

The average groundwater abstraction for the Western Aquifer Basin from 1980 to 1999 is shown in Table 1. Data have been taken from a variety of sources: The Israeli Hydrological Services year book (HSI 1999) and the Palestinian Water Authority spring and borehole databases (SUSMAQ 2002). Abstraction has been taken as an average over 20 years (or the longest period available if the record is shorter than 20 years), to smooth short-term variations. For example, Israeli abstraction from the Western Aquifer Basin has been estimated as 570 Mm^3 for the hydrological year 1998/99. Estimates of annual recharge for the Western Aquifer Basin range from 318 to 366 Mm^3 per year (Hughes et al. 2008).

Table 1. Average annual groundwater abstraction from the Western Aquifer Basin during the period 1980-1999. Figures are in million cubic metres per year (Mm^3).

	Palestinian abstraction in West Bank		**Israeli abstraction in West Bank**	**Israeli abstraction outside West Bank**		**Total**	
	Borehole	Spring	Borehole Spring	Borehole	Spring	Borehole	Spring
Agriculture	15.5[a]						
Domestic	5.8[a]						
Sub-total	21.4	2.4[b]	2.1[a]	330[c]	5 (45)[cd]	353.4	52.4

		0[b]		
Total	**23.7**	**2.1**	**380**	**405.8**

[a] Data from Palestinian Water Authority (PWA) borehole database

[b] Data from PWA Springs database

[c] Data from HSI (1999)

[d] Figures in brackets denote brackish water.

Table 1 illustrates that much of the abstraction from Upper and Lower Aquifers is from within Israel, on the western side of the 1949 Armistice Line. Only 6% of the average annual abstraction of 406 Mm^3 is from within the West Bank.

4. Groundwater costs mapping

4.1 Introduction

The West Bank is rugged and the depth to the water table varies considerably over short distances. This has a significant impact on both the cost of drilling new boreholes, and the costs of pumping water from them. It also influences the costs of reticulating water across the West Bank. The cost of supplying water can, therefore, be divided into three components:

- **Installation Costs** – the cost of drilling and installing a new borehole. This is dependent on the aquifer geometry, drilling and labour costs and specifications.
- **Pumping Costs** – the cost of pumping the water from the borehole to the ground surface. This is dependent on pump and borehole efficiencies, aquifer parameters, the depth to the water table and energy costs.
- **Reticulation Costs** – the price of transferring water from the borehole to the area of demand. This is dependent on factors such as the transfer route, topography and energy costs. Various models have been designed to predict costs, with some estimates for the West Bank provided by CH2MHILL (2002).

Given sufficient spatial data, maps can be generated for the variations in installation and pumping costs. Reticulation costs do not easily lend themselves to being portrayed on a map, since they are not fixed for a certain location, but depend on the route taken and starting and finish point. They are not considered further within this paper.

The development of a recharge model (Hughes et al. 2008), the creation of a hydrogeological map (PWA 2004), and the development of a detailed groundwater flow model for the Western Aquifer Basin (Aliewi et al. 2005) generated sufficient spatial data to estimate the variations in installation and pumping costs. The transient groundwater model was developed using MODFLOW after a considerable data gathering exercise on abstraction, water levels, geology and aquifer properties. The model was calibrated using long term groundwater-level monitoring data (Aliewi et al. 2005).

The input data for the model, rather than the model results, were mainly used to estimate the costs of installation and pumping. The resulting maps of variation in costs were termed *groundwater cost maps*. Some of the input data are shown in Figure 3.

4.2 Pumping costs

4.2.1 General

The costs of pumping groundwater to the ground surface are governed by the energy costs and the depth from which the water has to be pumped. The costs of pumping for one day are calculated using the equation,

$$Cost\ of\ pumping = \frac{C\rho\, g\, Q}{E} h_{total} \qquad [1]$$

Where:

Q = abstraction rate

C = cost of power

ρ = density of water

g = acceleration due to gravity

h_o = depth to rest water level

E = efficiency of the pump motor

It is not the purpose of this paper to carry out detailed research on the variability of energy costs, so a fixed energy cost from 2000 is used – US$ 0.06 per kW hour (PEC 2005).

The height that the water has to be pumped (h_{total}) is governed by the rest water level in the borehole (h_o) and the drawdown in the borehole due to both aquifer loss ($s_{aquifer}$) and borehole loss ($s_{efficiency}$):

$$h_{total} = h_o + s_{aquifer} + s_{efficiency} \qquad [2]$$

Information on rest water levels (h_o) is available from survey data (e.g. the hydrogeological map of the West Bank (PWA 2004)). Groundwater models can also be used to help extrapolate individual measurements of rest water level across larger areas.

Drawdown in a borehole due to aquifer loss ($s_{aquifer}$) can be calculated from the analytical equations governing the behaviour of groundwater in response to pumping. Regional groundwater models do not give information on drawdown within individual boreholes, but are designed to show how regional groundwater levels are affected by pumping. Although a groundwater model could be modified to generate potential drawdown within a borehole, to do this at all locations on the surface of the model would be highly cumbersome and time consuming. Jacob's equation calculates the drawdown in an aquifer due to pumping at a certain time, and has been shown to accurately represent borehole behaviour at late times (e.g. Meier et al. 1998; Mathias and Butler 2006). Although the assumptions of anisotropic, homogeneous aquifer conditions, and a confined environment, are not strictly met throughout the Mountain Aquifer, they are common to most conventional models and well analysis. Conventional techniques have been shown to be valid in fractured environments so long as the borehole penetrates a representative volume of aquifer (Snow 1968) and drawdown is limited to ensure that groundwater flow is mostly horizontal.

Drawdown due to borehole inefficiency ($s_{efficiency}$) is dependant on cQ^2, where c is a constant given by the design of each individual borehole, and Q is the pumping rate of the borehole.

Jacob's equation for calculating aquifer drawdown, and the quadratic term for estimating drawdown due to well efficiency can then be substituted into Equation 2.

$$h_{total} = h_o + \frac{2.3Q}{4\pi T}\log_{10}\left(\frac{2.25Tt}{r^2 S}\right) + cQ^2 \qquad [3]$$

h_o = depth to rest water level

T = transmissivity

t = time since pumping started

S = aquifer storage coefficient

r = radius from pumping borehole (approximated as borehole radius for pumping boreholes)

Q = pumping rate

c = well efficiency constant.

For a borehole of a specific design and pumping rate, the only variables affecting h_{total}, are h_o, T and S, with T and h_o the dominant factors. Notably, the well efficiency factor becomes a constant.

Substituting [3] into [1] gives:

$$Cost\ of\ pumping = \frac{C\rho gQ}{E}\left[h_o + \frac{2.3Q}{4\pi T}\log_{10}\left(\frac{2.25Tt}{r^2 S}\right) + cQ^2\right] \qquad [4]$$

4.2.2 Application to the Western Aquifer Basin

Most of the parameters in Equation 4 are either known or can be estimated for the Western Aquifer Basin from the input data to the detailed hydrogeological modelling carried out by the Palestinian Water Authority and Newcastle University as part of the SUSMAQ programme. Information on the setup and calibration of this MODFLOW model are given in Aliewi et al. (2005).

Separate maps of pumping costs across the Western Aquifer Basin were developed for the Upper and Lower aquifers. The variables h_o, T and S were taken from the SUSMAQ groundwater model (Aliewi et al. 2005). Several assumptions were made:

- For the purpose of this study a time of one year was used since pumping started and r was assumed to be 0.15 m (the calculations are relatively insensitive to time and radius).

- A condition was put on the calculation that at the end of one year's pumping the saturated aquifer should be greater than 50 m thick, to stop the aquifer dewatering.

- The efficiency of the borehole and the pump were assumed to be each approximately 75%, which is reasonable for the type of borehole and pumps used in the region (Driscoll 1986).

- The maps were based on a pumping rate of 1 Mm^3 per year from an individual borehole, which again is reasonable for boreholes drilled into the Western Aquifer (PWA 2000, Aliewi et al. 2005; Zeitoun et al. 2009).

- The calculations assume no interference between boreholes. This is reasonable since the maps are designed to show the *relative* costs of developing groundwater in different parts of the aquifer, not the detail of individual boreholes or well fields. To account for interference the groundwater model would have to be re-run for each scenario.

The resulting map of pumping costs for the Upper and Lower aquifer are shown in Figures 4 and 5. Pumping costs reduce to the west, since water levels are shallower in this area (see Figure 2) and transmissivity also increases. The pattern is broadly similar for the Upper and Lower aquifers.

4.3 Installation (capital) costs

The costs of drilling and constructing boreholes in the region are high. This is due to a number of factors:

- The depth of the boreholes is generally greater than 200 m and can be up to 800 m. The cost of screen and casing for such deep boreholes is therefore high: good quality materials must be used to withstand the pressures and the diameter of the borehole must be large, typically greater than 300 mm.

- The drilling conditions are difficult. The great depth of the boreholes introduces many difficulties and means that high capacity drilling systems must be used. The aquifers are karstic and high yielding, with the corresponding problems of circulation loss and collapse. Hence, expensive drilling methods must be used, with contingencies made for potential problems

- The insecurity in the region adds significantly to the costs.

The costs of drilling and completing groundwater sources at a variety of locations in the West Bank were comprehensively assessed by the Palestinian Water Authority in 1999 as part of the Palestinian National Water Plan (PWA 2000). This plan comprised fully costed capital projects for the West Bank. Typical public construction costs for public water supply borehole with pump and headworks comprised a fixed capital cost of US$ 500 000 for each borehole, plus a cost of US$ 1500 per metre drilled. Similar costs were encountered by CH2MHILL when drilling 11 production boreholes in the Eastern Aquifer Basin.

Figures 4 and 5 show maps of the relative drilling costs across the Upper and Lower Aquifers. The boreholes are assumed to be drilled 200 m below the top of the aquifer or to the base of the aquifer if the saturated thickness is less than 200 m thick. Note that the costs are generally high – in excess of high of US$0.75 million per completed public water supply borehole. Drilling costs increase to the west as the aquifers became deeper, and are greatest for the Lower aquifer, since it lies at a greater depth below ground surface.

4.4 Groundwater development costs

To produce a map of the relative groundwater development costs across the Western Aquifer Basin, the capital costs from drilling must be combined with the ongoing pumping costs to give an estimated annual cost. Costs were estimated for the year 2000, which is when most of the data were available from.

Annual capital repayment, labour and maintenance costs were taken to be 9% of the total drilling and installation costs estimated earlier. This proportion was estimated by annualising the capital costs, and estimating ongoing labour and maintenance costs from the detailed information provided in the Palestinian National Water Plan (PWA 2000). The method used for converting capital costs to an annual sum was to assume that the length of life of the installation is 25 years, and the cost of borrowing is a real rate of interest of 3%. This converts to an annual charge of approximately 6% (i.e. each 1000 US$ of capital will cost 57.50 US$ per year). Labour and maintenance costs were taken from the detailed information provided in the Palestinian National Water Plan (PWA 2000), which estimated labour and maintenance to be approximately 2.5 - 3% of the total capital cost. Given contingencies and a margin for error, 9% of total capital cost is considered a reasonable annual proportion to cover capital repayment, labour and maintenance costs.

For ease of comparison, annual energy costs were assumed to be only the pumping costs (i.e. no reticulation costs were included). The costs were standardised to the cost of abstracting one million cubic metres (Mm^3) per year from a source, and are given in US$ at year 2000 prices.

The resulting estimates of groundwater development costs for the Upper and Lower aquifers are shown in Figures 4 and 5.

5. Discussion

5.1 Costs of groundwater development in Western Aquifer

Using the hydrogeological information gathered by Aliewi et al. (2005) and interpreting it as groundwater development costs allows the transboundary aquifer to be viewed in a different light. Costs of development (at 2000 prices) vary from less than 0.1 US$ per cubic metre to over 0.3 US$ per cubic metre, prior to reticulation. There are also areas of the aquifer that cannot be exploited – either because the aquifer is dry, or because the drawdown in the boreholes would be too great for them to support a useful yield. The spatial variation of the costs of groundwater development across the Western Aquifer Basin is highly instructive. The resulting maps show a clear pattern:

- Groundwater development from both the Upper and Lower aquifers is most economic in a narrow zone around the 1949 Armistice Line in the northern part of the West Bank. Costs significantly increase with distance from the Armistice Line. This is a fact not lost on those developing the aquifer – this is where most of the operational boreholes are located.
- There are areas of the Upper Aquifer which cannot be properly developed. In fact, only a small area around Qalqilya and Tulkarem can be developed economically. Any slight eastern migration of the Palestinian border will have a serious effect on the ability of the Palestinians to develop this aquifer. The separation wall, which is being built to the east of the Armistice Line in

Palestinian territory, will therefore significantly reduce the ability of the Palestinians to develop groundwater resources in the Western Aquifer Basin.

- There is greater potential to develop the Lower aquifer than the Upper aquifer within the West Bank. However pumping costs significantly increase with distance from the Armistice Line. Although not discussed here, the supply may also be less reliable further east in the Lower Aquifer (Calow et al. 2003).

5.2 The usefulness of groundwater cost maps

Groundwater cost maps can potentially communicate complex hydrogeological issues to a much broader audience. The maps developed for the Western Aquifer proved very useful as the basis for discussions with social and political scientists, as well as for communicating with politicians in the West Bank. Costs are a much easier concept to grasp than transmissivity, or even water levels. The maps developed for the Western Aquifer engaged, and even animated, non-hydrogeologists in discussions about the aquifer. Similar maps could prove useful in other situations, particularly where hydrogeological conditions vary significantly across an aquifer.

Groundwater cost maps must be used appropriately, however, as they are necessarily a simplification of the hydrogeology, engineering and economics. They are best used to show *relative* changes, rather than absolute costs, and are no substitute for detailed financial planning. Developing the maps was also fairly data intensive: it required good spatial data on hydrogeology, and drew from a detailed financial planning exercise for the water sector for some of the economic information. However, the hydrogeological information is no more than normally required for a groundwater model or hydrogeological map, and the economic information should be available within the planning department of most water authorities.

To show the information on a map, various information were assumed constant, e.g. pumping rate and well efficiency, and the costs of reticulation were omitted altogether. Any future development of these maps that includes variation in these factors would require an interactive map, where it is possible to estimate the reticulation costs between two points, vary pumping rates and well efficiencies, and use designs of boreholes with different capital costs per metre.

Conclusions

Generating groundwater development cost maps from hydrogeological data collated for constructing a numerical model and financial data from a national water plan has proved relatively straightforward. The resulting maps allow the impact of spatial variations in hydrogeological properties to be simply understood and easily displayed. Such an approach could be applied to other aquifers to help demonstrate the effect of hydrogeology on the costs of accessing water resources.

For the transboundary Western Aquifer Basin, the cost maps indicate that groundwater development excluding reticulation will cost more than approximately 0.1 US$ per cubic metre (at 2000 prices) at the optimum locations in the aquifer, rising to more than 3 times this in other locations in the aquifer. Groundwater development from both the Upper and Lower Aquifers is most economic in a narrow zone around the 1949 Armistice Line in the northern part of the West Bank. Costs significantly increase with distance from the Armistice Line. Therefore, the separation wall, which is being built to the east of the Armistice Line in Palestinian territory, will significantly reduce the ability of the Palestinians to develop groundwater resources in the Western Aquifer Basin.

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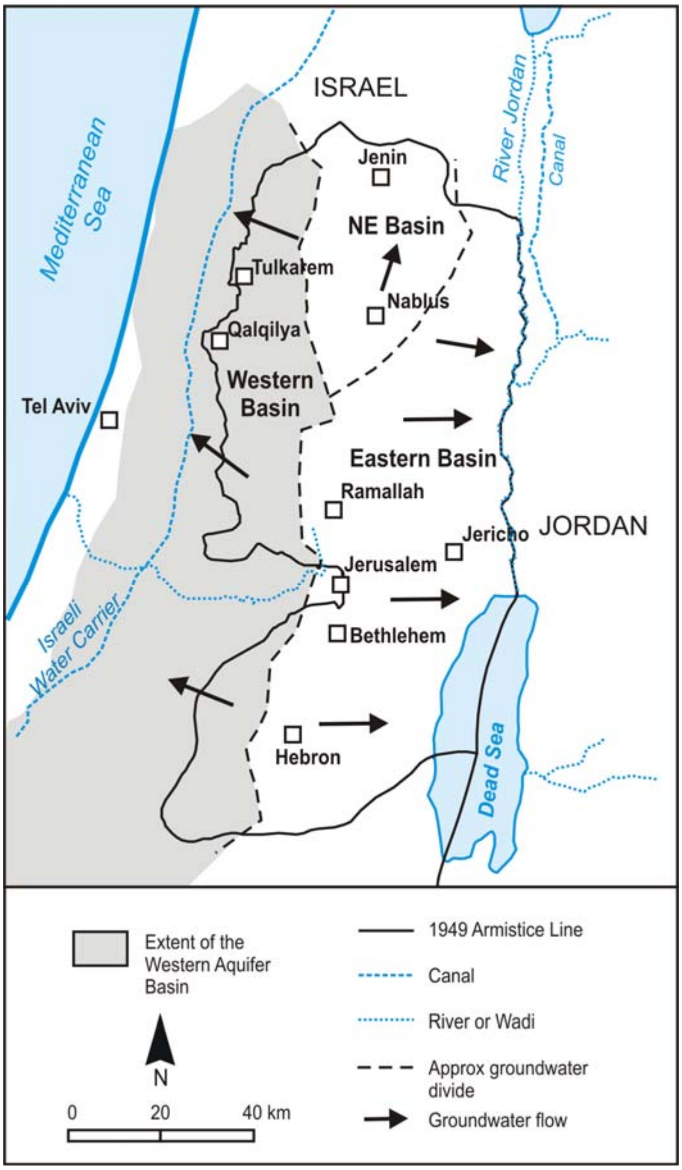

Figure 1 Groundwater basins in the West Bank and the outline of the Western Aquifer Basin

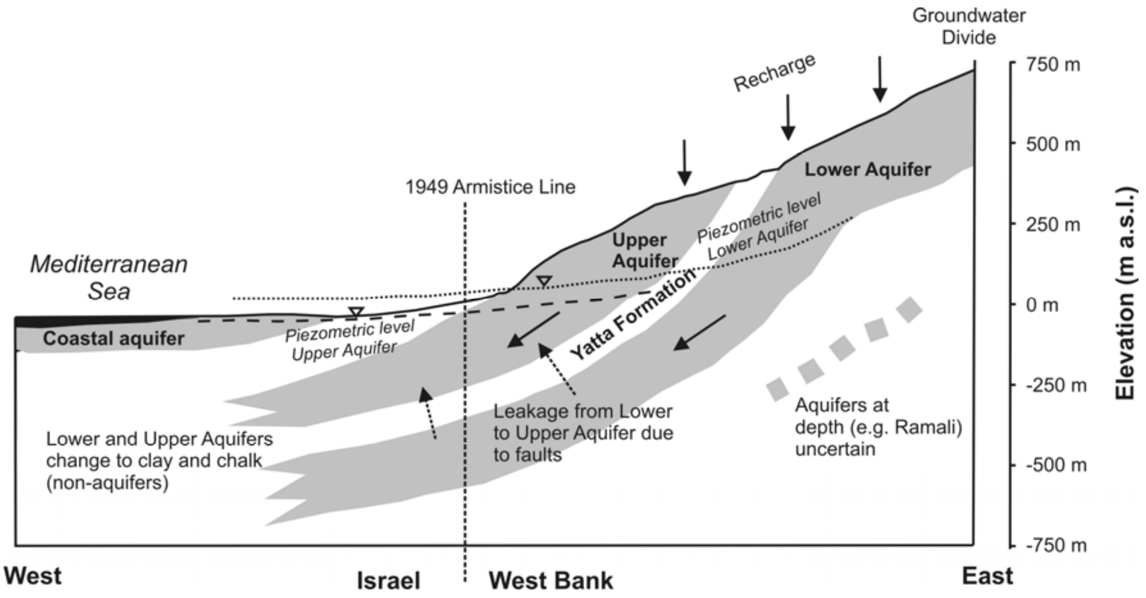

Figure 2 Schematic cross section of the Western Aquifer Basin from approximately Ramallah to Tel Aviv (see Figure 1). The Coastal Aquifer Basin is also shown

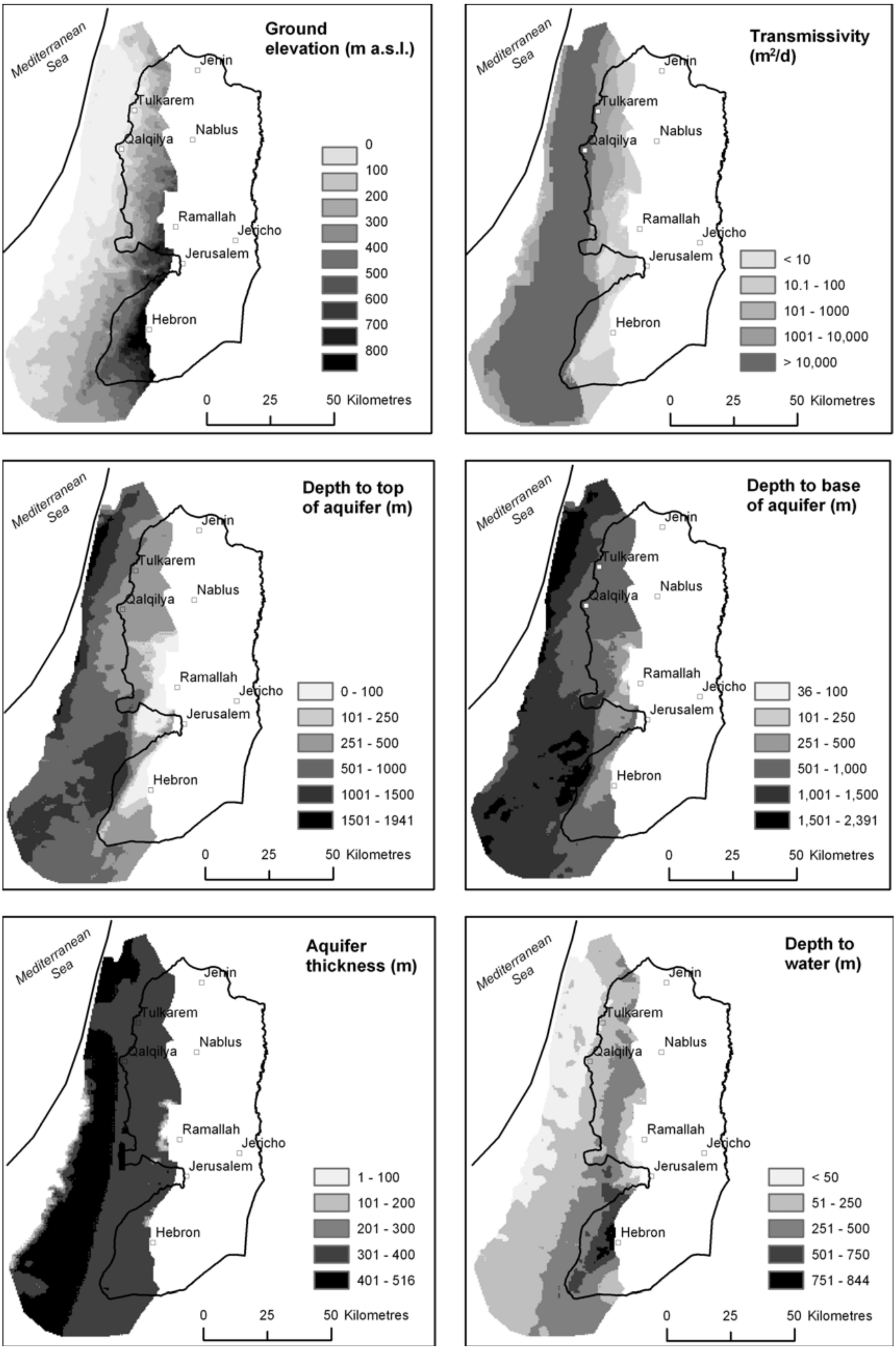

Figure 3 Some of the input data required to generate groundwater cost maps for the Lower Aquifer. The data are derived from input data to the groundwater flow model for the area

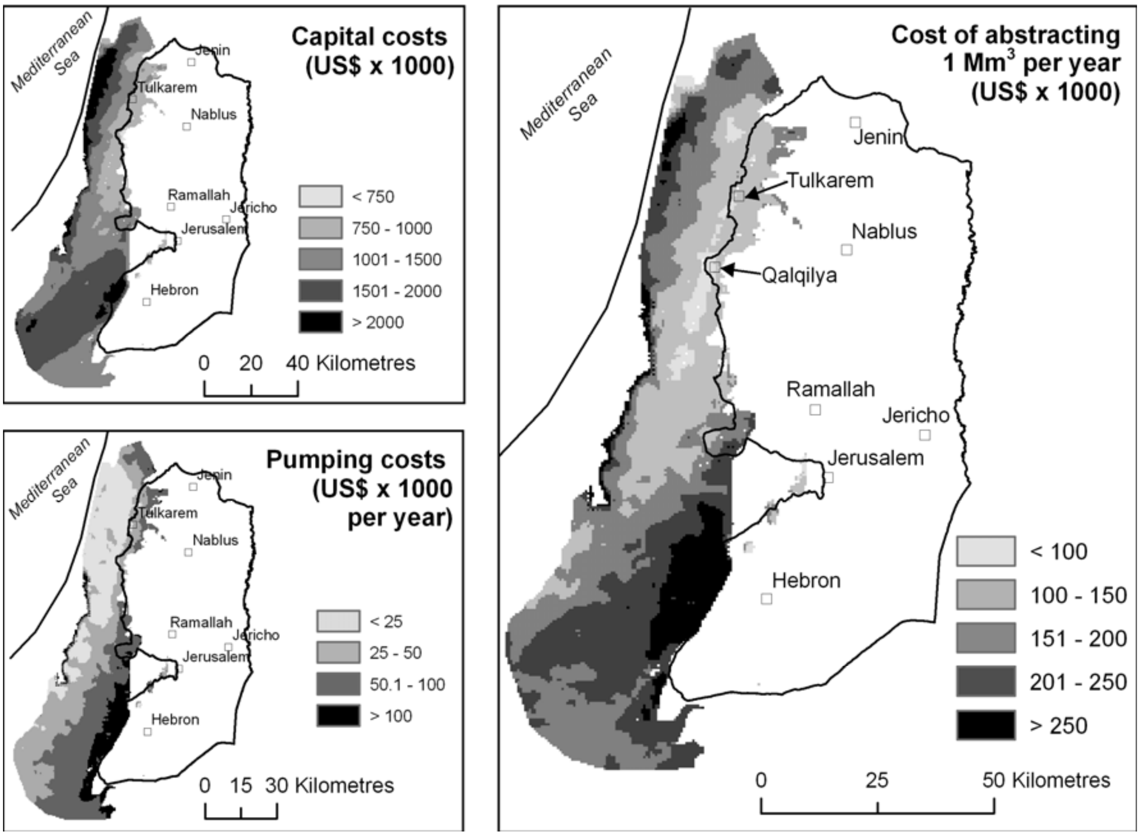

Figure 4 Groundwater development costs in the Upper Mountain Aquifer

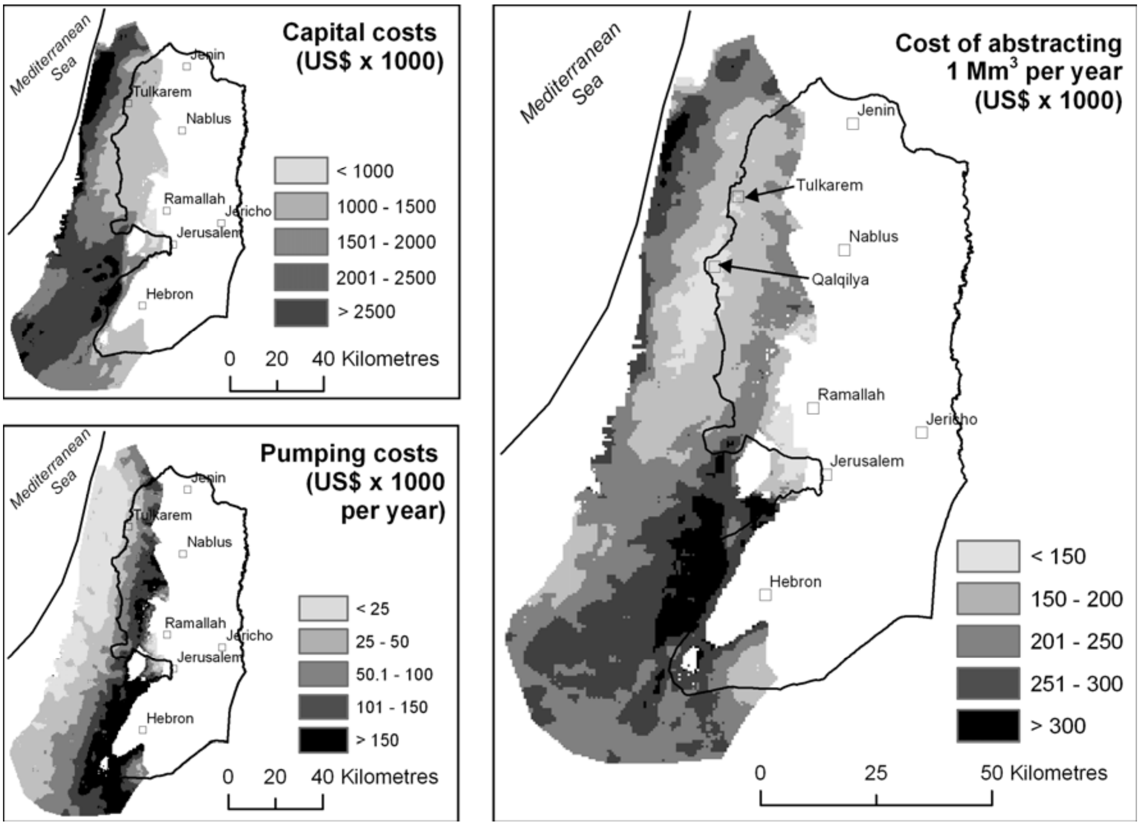

Figure 5 Groundwater development costs in the Lower Mountain Aquifer