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**Individual numerical transient flow
models for each sub-basin**

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1 Sub-basin Al-Arab

Tino Rödiger and Christian Siebert

1.1 Groundwater flow model software - FEFLOW

The software FEFLOW (Finite Element subsurface FLOW system - WASY, 2006) is usable for simulating groundwater flow, mass transfer and heat transfer in porous media. FEFLOW practices finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions. In general, three-dimensional groundwater flow is based on mass balance and Darcy's law according to Eq. 1.1:

$$\delta/\delta x*(k_x*\delta h/\delta x)+\delta/\delta y*(k_y*\delta h/\delta y)+\delta/\delta z*(k_z*\delta h/\delta z)+q_s=S_s*\delta h/\delta t \quad (\text{Eq. 1.1})$$

Where h is the hydraulic head, S_s is the specific storage, q_s is a sink or source term and k_x , k_y and k_z are the hydraulic conductivity in x , y and z direction, respectively. The modelling software FEFLOW is able to simulate the groundwater flow by solving equation (1.1) if specific boundary conditions, initial conditions and spatial distributed hydrogeological parameters are available.

1.2 Study area Wadi al Arab

The study area of Wadi al Arab is situated in the northwestern edge of Jordan (Fig. 1a). The catchment is bounded by the Yarmouk valley in the north and by the Jordan Valley in the west. To the SE and E it continues into the foothills of the Ajlun Dome and the branch of the Azraq plain, respectively. Altitude varies from -200 m mean sea level (msl) in the Jordan River Valley to over $+1100$ m msl in the mountain ranges of the Ajlun. Coming from the south, the wadi incises into its Cretaceous and Cenozoic bed NW-wards, passing Irbid as the second major city of Jordan. Just south of village Umm Qais, the Wadi course suddenly changes its flow direction from NW to SW. The surface catchment area covers about 200 km^2 , whereas the subsurface catchment comprises an estimated area of about 300 km^2 .

The annual precipitation ranges from less than 200 mm to about 500 mm and almost all is falling between October and April. About 80% of the wet season rainfall is concentrated on the period between December and February. Since very often the entire annual precipitation amount falls within one day, the intensities of single precipitation events are often very high.

The average daily temperature is 12.4 °C during the winter season (November to April) and 23.0 °C during the summer season (May to October).

Hydrogeological background

The multi aquifer system of the catchment consists of fractured and karstified Upper Cretaceous (A7-B2) and Tertiary (B4) deposits. Its basement is given by the marly limestone aquitard of the Upper-Cenomanian Shueib Fmt. (A6). The Turonian-Senonian A7-B2 aquifer package consists of limestones of the Wadi Es Sir (A7), the chalky marls of the Wadi Ghudran (B1), the silicified limestones and phosphates of the Al Hasa (B2a) and Amman (B2b) formations, respectively. Within the catchment, its thickness ranges between 200m in the outcrop areas (middle and SE' part) to more than 700 m in the NW. The uppermost Cretaceous formation on top of A7-B2 is represented by the chalky and marly Muwaqqar aquitard (B3). Above, Cenozoic deposits of the Umm Rujam Fmt. (B4), around 300 m thick, build up the uppermost sequence of the study area. B4 consists of chert-rich limestones and built a locally productive aquifer in the NW' part of the study area (Fig. 1.1a). A7-B2 aquifer is hydraulically separated from the B4 aquifer by the B3 aquitard (Table 1.1).

The entire complex generally dips NW-wards. The hydraulic conditions of A7-B2 change from unconfined to confine as soon as the B3 aquitard appears.

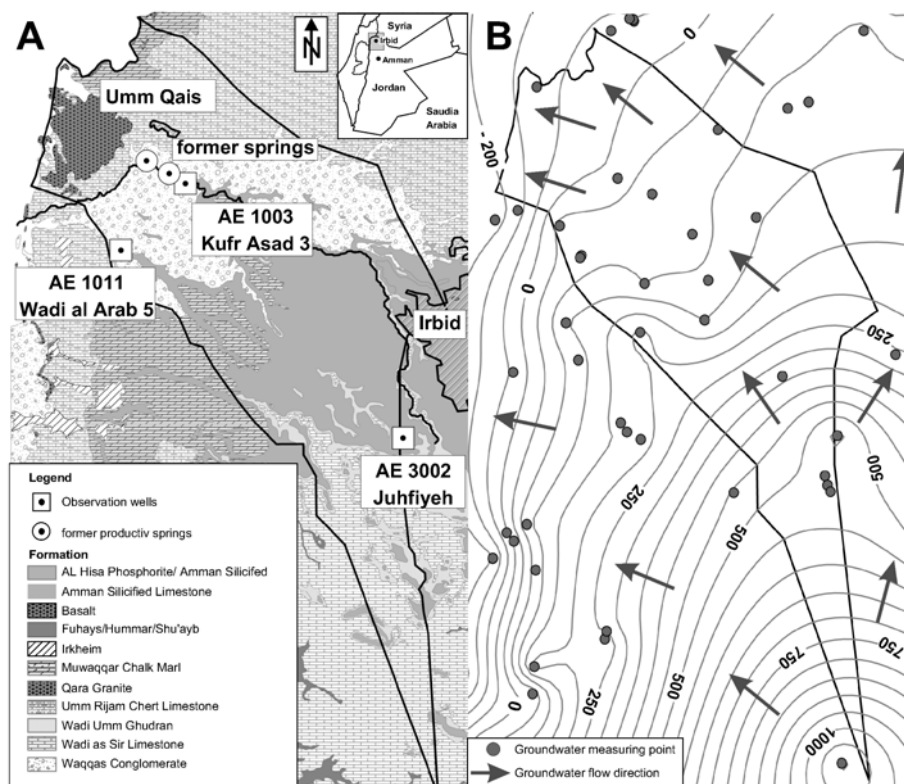


Fig. 1.1: a) Geological map of Wadi al Arab catchment. Urban areas, observation wells and former springs (emerged from A7-B2) are indicated. b) Map of the catchment with water table isohypses, groundwater flow directions and the watershed of aquifer A7-B2, respectively.

Table 1.1: Hydraulic parameter of the main hydrogeological units of the study area.

hydro-geological unit	hydraulic conductivity k_f [m/s]	thickness [m] study area		specific storage	
		SE	NW	unconfined	confined
B4	$1 \times 10^{-5} - 1 \times 10^{-6}$		300	0.02	
B3	$1 \times 10^{-9} - 1 \times 10^{-11}$	0	700	0.001	
A7-B2	$1 \times 10^{-4} - 1 \times 10^{-7}$	200	700	0.02	0.001

To receive the heterogeneous thicknesses of hydrological units, available well logs were interpolated and the geological maps (1:50,000) of the area were dissected. The average values of the hydraulic conductivity were estimated by analysing pump test data and reports from BGR and WAJ (1995, 1996, 2001) and El-Naser (1991).

The groundwater flow in aquifer A7-B2 is structurally dictated and is directed from the southeast down to the Yarmouk gorge and the Lower Jordan Valley in the northwest (Fig. 1b). On the southern edge, close to the foothills of the Ajlun Dome, the groundwater flow lines show a circumfluent pattern and the hydraulic heads range from >1000m msl to 250m msl. Further NW-wards, the hydraulic heads decrease to -150m msl in the Yarmouk and to -200m msl along the eastern flank of the Lower Jordan Valley. In the entire area, groundwater flow is hydraulically autonomous from the morphological gains of the wadis.

Time periods for water level observation data are sparse in the study area. Existing observation wells for aquifer A7-B2 are AE 1003 (Kufr Asad), AE 1011 (Wadi al Arab 5) and AE 3002 (Juhfiyeh) (Fig. 1a). Although the last one is situated already outside the subsurface catchment, it was included into the study because of its closeness to the groundwater divide and the limited amount of stations. Groundwater levels of AE 1003 were measured every three months in the period 1983–2006. The monthly records of observation wells AE 1011 and AE 3002 cover several months in 1993 and the years 2000 and 2001. The records in AE 1003 and AE 3002 show (1) seasonally increasing and dropping groundwater level and (2) the general trend of decreasing levels since 1993.

The recharge zones of the aquifers are located in the outcrop areas of the deposits of A7-B2 and B4. Roediger et al. (2014) estimated the average groundwater recharge for the aquifers, derived from infiltrating precipitation, to be 60 mm a^{-1} .

Groundwater abstraction from A7-B2

In Wadi al Arab, groundwater abstraction from A7-B2 is mainly realised by two major well fields: Al Arab and Kufr Asad. Amounts of abstraction from Al Arab well field are available from the Water information system of Jordan, while for Kufr Asad neither amounts nor pumping rates are known. For period 1980–1988, abstraction rates for Al Arab well field were only given as total annual sums. Since 1989 density of data increased and information to

monthly pumping rates from 1989–2006 are known for 15 wells. The abstraction rates increased quickly after the completion of the Al Arab well field until 1983, when the abstraction reached its maximum with over 25.93 Million $\text{m}^3 \text{a}^{-1}$. Until 1986 the abstraction was reduced to 17 Million $\text{m}^3 \text{a}^{-1}$. Since 1997 the abstraction rates were decreased further and achieved around 10.5 Million m^3 in 2006.

Model set up / Conceptual model

The model simulation period was set up for a time series from 1980–2008. The numerical groundwater model consists of 5 layers (Fig. 1.2). From down to top, layer 1 and 2 represent the aquifer A7-B2, layer 3 and 4 the aquitard B3 and layer 5 owns the properties of aquifer B4. The mesh generating process is made by triangular prism elements. During that process, observation and abstraction wells with reliable (hydro-) geological information were used as additional locations for mesh-refining nodes. Particularly along important structural features (e.g. fault systems), the mesh density is increased. The length of element edges varies between 50–400 m. The top-surface of the model is extracted from a digital elevation model with a pixel resolution of $25 \times 25 \text{ m}$. The final model body consists of 119,685 elements and 73,752 nodes.

Boundary conditions and source terms

To closely represent the hydrological background, the following boundary conditions are set (Fig. 1.2). The watersheds surrounding the catchment are predominantly defined as no-flow boundaries (2nd kind). Exceptions exist along the northern and NE boundary. The border to the Jordan Valley is defined as flux boundary (2nd kind) with 0.0006 m d^{-1} for the A7-B2 aquifer (layers 1 and 2). A transfer boundary (3rd kind) is defined along the northern face side of layers 3–5, where the Yarmouk gorge is deeply incised into these strata. The 4th kind boundary conditions are used for available abstractions wells in the study area.

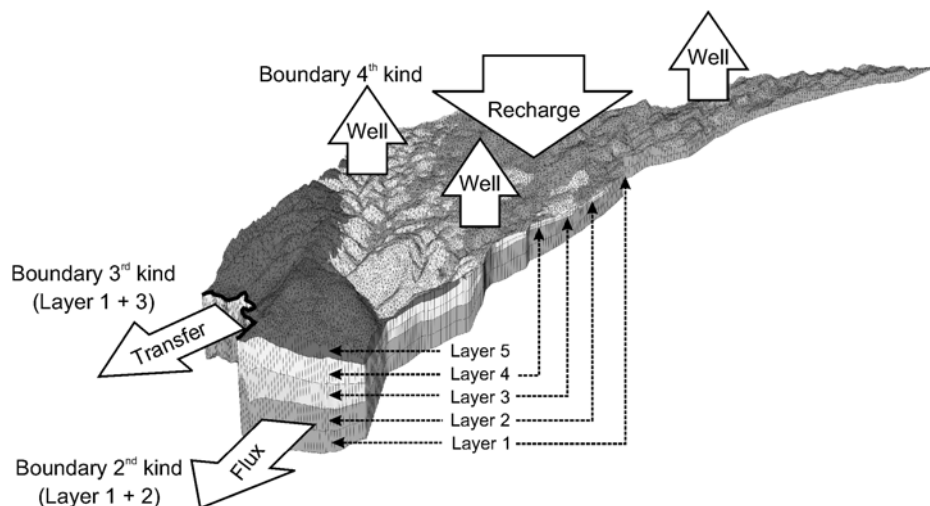


Fig. 1.2: The conceptual model and the set boundary conditions of the study area are shown.

The groundwater recharge as consequence of infiltrating precipitation is set as source term. In the transient model, the temporary and spatially variable groundwater recharge is derived from the hydrological model J2000g of Wadi al Arab, which is described in detail in Roediger et al. (2014). The combination of the process-oriented hydrological model J2000g with the FEFLOW transient groundwater model was used to obtain realistic, spatially and temporally variable groundwater flow scenarios.

1.3 Results and discussion

Steady state model

The objective was to simulate the undisturbed groundwater heads in time for the completion of the well fields in the study area. The calibration of steady state conditions was done with initial heads in the 15 static water levels given in Fig. 1.3 as an advantage it has to mentioned, that these observation wells are well distributed over the entire study area. The scatter diagram of the calculated versus measured water level is shown in Figure 1.3a, showing settling correlation $R^2 = 0.99765$.

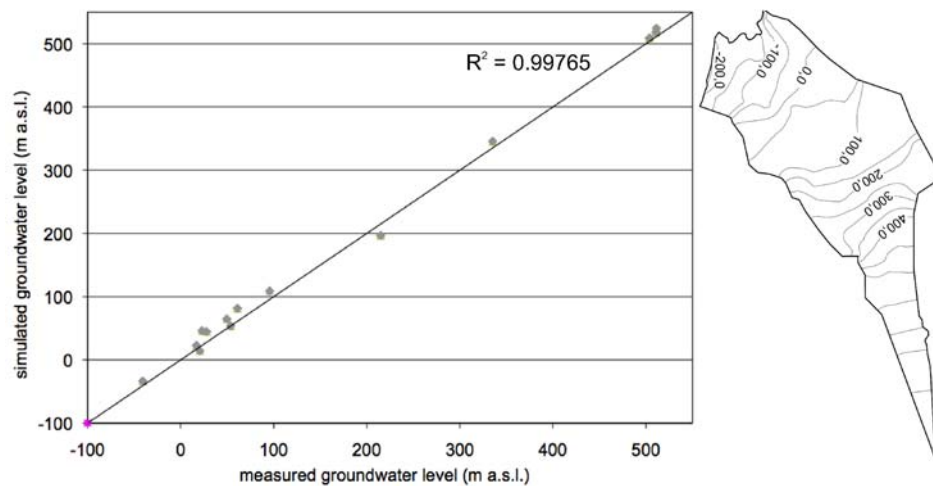


Fig. 1.3: a) the regression analysis and the coefficient of correlation $R^2 = 0.99765$ refer to the existence of a direct relationship between measured and simulated groundwater levels. b) shows the according simulated hydraulic heads under steady state conditions.

Calculated water levels represent the measured levels under steady state conditions very well and show, that simulated hydraulic heads (Fig. 1.3a) represent the general groundwater flow pattern (Fig. 1.3b). The calibration result of the adjustment of the hydraulic conductivity for main hydrological units is shown in figure 4. Average hydraulic conductivities are $9.5 \times 10^{-6} \text{ m s}^{-1}$ for aquifer A7-B2, $1.0 \times 10^{-8} \text{ m s}^{-1}$ for aquitard A3 and $1.0 \times 10^{-6} \text{ m s}^{-1}$ for aquifer B4, values that range in a realistic natural size.

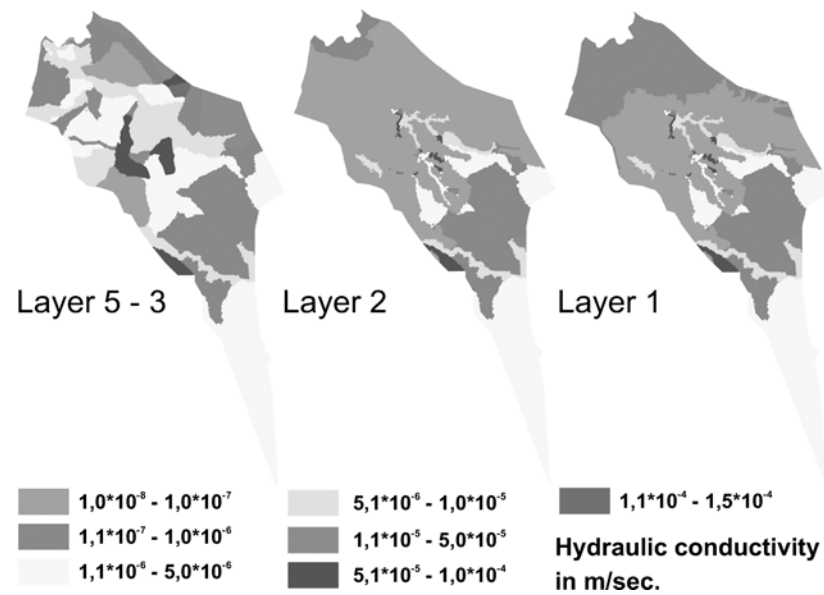


Fig. 1.4: Distribution of the adjusted values of hydraulic conductivity in Layer 1 to 5.

Transient model

The simulation period was from 1980 to 2008 according to calculated monthly values of groundwater recharge by the hydrological model J2000g (Roediger et al, 2014). Storage coefficient of 0.001 is set in the confined model area and 0.02 in unconfined model areas (Table 1.1). The information of storage is based on pumping test and reports in BGR and WAJ (1995, 1996, 2001). In contrast to the steady state model, that time-varying abstractions rates are set for the 15 pumping well's. To calibrate the transient model, available water level records of the wells AE 1003 (Kufr Asad), AE 1011 (Wadi al Arab 5) and AE 3002 (Juhfiyeh) are used.

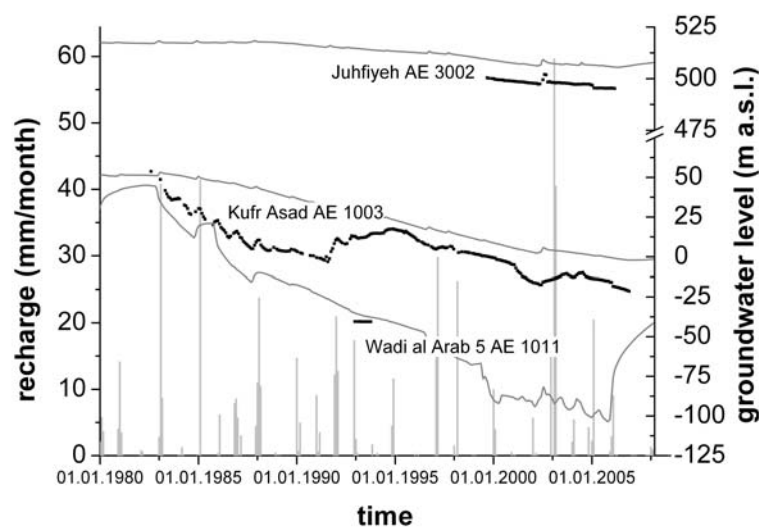
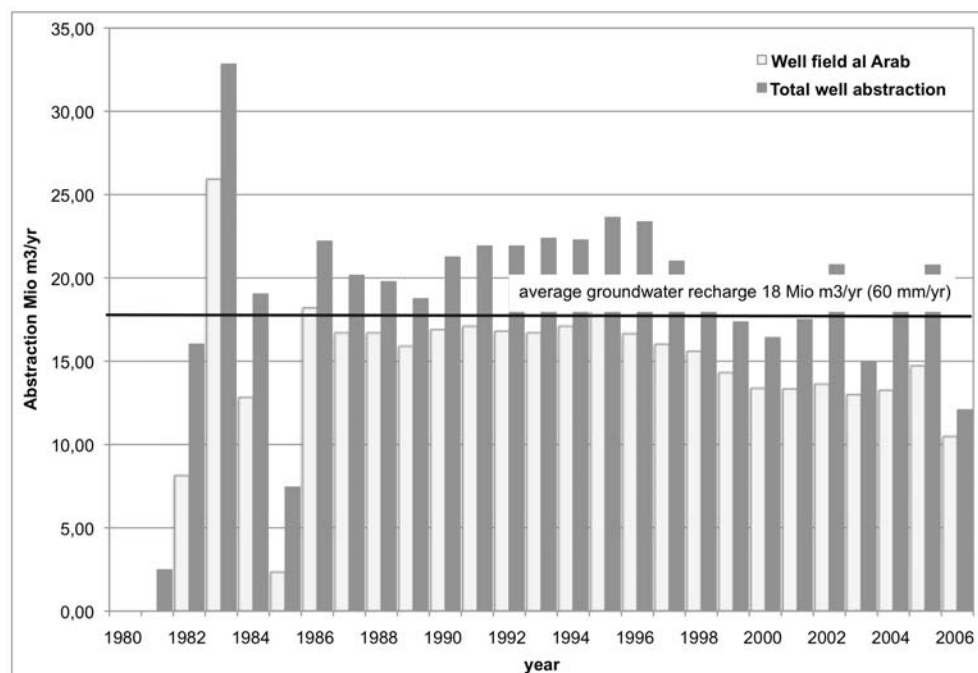


Fig. 1.5: First simulation results of the transient model. Visible are measured (black dotted line) and simulated (grey line) groundwater levels and average recharge curves (grey column) of the study area.

Table 1.2: The result of the water budget analysis by FEFLOW in the time period.

Water budget	Inflow (Mio m ³)	Outflow (Mio m ³)
Flux boundary (2 nd kind)	0	223.4
Transfer boundary (3 rd . kind)	215.3	267.5
Well boundary (4 th kind)	-	440.7
Groundwater recharge	548.6	-
Sum	763.9	931.5

In summary the water budget analysis is shown in Table 1.2 for the time period 1980 -2008. It is obviously that the catchment of Wadi al Arab is characterized by an unbalanced budget. The strong impact of the pumping rates open up also in the Fig. 1.6. The simple figure illustrate, that inherently the known pumping rates of the well field al Arab are in the same scale of the average groundwater recharge of 18 Million m³ a⁻¹. This results lead to the adoption, that no safe yield were considered in the past.

**Fig. 1.6:** Relation between known abstraction rates and average groundwater recharge in study area.

2 Sub-basin Shueib

Paulina Alfaro

2.1 Introduction

The Lower Jordan Valley is a narrow and long basin located in Jordan, Israel and the west bank. This study is focused on one location at the Jordanian part, where agriculture is the most important activity and thus, the use of the water resource plays an essential role in Jordan's development. The source for this irrigation water is mainly groundwater, which is extracted with pumping wells. In order to study the groundwater system a two dimensional steady state groundwater model in the area downstream of Wadi Shueib is created.

2.2 Study area

The study area is located on the western border of Jordan within the Jordan Valley and at the outlet of the Wadi Shueib catchment; it is located between the cities of Al Karamah and Jawfat Al Kafrein, downstream of Wadi Shueib as shown in the Fig. 2.1. The elevation ranges from -200 m asl on the eastern border to even -370 m asl on the western side next to the Jordan River. The region, as defined in this study, features an area of around 70 km². The central municipality is South Shunah, in Arabic Shuna al-Janubiyya, and the main activity in the area is agriculture with cultivations of banana, palm trees, tomatoes and herbs among others.

Hydrogeological Setting

The geology of the study area consists mainly of the Jordan Valley Aquifer and the Lisan formation (Fig. 2.2). Most of the groundwater resource is exploited from the Alluvial Aquifer, part of the Jordan Valley aquifer complex.

The surface water bodies found in the study area are the King Abdullah channel (KAC), which contributes with a small part of the irrigation water (see Fig. 2.3) and the Jordan River, which serves to delineate the western limit of the zone of interest.

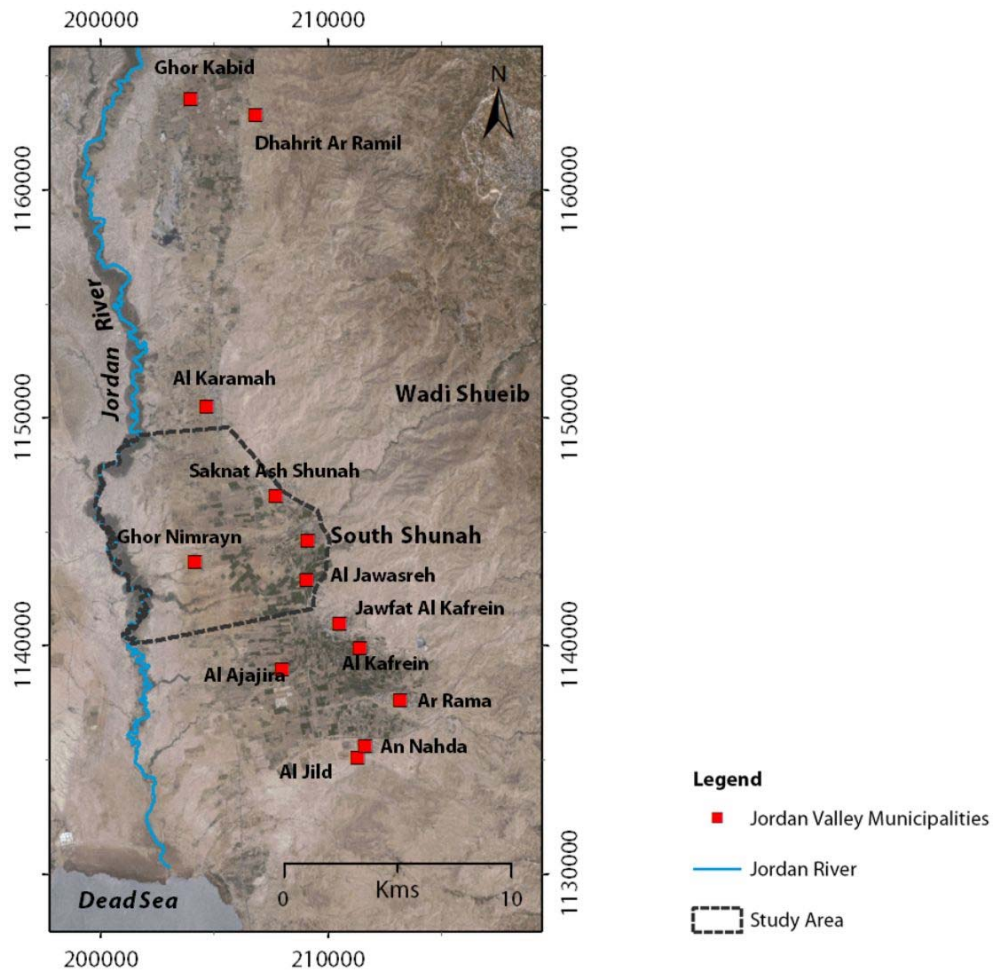


Fig. 2.1: Municipalities in the Jordan Valley and delineation of the study area, east of the Wadi Shueib. South Shunah is the main municipality.

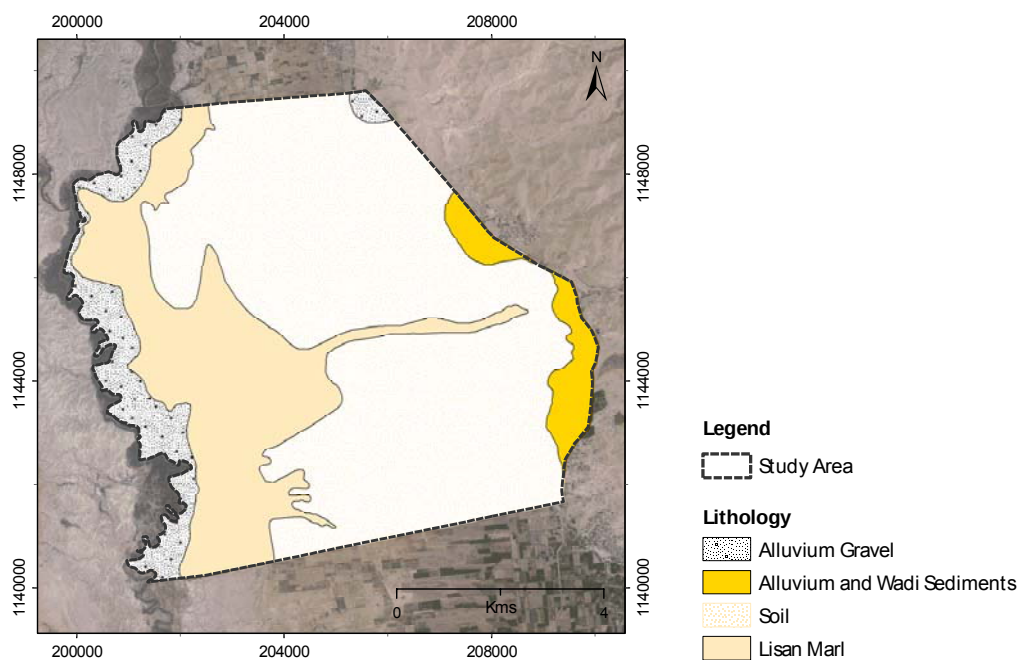


Fig. 2.2: Geological formation in the study area (Toll, 2008; Sahawneh, 2011).



Fig. 2.3: KAC in the study area.

The groundwater flow is determined by the geological structure from the highlands at the east of the study area. A lateral inflow from the adjacent aquifers takes place and it is expected to flow from east to west and east to southwest (see Fig. 2.4).

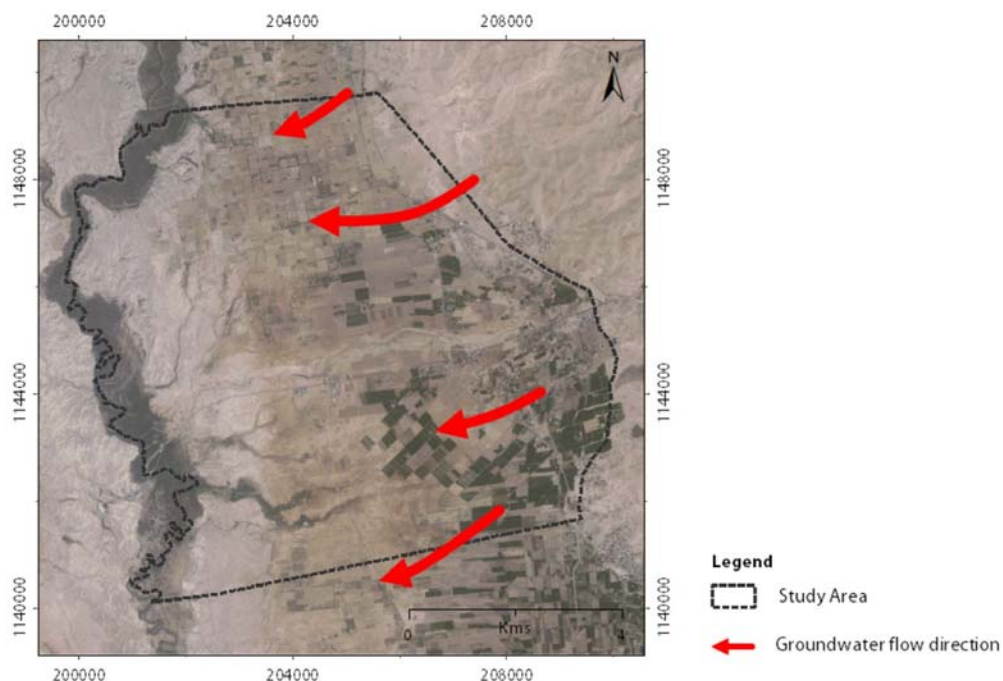


Fig. 2.4: Groundwater flow direction in the study area.

The yearly average precipitation of the last 30 years is around 160 mm and the average minimum and maximum temperatures are 16 °C and 31 °C, respectively (see Fig. 2.5). Due to the low precipitation in the lower Jordan Valley, the main groundwater recharge for the study area is the lateral inflow mentioned before. Active wells located in the Jordan Valley extract water from the Jordan Valley deposits, which consist primarily of young sediments in the subsurface. Groundwater levels in the Jordan Valley fluctuate seasonally due to variations in precipitation in the highlands and flood flows. This variation is specially observed in the wells located close to the escarpment of the Wadi Shueib

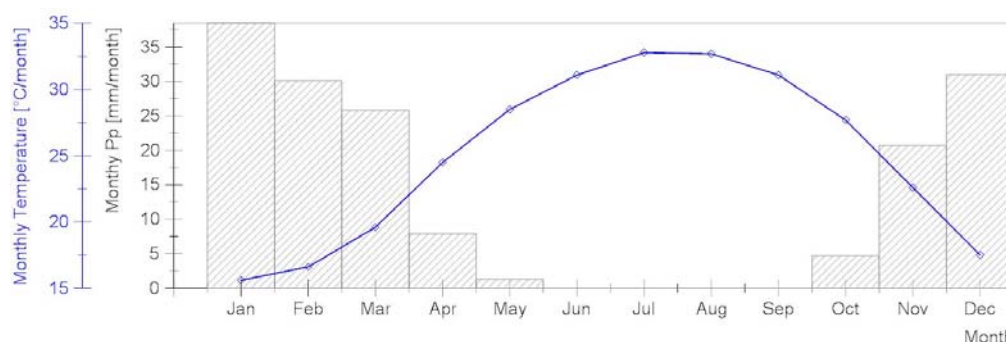


Fig. 2.5: Monthly values for precipitation and temperature from climate station South Shunah AM0007. The annual average precipitation is 160 mm, whereas the annual average temperature is 25 °C. (Based on data records from MWI).

Agricultural Activities

In the study site, the economy consists of agriculture only, which is only possible due to intensive irrigation, whereby 98% of the crops are irrigated (Toll, 2008). Crops found in the study area are bananas, sweet corn, eggplant, tomatoes, zucchini, olives, wine grapes, date palm, and herbs, among others. According to the work of Shatnawi (2012), which performed a land use supervised classification using Landsat 5 (December 2010) and Landsat 7 (June 2011) using the maximum likelihood algorithm, the irrigated area within the area of interest is estimated to be around 26 km². During November 2012 a field supervision was performed to estimate the proportion of the crops cultivated in the area. The crops, which its identification was not possible, fell in the category “crops”. The results with the final distribution of crops cultivation in the study area can be seen in Fig. 2.6, while the estimated area can be seen in Table 2.1.

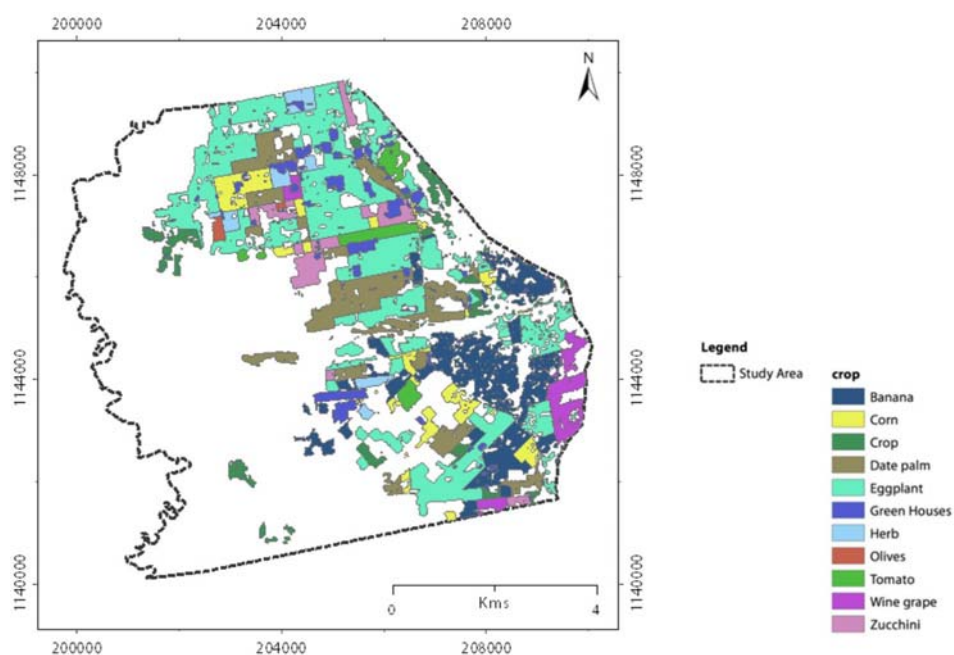


Fig. 2.6: Crops distribution in the study area as a result of remote sensing analysis and field supervision.

Table 2.1: Estimated area of the cultivated crop in the study area, considering the remote sensing results and the field supervision.

Crop	Estimated of cultivated Area [km ²]
Banana	4.4
Corn	1.7
Crop	1.4
Date palm	3.8
Eggplant	10.6
Herb	0.8
Olives	0.1
Tomato	0.8
Wine grape	1.1
Zucchini	1.2
Total	25.9

2.3 Data collection and processing

The determination of the water balance, as well as for the construction of the groundwater model, requires data which involves the different elements which influences the water cycle. These components can also be seen in the groundwater conceptual model in Fig. 2.11.

Climate data and information about water extraction and observation wells were collected from data banks from the Jordanian Ministry of Water and Irrigation (MWI).

Climate Information

The climate station South Shunah AM0007 is located at the study area and includes information of precipitation, temperature, evaporation and wind speed. The data exists mainly during the period 1972–2010, although there is some missing information for some parameters, which had to be refilled. Moreover, the reference evapotranspiration ETo was calculated using the FAO Penman-Monteith equation and the class Pan A method (also called Kp method), described by FAO (1998). The final results are compared and it was found that the values obtained by the Penman equation are smaller than the values obtained with the Kp method, especially for the period 2006–2007, this can occur from an underestimation of the evapotranspiration calculated with the Penman equation for semiarid areas. Therefore, the values obtained by the Kp method are selected to calculate the crop water requirement (see Fig. 2.7). On the other hand, the ETo values have a good behaviour with the temperature as shown in Fig. 2.8.

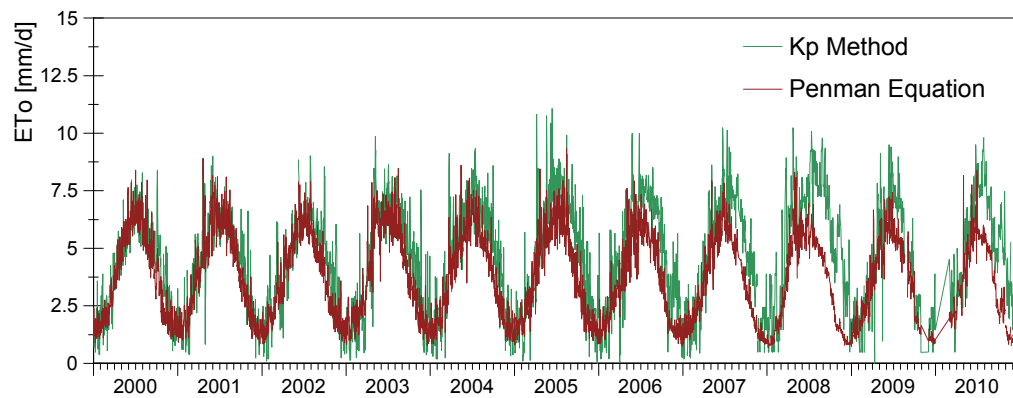


Fig. 2.7: Values refilled for the period 2002-2005, where no information was available.

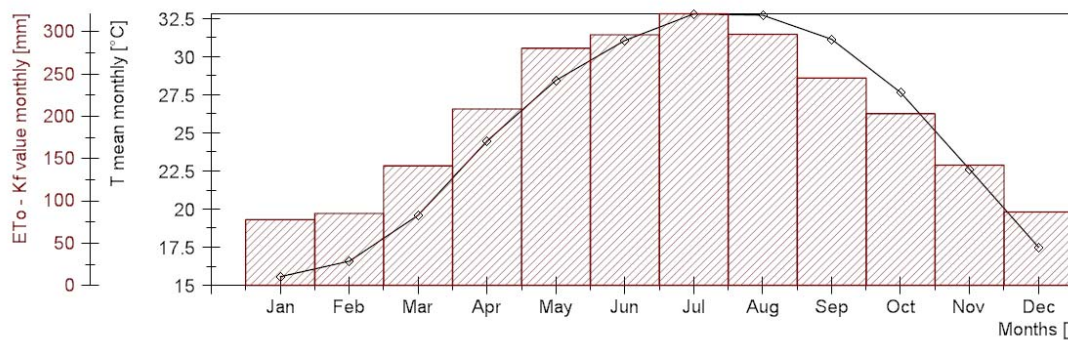


Fig. 2.8: Relation between the evapotranspiration values ETo and the monthly mean temperature.

Wells and aquifers

According to the MWI catalogue, updated until November 2011, there are 212 wells in the study area, 60 of them have particular lithology information. From the total, 12 wells are governmental and only three of them are actually being used as monitoring wells (Fig. 2.9).

The groundwater levels of the observations wells show for the well AB3148 a pronounced seasonal variation due to its proximity to the escarpments of Wadi Shueib dam, where infiltration to the groundwater takes place and no agricultural activity, directly upstream of these well, is found. On the other hand, the wells AB1341 and AB1340 have a very similar behaviour, where a water level decrease over the years can be observed (see Fig. 2.10)

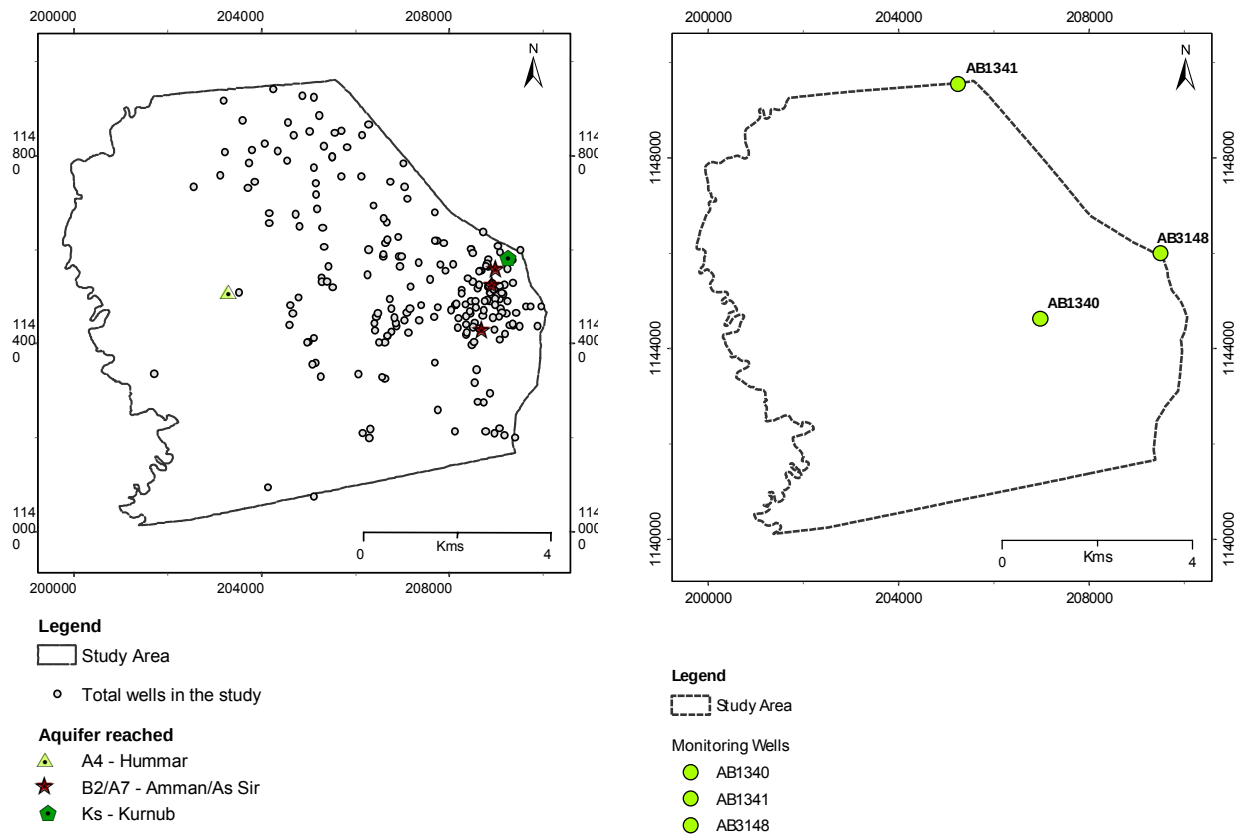


Fig. 2.9: (Left) Wells in the study area. Only 5 wells reach another aquifer besides the alluvium. (Right) Monitoring wells found in the study area (Based on data records from MWI).

2.4 Groundwater conceptual model

The groundwater conceptual model represents the system with its inflow and outflows. Since the precipitation and the infiltration from surface water are very low, both parameters can be neglected from the recharge to the groundwater. The evaporation and groundwater extraction are represented through the potential evapotranspiration value (ET_o) and the water requirement for each crop according to the agricultural activities presented in Section Agricultural Activities. Therefore, the groundwater conceptual model, which is defined for the construction of the numerical model, is then defined in two dimensions with the elements shown in Fig. 2.11.

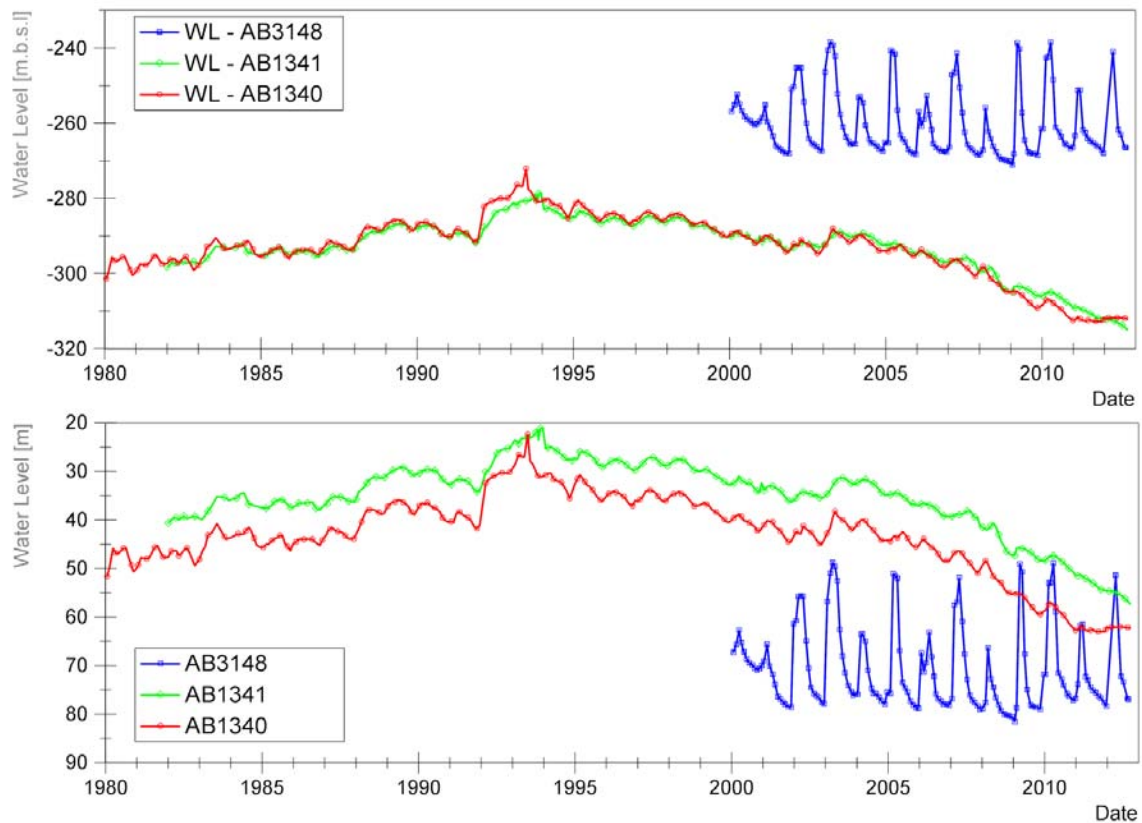


Fig. 2.10: Water level in observation wells in the study area AB3148, AB1341 and AB1340. On the top the levels are shown in respect to the height in meters below sea level, while in the bottom the reference is on the depth to the water. (Based on data records from MWI)

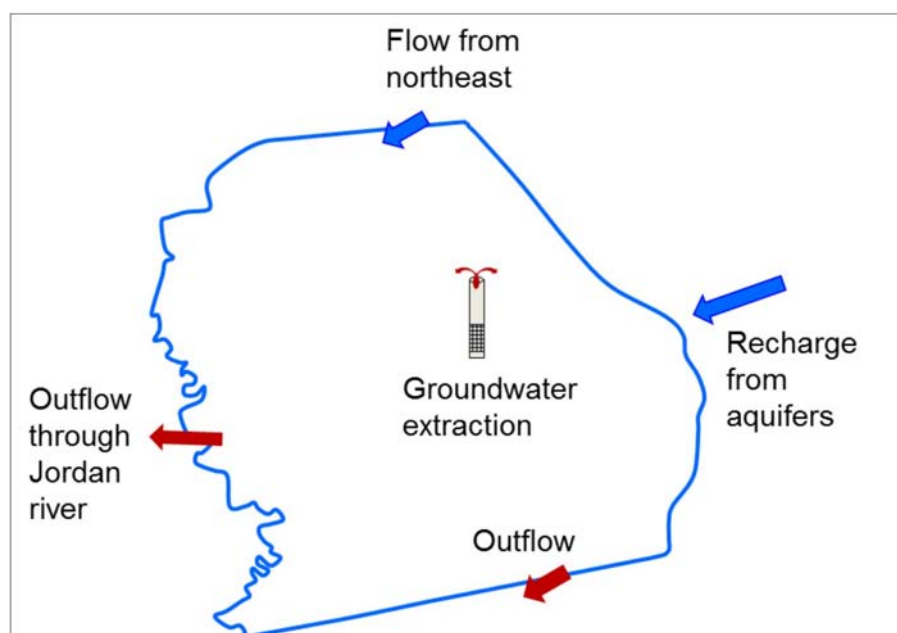


Fig. 2.11: Groundwater conceptual model of the study area

2.5 Model set up

The model is constructed in MODFLOW in two-dimensions, steady state with unconfined flow. It has a cell centered grid type, around 10 x 10 km² and 89 x 112 cells. The grid is especially refined in the center of the area, where a better definition is needed due to the inflow from the adjacent Wadi. Since it corresponds to a two-dimensional model, only one layer is defined, which represents the alluvium aquifer, where most of the groundwater extraction take places. The geometry can be seen in Fig. 2.12.

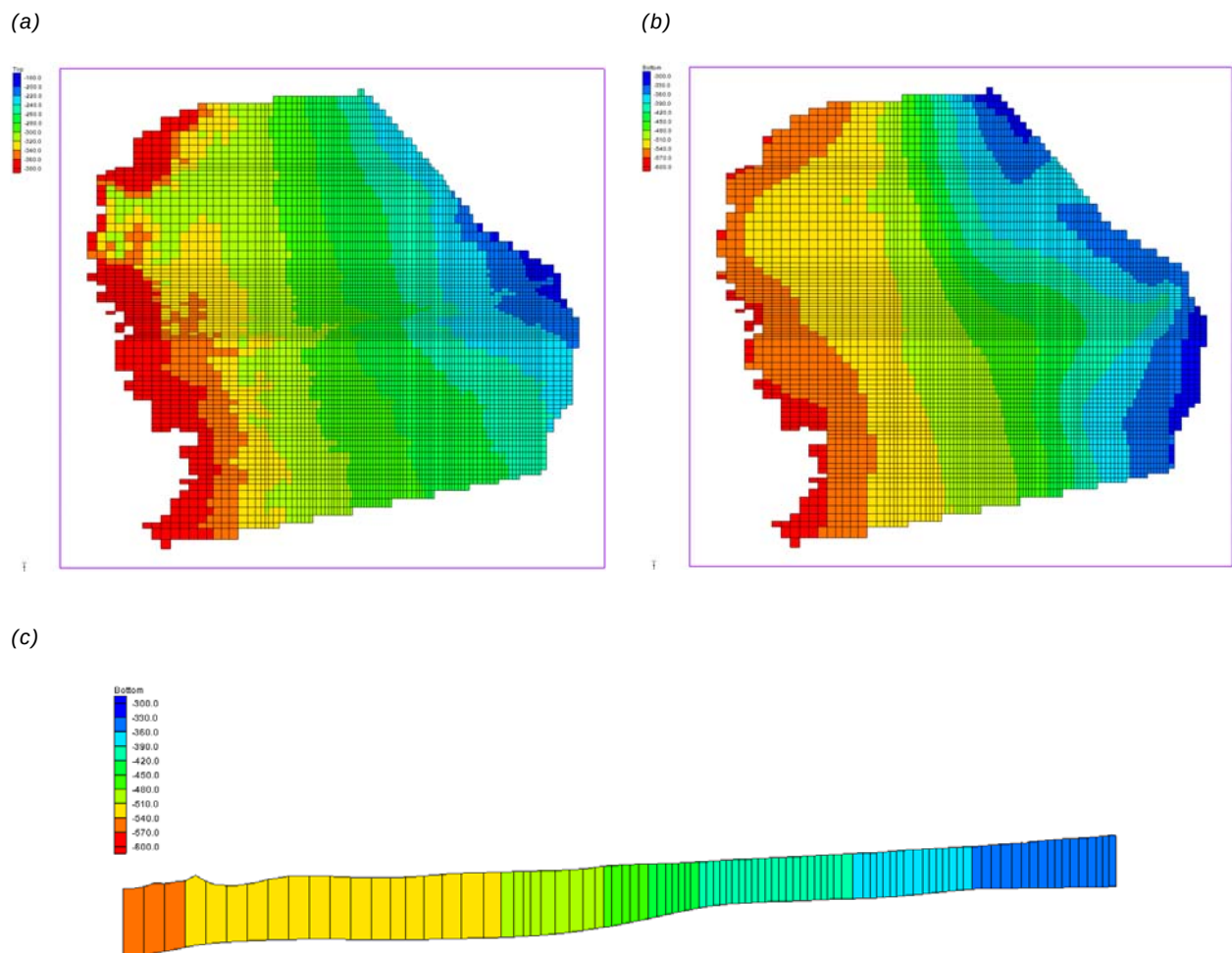


Fig. 2.12: Geometry of the groundwater in MODFLOW. The scale shows the values of the elevation (a) and the bottom of the aquifer (b and c). In (c) a magnified cross-section in the middle of the study area is shown, the thickness varies from around 50 meters at the north-east part of the study area until 250 m close to the Jordan River (west part). The grid refinement in the center part is also observable in figures (a), (b) and (c).

The different parameters of the conceptual model are defined in MODFLOW as border conditions and sources and sinks (also called packages) as shown in Fig. 2.13.

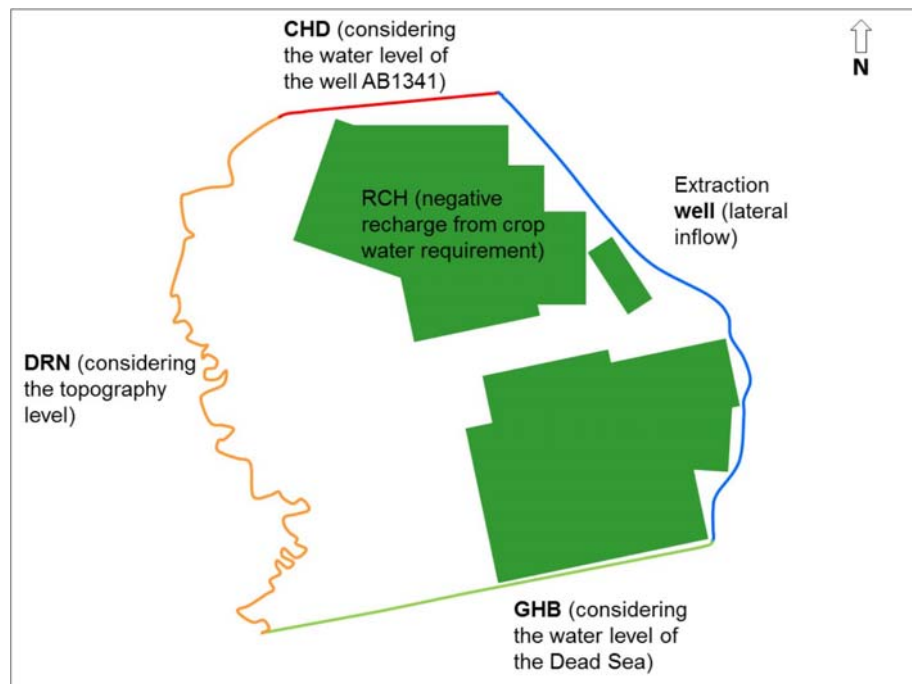


Fig. 2.13: Border conditions and sources and sinks for MODFLOW. CHD stands for specific heads, GHB for general head condition and DRN for drain.

The boundary conditions are defined as:

Hydraulic-Head

At the northern boundary. The specific head (CHD) with head-stage in meters is estimated using the water level values from the monitoring well AB1341.

General Head Boundary

At the southern boundary. The general head condition (GHB) is specified by assigning a head and a conductance in $\text{m}^2 \text{d}^{-1}$. In this case the water table of the Dead Sea will be used to estimate if the water flows out of the aquifer.

Drain

At the western boundary. Drains remove water from the system when the water table is above the elevation of the drain. In this case the topography of the Jordan River is taking into consideration, as well as an estimated conductance, which is function of the hydraulic conductivity, the cross sectional area and the length.

Extraction wells (lateral inflow)

At the eastern boundary. The lateral inflow is represented with a series of injection wells. As they are not extracting water they have a positive constant flow rate in $\text{m}^3 \text{d}^{-1}$.

Moreover, the groundwater extraction is calculated according to the water demand of agriculture located in the area, based on the land use from Section Agricultural Activities. These polygons are defined with a negative recharge rate in m d^{-1} , since water is being extracted from the system. The hydraulic conductivity is defined in m/d and it is independent from the thickness of the aquifer. The distribution of the hydraulic conductivity can be seen in the Fig. 2.14.

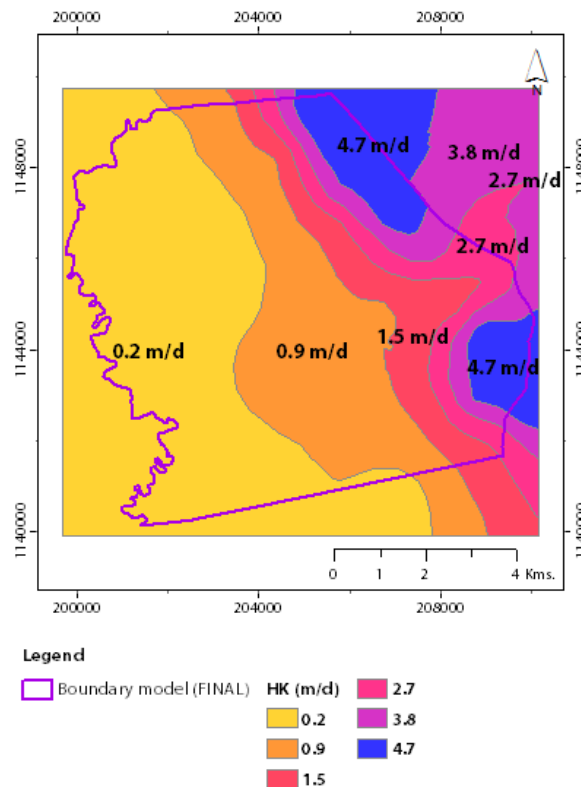


Fig. 2.14: Hydraulic conductivity distribution in the study area.

2.6 Discussion

Since the MODFLOW Model has many assumptions and therefore, uncertainties, it is expected to execute a sensitivity analysis, in order to define those parameters of the model which have more influence on the system. On this way, it is expected to define during the calibration process a value which estimates the groundwater lateral inflow from the adjacent aquifers.

A transient model is planned to be built after the calibration of the steady state model, considering the period 1975–2010. Moreover, the validation of the model is expected to be executed with present water table measurements.

The lack of information and data in the study area, starting from a complete geology knowledge of the underlying layers to more observation wells which help to monitor the water

table with a more disperse distribution, makes the groundwater modelling a real challenge. Nevertheless, the results obtained by this kind of application are a start to understand the system and the evidence that an adequate monitoring network helps to validate the outcomes, which main purpose is to simulate future scenarios based on management strategies.

3 Sub-basin Kafrein

William Alkhoury and Mohammad Azizur Rahman

3.1 Introduction

Groundwater resources

Groundwater is the principal source to meet drinking and agricultural water demand in Jordan. Due to increase in population and stress in political situation, the ground water resources are being overexploited. Hence, the groundwater level (GWL) is decreasing continuously due to high demands and lack of sustainable management of the available water resources. A detailed study of the available ground water resources is essential in order to enhance the water use efficiency, to restore the GWL and to apply an effective management plan for sustainable use and development of groundwater resources. Mathematical models are effective tools to assess groundwater resources that supports the decision makers with necessary information to implement the best practices to manage water resources of this region.

Previously, a 3D groundwater model was developed to estimate the groundwater resources in the unconsolidated region, located north of the Dead Sea extending from Wadi Hisban in the south up to Wadi Shueib in the North, using FEFLOW finite element code (Toll, 2008). This study assumes the flux from the consolidated mountain aquifer to the unconsolidated aquifer as a boundary condition. Another study was conducted to simulate the groundwater flow in the upper side of Wadi Kafrein, using OpenGeoSys scientific modeling software (Wu et al., 2010). Both studies mentioned the data scarcity and hence, only either upstream or downstream of the catchment area was considered.

This study is one of the primary approaches to combine both, consolidated mountain aquifer and unconsolidated aquifer in one modeling platform.

Objectives

This study aims at assessing the groundwater fluxes originating from the consolidated mountain aquifer and flowing to the unconsolidated aquifer using numerical modelling technique.

Some specific objectives are:

- (1) Development of a calibrated Modflow model for the end user/decision maker to simulate several water resources scenarios.
- (2) Estimation of groundwater flux entering into the unconsolidated aquifer from the consolidated mountain aquifer.

3.2 Study area

Geographic location and geomorphology

The study area, Wadi Kafrein, is located 15 km northeast of the northern Dead Sea shore. The catchment area drains to the Kafrein Dam reservoir and runoff goes from the Highlands of the east to the Jordan Valley in the west (Fig. 3.1a). The geographical borders were taken to be the same as the surface catchment area of Wadi Kafrein. The rectangular border coordinates are 31° 50' 37.7" to 32° 0' 32.2" Northing and 35° 40' 1.8" to 35° 51' 24.7" Easting in World Geodetic System (WGS84). Wadi Kafrein drains an area of 161.4 km².

The area has a complex topography with relatively large elevation differences over short distances, meaning a steep relief with elevations ranging from 1,079 m asl (asl indicates above sea level) at the upper east side (east of Fuheis City) down to nearly -139 m asl near the Kafrein Dam. The average elevation is 605 m asl (Alkhoury, 2011).

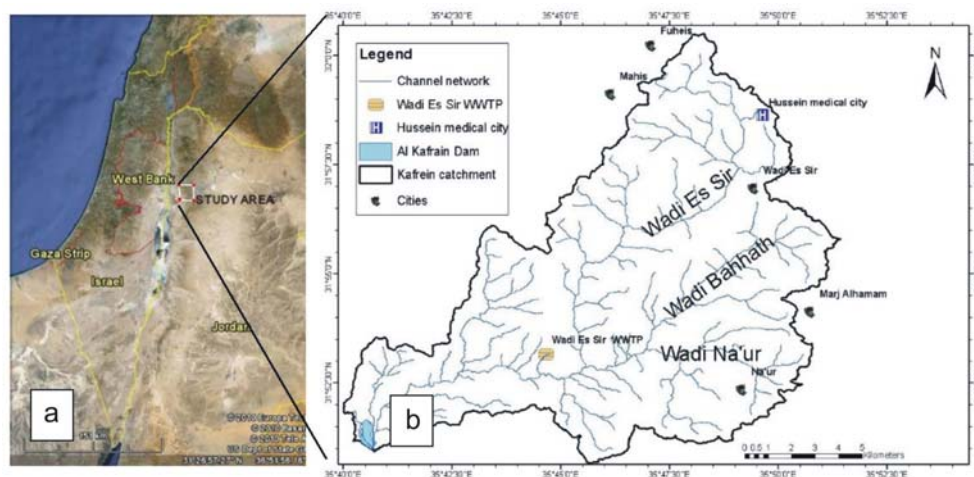


Fig. 3.1 a: The study area of Wadi Kafrein in Jordan (Google earth®). **b:** Main cites and locations in the study area of Wadi Kafrein.

The surface features of a drainage basin determine the characteristics of runoff, flooding, and groundwater, and to some extent rainfall occurrences in the semi arid and arid regions (Sen, 2008). The highlands in the upper eastern part of the study area are

geomorphologically distinct and are characterized by high relief variations, as illustrated above. Some flat plateaus exist in the middle part of the study area. Agriculture is present on these plateaus and is sustained by irrigation from the discharge of local springs.

Wadi Kafrein watershed consists of three main tributaries with corresponding catchment areas. The areal extent of Wadi As Sir catchment, Wadi Bahhath catchment, Wadi Na'ur catchment are 59.2 km², 25.6 km², and 22.8 km², respectively (Fig. 3.1b). These three main tributaries contain springs draining within their respective catchment areas, which are the main sources of baseflow. Tributary catchments, located in the west and southwest, are small in size and are sources of large volumes of sediments due to the erosion of the sparsely vegetated landscape, which is a general characteristic of this area within the Wadi Kafrein watershed.

Aquifer systems

The groundwater withdrawal is done primarily from three main aquifer complexes which have been divided, in this report, based on their spatial distributions, lithologies and the age of the geological units (Salameh and Bannayan, 1993; MWI and GTZ, 2004).

These complexes are:

(a) Deep Sandstone Aquifer complex

1. Ram and Khreim Group (Paleozoic age: Cambrian-Silurian)
2. Zarqa and Kurnub Group (Mesozoic age: Jurassic-Lower Cretaceous)

(b) Upper Cretaceous Aquifer complex

1. Lower Ajlun Group (A1/6) which includes the Na'ur aquifer (A1/2), Fuheis aquitard (A3), Hummar aquifer (A4), and Shueib aquitard (A5/6). (Mesozoic age: Upper Cretaceous).
2. Amman-Wadi As Sir aquifer (B2/A7), (Mesozoic age: Upper Cretaceous).

(c) Shallow Aquifer Complex

Basalt Aquifer, sedimentary rocks, and alluvial deposits (Cenozoic age: Tertiary-Quaternary).

Also these aquifers can be divided into two main types:

A. Bedrock (consolidated) aquifers:

This aquifer type includes the Deep Sandstone Aquifer Complex, the Upper Cretaceous Aquifer Complex and the basalt aquifer of the Shallow Aquifer Complex. These aquifers together compromise the main source of groundwater in Jordan.

B. Unconsolidated aquifers:

Unconsolidated aquifer is limited to the aquifers in the Jordan Valley. Of minor importance compared with the Bedrock aquifers.

In the Wadi Kafrein watershed, the spring discharge, originated at Wadi As Sir aquifer (B2/A7, at the upper Cretaceous aquifer complex), is used to meet the drinking water demand of the city Wadi As Sir. In the lower part of the catchment area, from the Kafrein dam reservoir down to the Jordan River, hundreds of wells are in operation for irrigation purposes. The wells withdraw the groundwater from the Shallow Aquifer Complex. In this context the aquifer system could be divided into two main types as bedrock or consolidated aquifers which include the deep sandstone aquifer of Kurnub Group and the unconsolidated aquifer which is the aquifer of the Jordan Valley.

3.3 Modelling

Modflow model

A groundwater flow model of the study area was set up employing Visual Modflow software (v.2009; SWS, 2009). Visual Modflow uses the finite difference code MODFLOW (Harbaugh and McDonald, 1996) to simulate groundwater flow. Visual Modflow is a complete and easy-to-use modeling environment for practical applications in three-dimensional groundwater flow and contaminant transport simulations. It is a finite difference model, which solves a system of equations describing the major flow and related processes in the hydrological system. The partial-differential equation of groundwater flow used in Modflow can be represented by the equation 3.1 as shown below:

$$\frac{\partial}{\partial x} \left(K_{xx} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_{yy} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_{zz} \frac{\partial h}{\partial z} \right) + W = S_s \frac{\partial h}{\partial t} \quad (\text{Eq. 3.1})$$

where,

K_{xx} , K_{yy} , and K_{zz} = Values of hydraulic conductivity along the x, y, and z coordinate axes ($L T^{-1}$);

h = Potentiometric head (L);

W = Volumetric flux per unit volume representing sources and/or sinks of water, with $W < 0.0$ for flow out of the ground-water system, and $W > 0.0$ for flow in (T^{-1});

SS = Specific storage of the porous material (L^{-1});

The modelled groundwater flow, more precisely the head distribution, is calculated from a partial differential equation (Eq. 3.1), which is derived from the conservation of mass/water volume and Darcy's law. The latter assumes laminar flow. Therefore, laminar flow is also assumed for the model.

Visual Modflow comes with different solvers for numerical equations for the flow simulation as specified below:

- SSOR - Slice-Successive Over-Relaxation
- SIP - Simply Implicit Procedure
- PCG2 - Preconditioned Conjugate Gradient
- LMG - Algebraic Multi-Grid.
- WHS - Bi-Conjugate Gradient Stabilized

The different solvers had been tested during the studies and the best one was used for simulation.

General approach of the model development

Modeling activities refer to the iterative development of a model. Model refinements are based on the availability and quality of data, hydrogeological understanding and modeling scope. For this study purposes, the following general approach was adopted as shown in the Figure 3.2. The development of a conceptual model was not included in the numerical model development approach.

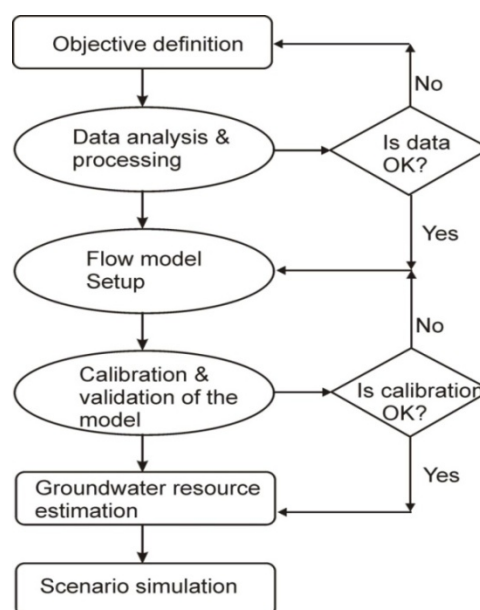


Fig. 3.2: General workflow of the model development.

Conceptual groundwater flow model

The development of a conceptual model of a problem is the first step in the procedure of mathematical modeling. A conceptual model of groundwater flow is a qualitative framework upon which data related to subsurface hydrology can be considered (Leon et al., 2003). It is important to identify knowledge or data gaps that must be filled before a quantitative model can be constructed. The sources and sinks, the physical boundaries and the distribution of hydraulic properties within the region are the basic components of a conceptual model.

The set of aspects that represent simplified perception of the project are:

- general hydrological skill and knowledge,
- knowledge about the local hydrogeological system,
- an analysis of available field data,
- soft data such as previous regional studies, local consultations or interviews.

One of the most important aspects of the conceptual model is the definition of the geology (horizontal and vertical extent) of the area including structures (e.g. fault). A description involves layers, faults and hydraulic properties. Other important aspects of the conceptual model development are (considering the study area):

- Identifications of boundary conditions and determination of initial conditions.
- Horizontal and vertical discretization.
- Identification of sources (recharge) and sinks (pumping wells)
- Inclusion of fault zones.
- Identification and inclusion of rivers or streams (if available).

Considering the above aspects, a conceptual model was developed for this study. Findings from different components of conceptual model are given in Table 3.1.

Table 3.1: Components of preparation of conceptual model.

Component	Derived from	Findings
Rainfall (included within the model as recharge)	analysis of available data & Hydrological knowledge	# Scarcity of rainfall from May to October, and scatter rains and intense precipitation events during November to April. # The rainy season is quite irregular with a range (maximum) of 200 mm to 600 mm rainfall in highlands, represents the main source of groundwater recharge. Precipitation in most parts of Jordan is less than 200 mm.

Component	Derived from	Findings
Evaporation	General Experience & analysis of available data	# The evaporation rate is high. # Modflow model considers only recharge which is a net result of rainfall and evaporation/ evapotranspiration. # No information about groundwater evaporation is available
Topography	General Experience & analysis of available data	# The landscape is basically steep. # Topography of the area varies from 1,079 m asl at the upper east side (east of Fuheis City) down to nearly -139 m asl near the Kafrein Dam. # Problem of flash flood during the high rainfall events due to steep slope.
Groundwater use	General Experience & analysis of available data	# Groundwater is the main water resource in Jordan and in some areas groundwater is the only available water resource # In some places the annual average abstraction from groundwater exceeds the average recharge. Hence GWL declines.
Land use	General Experience & Information from recent and previous studies	# 6.6% of the total area is urbanized, ca.5% area is covered by natural forest, 13.6% of the total area is being used for agriculture, sparse vegetation covers 27.4% of the catchment area. # Main crops are olive (ca. 15% of the total area),vegetables, etc
Hydrostratigraphy	General Experience & analysis of available data	# Five main geological layers. Two layers and relatively high conductive and possesses high yield capacity (Amman & Wadi as Sir , and Kurnub Aquifer) # Some faults exist.
Pumping	Analysis of available data	# Data related to pumping are available only to the west part of the model area. # The wells withdraw groundwater from Amman & Wadi as Sir aquifer.
Springs	Recent and previous studies & analysis of available data	#Springs are important source for drinking water and irrigation. # No springs is located along the cross section considered in this modeling study.
Streams or rivers	Recent and previous studies & analysis of available data	# Only intermittent streams are available that can seen during the precipitation events. # No stream was considered in this study
Boundary	Recent and previous studies & analysis of available data	Eastern side of the model has a water barrier. The Jordan river acts a boundary on the western side

(meters above sea level) and 350 m BSL.

The study area was delineated based on the structural maps of the region where it forms the boundaries of the aquifers, from a previous study of Toll, 2008. The cross section extends 23 km from the Jordan River towards east in the high lands with horizontal grid size ranging from 10 m to 100 m. The vertical layers extends to around 1 km based on the different hydrological units thicknesses which range from 50 m as in Wadi Shueib A5/6 aquitard to around 200 m as the Kurnub (K1) aquifer (Table 3.5). The geological layers, along the z-axis, were discretized using the information available in published papers and reports (e.g., Alkhoury, 2011). After lumping the aquifer and aquitard characteristics, five geological layers with variable thickness were defined and included in the model representing the Kurnub aquifer of lower Cretaceous to Wadi As Sir aquifer (B2/A7) of Upper Cretaceous. Three major faults have been identified and incorporated in the flow model.

In the unconsolidated aquifer, no information about geological layers exists to the authors. So, one layer was considered (by assigning same aquifer properties to all vertical segments)

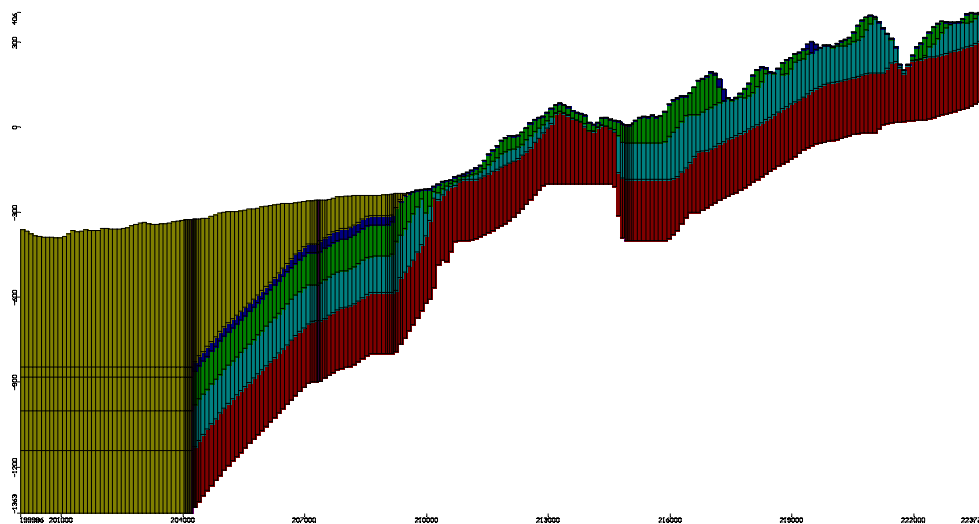


Fig. 3.4: Model layout showing the vertical cross section and distribution of hydraulic conductivity

Boundary condition

The borders of the model region are set as boundaries of the first and second type. On the one boundary on the left side, where the groundwater body is in contact with the Jordan River, the Dirichlet condition is applied, predefining a constant head. The value of the constant head is -380 m asl and kept constant for the entire simulation period. The other three boundaries on the top, the bottom and the left side of the model region are defined as boundary conditions of the second type: Neumann boundary condition with a preset constant gradient of zero and therefore no flow occurs across the boundary.

Initial conditions

Initial conditions in terms of groundwater hydraulic heads were specified in the model. Existing hydraulic heads of the monitoring wells were used to generate an initial condition contour map. Initial groundwater level varies between 406 m asl and -402 m asl.

Aquifer properties

Aquifer properties such as hydraulic and vertical conductivity, specific yield (S_y), and storage coefficient (S_c) were defined for each layer from the secondary data and published reports (see Table 4.5) (Margane et al. 1999; WAJ and BGR, 1997; MWI and BGR, 1997). The aquifer properties were considered as homogenous and isotropic. Vertical conductivities were considered as half of the horizontal conductivities of the corresponding layers. S_y and S_c were defined according to the table 4.5. Effective porosity (n_e) and total porosity were set to be 0.10 and 0.20, respectively. Proper adjustment of the above mentioned parameters were made during the calibration of the transient model. It is clear from the table 4.5 that Layer 1 (Amman & Wadi as Sir formation); Layer 4 (Na'ur formation) and Layer 5 (Kurnub aquifer) possess relatively higher hydraulic conductivity than the other two layers. Kurnub aquifer possesses the highest aquifer yield amongst the aquifers. Horizontal anisotropy was neglected.

Table 3.2 : Distribution of aquifer properties in five layers.

Layer No.	Description	Average thickness (Alkhoury, 2011) m	Horizontal hydraulic conductivity (Margane et al. 1999) (m/s)	Vertical hydraulic conductivity (m/s)	Specific yield (MWI and BGR, 1997) -	Storage co-efficient (WAJ and BGR, 1997) (/m)
Layer 1	Amman & Wadi as Sir (B2/A7)	100	2×10^{-5}	1×10^{-5}	0.05	1×10^{-5}
Layer 2	Shueib & Hummer (A5/6)	50	1×10^{-9}	5×10^{-10}	0.01	1×10^{-5}
Layer 3	Fuheis (A3)	50	1×10^{-9}	5×10^{-10}	0.01	1×10^{-5}
Layer 4	Na'ur (A 1/2)	180	7×10^{-6}	3.5×10^{-6}	0.01	1×10^{-5}
Layer 5	Kurnub aquifer	200	3×10^{-5}	1.5×10^{-5}	0.25	1×10^{-5}

Water extraction

For the model simulation, the water requirement and abstraction data from the years 2002 to 2009 were used. There are five abstraction wells within the model domain which are, AB 1292, AB 1276, AB1221, AB1042, and AB 1190. The abstraction data were obtained from MWI, 2012.

Recharge

Recharge was estimated from the results of Wadi Kafrein hydrological model from 2002-2009 (Alkhoury, 2011). A physically based spatially distributed hydrological model was developed for Kafrein catchment area (Alkhoury 2011). The model was calibrated and validated for the time period from 2007 until 2009. The availability of historical measurements of the Kafrein dam reservoir made it possible to further validate the model from 2002 until 2007. The calibrated model was applied and run from 2002 until 2009 and the results of the model with regards to recharge were used as input for the current ground water model for the Kafrein catchment. Figure 3.7 shows precipitation and recharge values, monthly basis, from October 2002 until October 2009. It can be noticed that a decrease trend of precipitation amount in the last three years which off course caused a decrease in the recharged amounts. The hydrological year 2007/2008 is considered to be one of the driest years in the historical records (Alkhoury 2011). During the model calibration recharge was also adjusted. Recharge is applied on each cell of the model.

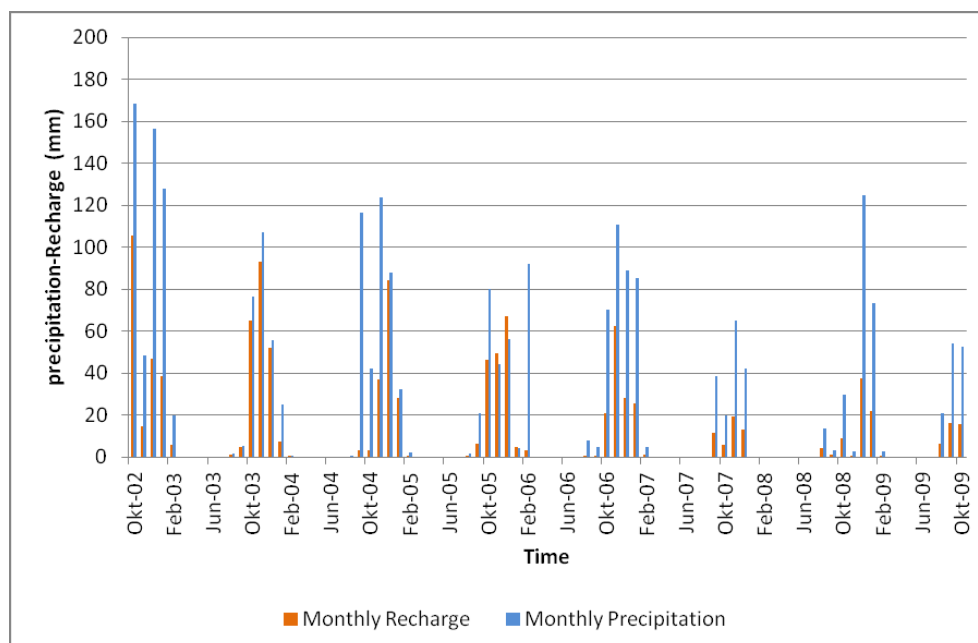


Fig. 3.5: Precipitation and recharge amounts for Wadi Kafrein from 2002-2009.

Model calibration

The calibration was basically done by trial-and-error combined with hydrogeologic knowledge, considering the information from reports and personal experiences. The model was calibrated against observed groundwater levels at South Shuna monitoring well (AB 1340). As the model setup considers only two-dimensional vertical cross section, calibration procedure was considered only for transient condition. Steady state simulation was done to construct the initial condition for the transient model. The calibration time was from October 2002 to February 2010.

Transient model

The time resolution of the transient model is monthly. Each time periods were divided into 10 equal time steps. The model was simulated for 2617 days, total time step is 1710.

Figure 3.6 shows the calibration output of the transient model. The figure was extracted from the visual Modflow software. The calibration plot shows that the simulated GWL matches nicely with the observed GWL after some period (210 days) of simulation starts. The system took these periods to stable the groundwater level originated from the initial condition. As the same initial condition was used for each layers (due to lack of information), it is quite understandable that the system require time to set proper water level condition for each aquifer. After that the model parameters were quite good to generate the GWL that matches with the observed values. During time period 1874 to 2056, the simulated groundwater level could not match the observed groundwater level. There might be error in recharge data or gathered abstraction data. Average standard error is 3.3 cm and correlation coefficient (estimated and observed GWL) is 0.975 considering the entire simulation period.

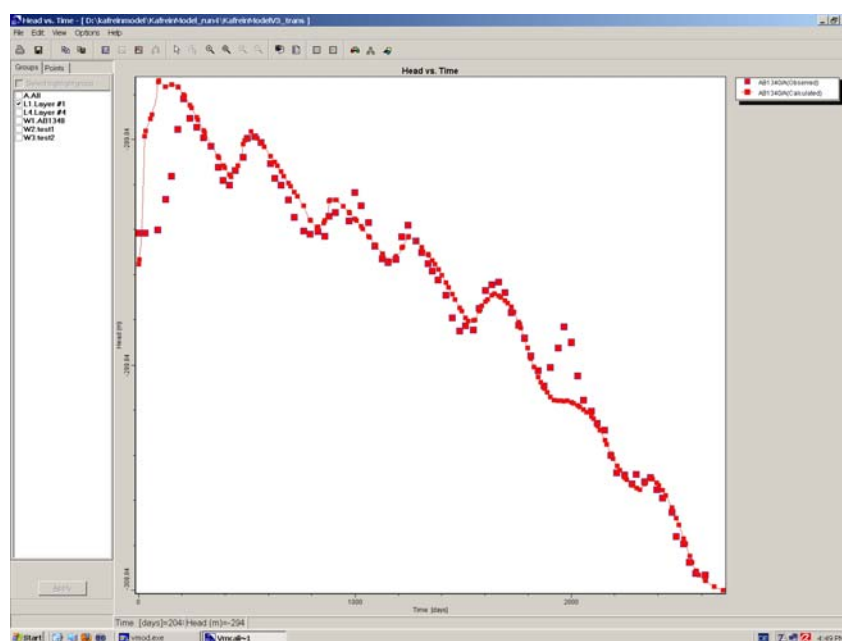


Fig. 3.6: Calibration plot.

Besides the aquifer properties, it was marked that the recharge plays a vital role to the model calibration. As the recharge was estimated from a 3D hydrological model, determination of recharge for this 2D model might not be accurate. Hence, some fine tuning of the recharge values were also made to calibrate the model.

The error in mass balance was more than 5%. As the calibration procedure was done only against one observation well that is located at the top most aquifer and no other information for another aquifer was available, the error in mass balance could not be reduced. Extensive efforts, use of personal experiences and available secondary information, were made to minimize the error.

Sensitivity Analysis

Sensitivity analysis is a procedure for quantifying the impact on an aquifer's simulated response due to an incremental variation in a model parameter or a model stress. The purpose of sensitivity analysis is to identify those parameters which are most important in determining aquifer behavior. Sensitivity analysis was carried out for the aquifer properties K_h , K_v , S_y and S_s . From the analysis it was clear that the model is more sensitive to the change in K_h value. S_y was the second sensitive parameter. K_v and S_s have little sensitivity to the model.

Result Analysis

Figure 3.7 shows temporal variation of flux from consolidated aquifer to unconsolidated aquifer of Wadi Kafrein. The figure considers the flux per 1m length of the aquifer systems (in y direction).

From the figure two aspects are clear:

- (1) The trend of maximum peak flux is decreasing in each season.
- (2) From year 2008, the flux is increasing and does not show the similar pattern than has been observed from year 2002 to year 2007.

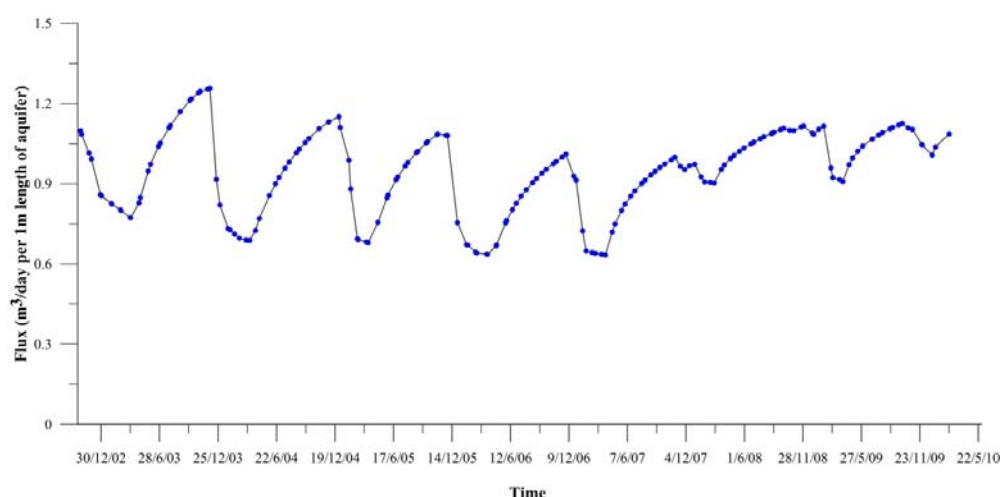


Fig. 3.7: Groundwater flux.

The groundwater level hydrograph of the observation well, located some distance upstream from the face of the unconsolidated aquifer, can explain this behavior to some extents. Groundwater flux largely depends on the hydraulic gradient. From year 2002 to year 2007, groundwater level was fluctuating seasonally, maintaining a decreasing peak in each season. Hence, the flux flow was also maintaining the similar trend. After 2007, there is a clear trend of groundwater lowering. Consequently hydraulic gradient increases overtime, allowing more groundwater flow to the downstream of the aquifer. Finally, the flux flow to unconsolidated aquifer started to increase from 2008. But the maximum flux flow did not cross the historical (from year 2002) maximum flux, due to the limitation of the storage capacity in the unconsolidated aquifer.

3.4 Conclusion and recommendations

This study successfully developed a 2D vertical cross-sectional groundwater flow model for the Wadi Kafrein catchment. The model is a principal model and hence does represent a basic pattern of groundwater flow. But this model can be used to evaluate groundwater flow from the mountain aquifer to the flat plain, predominantly to the unconsolidated aquifer. If we consider data scarcity of the area, a 2D model is more sensible approach to represent the general behavior of the groundwater catchment. The calibrated flow model was used to estimate the temporal variation of groundwater fluxes that are entering to the unconsolidated aquifer. The model can be used to simulate water resources development scenarios such as, climate impact, impact of agricultural development.

Considering the data scarcity, there are a number of opportunities to improve the model.

- (1) Use of more observation wells to calibrate the upper part of the model catchment
- (2) Acquisition of more geological data of the unconsolidated aquifer, means performing more drilling activities.

- (3) Gathering more geological information of the mountain regions.
- (4) Gathering of high resolution hydrogeological data (spatial and temporal).
- (5) The effects of fault zone can be investigated more extensively.
- (6) The model can be validated for other hydrological years.
- (7) The model did not consider separately the irrigation return flow. It was included cumulatively with the vertical recharge from rainfall. The return flow might be included separately and calibrated to estimate the actual value that is quite essential for agricultural water management. Based on the estimation, steps can be taken for effective irrigation practice.

4 Sub-basin Auja

Sebastian Schmidt, Florian Walter, Muath Abu Sadah

4.1 Introduction

Auja (ca. 4500 inhabitants) is the largest village in the Western Jordan Valley north of Jericho. The main economic activity in Auja is irrigated agriculture. Therefore, water demand is high and displays a high temporal variability. Water supply is constituted from the two main aquifer systems in the area:

- (1) The karst aquifer system:
 - upper aquifer layers naturally discharging at Auja spring,
 - lower (regional) aquifer layers, tapped by deep abstraction wells (depth up to 750 m),
- (2) The porous alluvial aquifer in the largely unconsolidated Quaternary sediments in the Jordan Valley, tapped by rather shallow abstraction wells (depth 40–100 m).

The availability of the water sources (e.g. discharge of Auja spring, which constitutes the main water resource) displays a high temporal variation. Therefore, a possibility to predict the water resources, which needs to be based on mathematical models, is required. However, the hydrogeology of both aquifer systems is poorly understood. Because the internal groundwater catchment boundaries of the carbonate aquifer system are unknown, distributed parameter numerical groundwater models can only be applied on a very large scale (e.g. SMART study area scale). The alluvial aquifer system is characterised by low recharge rates presumably from surface and spring runoff and possibly also cross-flow from the karst aquifer(s). However, during periods of low spring discharge, considerable quantities for irrigated agriculture can be obtained from the alluvial aquifer only.

In order to tackle the applied problems regarding the water resources:

- (1) the understanding of the flow system behaviour of the karst spring aquifer needed to be enhanced and a reservoir model (lumped parameter model) for the prediction of the discharge of the Auja spring, was developed,
- (2) a preliminary hydrogeological conceptual model and a numerical groundwater flow model of the alluvial aquifer system to evaluate options for managed aquifer recharge and underground water storage were developed.

4.2 Reservoir model of the Auja spring catchment

Background

The observed annual discharge of Auja spring is highly variable and ranges from 0.5 to 18 Million $\text{m}^3 \text{a}^{-1}$ (Fig. 4.1). This high variability has severe implications on agriculture in Auja village, where farming is the main mode of employment (e.g. planning of seedtime and general irrigation water availability). In addition to the highly variable discharge amount, Auja spring is displaying an unusual discharge behaviour compared to many other karst springs throughout the world (Schmidt et al., 2014). It is characterised by a limited flow capacity of the karst conduit network and hence by an upper limit of discharge around $0.5 \text{ m}^3 \text{s}^{-1}$.

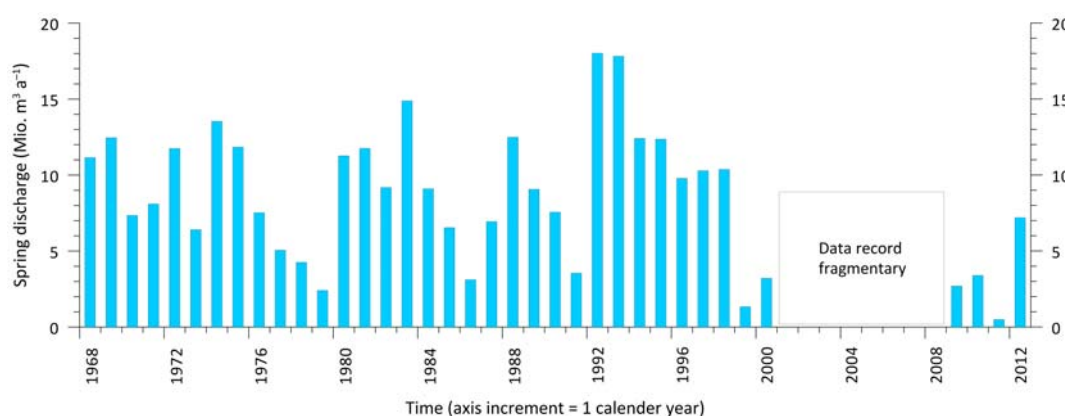


Fig. 4.1: Annual discharge of Auja spring from 1968 to 2000 (Palestinian Water Authority database) and from 2009 to 2012 (Schmidt et al., 2014).

Reservoir model

The reservoir model is documented in detail in Schmidt et al. (2014). Therefore, subsequently only a very brief summary is given but further discussion and recommendations are provided.

The mean long-term groundwater recharge fraction of precipitation of the Auja spring catchment could be estimated by a chloride mass balance method at about 34% (Schmidt et al., 2013). From the mean spring discharge and mean estimated precipitation depth over the catchment, a recharge catchment area of approximately 50 km^2 was calculated. This value is an important prerequisite for water balance calculations and lumped parameter modelling.

The aquifer system of Auja spring was investigated by a hydrogeological analysis, e.g. by conducting recession and event analysis of spring flow data (Schmidt et al., 2014). From the results, a conceptual model of the flow system was build. The spring flow system was modelled by a combination of a lumped soil water balance model and a reservoir model. The

reservoir model had to be specifically tailored in order to simulate the conduit restricted discharge behaviour, which was hitherto only in rare instances conducted in scientific literature. The soil/epikarst water balance module is split into two compartments in order to represent spatial variable system properties. It provides the recharge to the aquifer module. Also the aquifer module is consisting of two sub-modules, a highly permeable reservoir (karst conduit system, karst voids, and large scale fractures) as well as a low permeability reservoir (rock matrix with small scale fractures).

Due to the highly variable hydrometeorological conditions typical for semi-arid environments, an extended calibration period of 33 years was applied. The newly obtained discharge data for 2009–2012 (SMART I+II) provided the validation period.

Results

The lumped parameter model of the Auja spring aquifer system was used to refine the conceptual model and to derive a daily time series of groundwater recharge (deep percolation). For the 45-year time series analysed, the annual recharge rate is highly dependent on the annual precipitation sum and on the distribution of precipitation and potential evapotranspiration during the course of the winter season (Fig. 4.2). The bulk of recharge is constituted by high-precipitation years, whereas in average and less-than-average precipitation years, the aquifer is often not substantially recharged (Fig. 4.3).

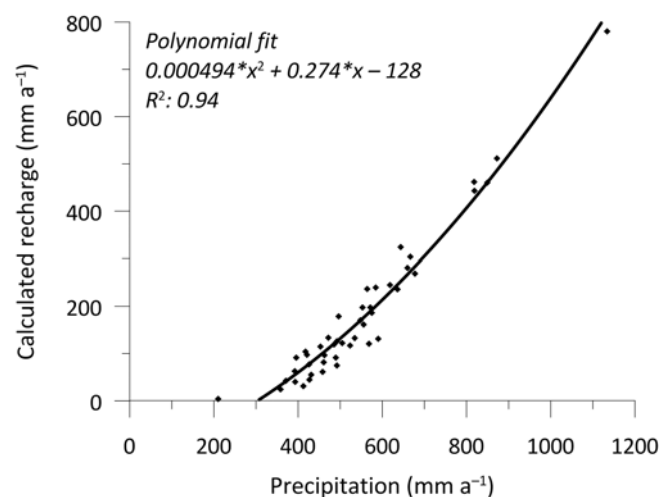


Fig. 4.2: Annual sums of groundwater recharge in the catchment of Auja spring calculated by the reservoir model and derived empirical equation from recharge estimation from annual precipitation sums. Modified after Schmidt (2014).

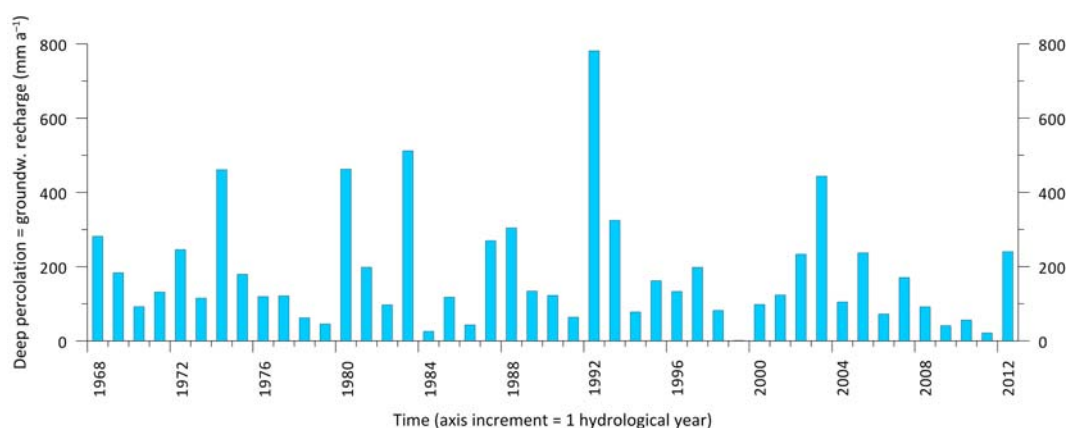


Fig. 4.3: Time series of annual groundwater recharge in the catchment of Auja spring calculated by the reservoir model.

Discussion, outlook, and recommendations

The model can be used to predict the spring discharge and hence irrigation water availability. A suitable time for prediction is after major precipitation events, especially when the last major precipitation event of the winter season has passed (which is usually the case around end of March = end of recharge period). At that time, the measured precipitation and temperature data can be included in the reservoir model and spring discharge during the summer season can be predicted. However, with the current model, three major issues have to be taken into consideration:

(1) Deep percolation calculated from the soil water balance implemented in the reservoir model is very sensitive to precipitation input quantity. For example for situations when the soil moisture storage is filled, any surplus in precipitation will become groundwater recharge. Because no continuous long-term daily time series are available from the expected recharge area for Auja spring, the daily precipitation time series for model calibration was obtained from station Jerusalem, located considerably to the south of the expected recharge area. The long-term mean precipitation in Jerusalem is expected to be similar to the long-term mean values in the catchment area and also to station Aqraba located north of the catchment area (Schmidt et al., 2014). Nevertheless for individual storms, large differences were observed, which are expected to be the cause of differences between measured and simulated values during certain periods (Schmidt et al., 2014). Therefore, it is highly recommended to implement reliable long-term daily precipitation monitoring schemes in the highland (=recharge) area. Those are especially important for springflow prediction. Also air temperature monitoring stations (daily minimum and maximum temperature) are recommended for the calculation of potential evapotranspiration. Nevertheless, this parameter displays less spatial variability and may be extrapolated from adjacent areas. However, it displays a strong correlation with altitude.

(2) In order to obtain enhanced model and prediction results, it is mandatory to delineate the catchment area of the Auja spring, e.g. by artificial tracer experiments, which will be

promoted in the follow-up project “SMART-MOVE”. This will enable (a) the enhanced measurement and model input of aerial catchment precipitation and (b) the enhanced measurement and model input of aerial potential evapotranspiration.

(3) In order to obtain unambiguous model results, the model complexity and accordingly the number of calibration parameters was kept as low as possible. However, for certain situations, the model results are deviating from the observations. Especially after prolonged with low or stopped spring flow, large precipitation events lead to less observed spring discharge compared to the model simulations. This may be attributed to recharge aurally entering the vadose zone as diffuse recharge and slowly percolating towards the water table. To include those effects into the model, further system investigation and subsequent model refinement is necessary.

4.3 Preliminary flow model of the Auja alluvial aquifer

Methodology

A transient groundwater flow model was developed by Dr. Muath Abu Sadah from Palestinian Hydrology Group in cooperation with Dr. Deeb Abdelghafour from Palestinian Water Authority. The model is based on measured and interpolated groundwater level data of four observation wells, using monthly time steps. Due to poor data availability in the study area, some of the input data, such as natural groundwater recharge rates, inflow from the mountain area or groundwater abstraction rates, is based on estimations and interpolation of the scarce data sets. For calibration, the time period of 2001 to 2009 was chosen.

The modelling approach allows a subdivision of the modelled aquifer in two groundwater flow regimes; the northern ‘Auja Region’ and the southern ‘Jericho Region’ (Fig. 4.4). The geological map was used as a basis to design the conceptual model. For the simulation of deep groundwater flow towards the carbonate aquifer and vertical fluxes between the aquifers, an additional thin layer at the bottom of the deep alluvial system has been defined. The thickness of the main layers has a maximum depth of around 1,000 m at the eastern system boundary. In order to represent the low permeable Lisan formation at the eastern part of the model area, an additional layer has been introduced.

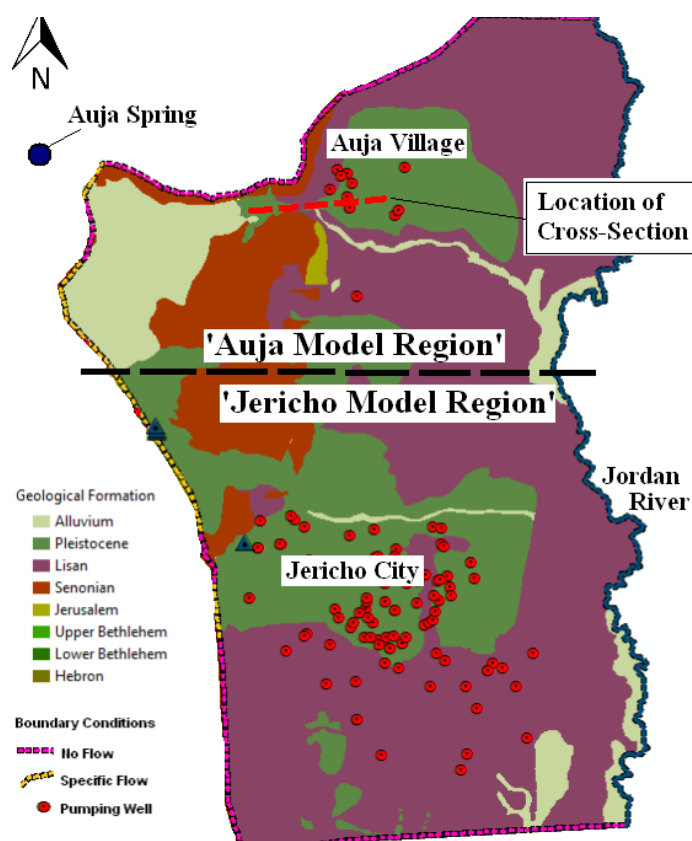


Fig 4.4: Modeling area with geology, wells and boundary conditions (Sadah, 2013, modified).

Natural Groundwater Recharge

Figure 4.5 provides an overview of the different recharge zones in the overall model region. This study, hence the following model description, concentrates on the northern part of model area, Wadi Auja.

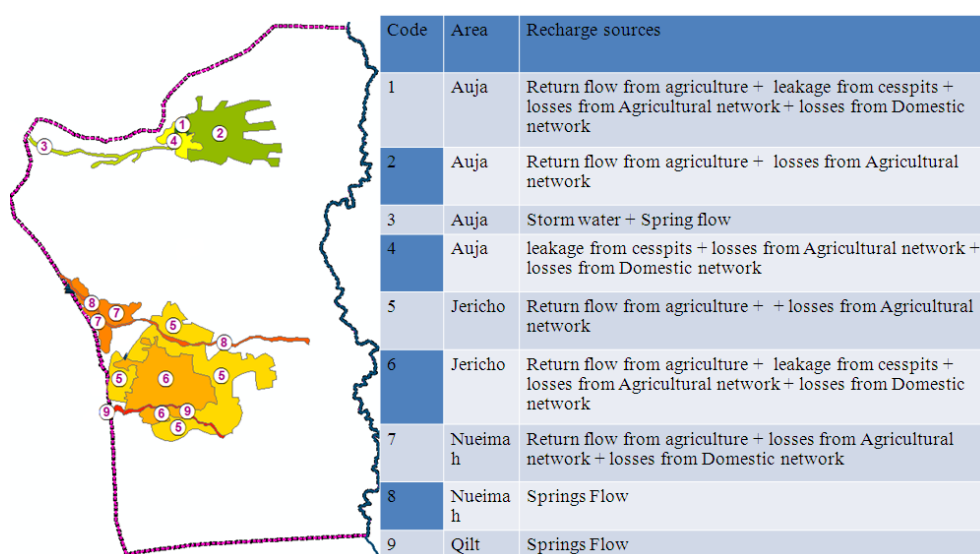


Fig. 4.5: Zones of natural groundwater recharge (Sadah, 2013).

For the Auja model four zones of natural recharge have been considered in the model. These zones are directly correlated to six sources of recharge; Auja spring discharge, storm water, return flow from agriculture, losses from agricultural network, losses from domestic network and leakage from cesspits. The recharge at zones 1,2 and 4 can be considered as insignificant. The recharge in zone 3 can achieve larger values in the Do-Nothing-Approach, but would be significantly reduced in case of the suggested pipeline construction between Auja spring and the surface reservoir at Auja dam on the one hand and the irrigated lands on the other. Further information on the hydrogeological model set-up, boundary conditions and flows, model calibration and hydraulic parameters are presented in Walter (2013).

Results

Several potential options of Managed Aquifer Recharge measures were tested applying the calibrated groundwater flow model of the alluvial aquifer. A Do-Nothing-Approach would result in a further groundwater table decline of 30 m within 20 years (Figure 4.6). In contrast, the implementation of the most promising MAR option would result in a stabilisation of groundwater head. The modelling results indicate that during periods of high groundwater head a considerable groundwater outflow towards the east (Jordan River area) has to be expected. For the most promising MAR option, the aquifer water budget for the 20 year simulation period is: Lateral inflow: 120 Million m³, well abstraction: 41 Million m³, and lateral outflow: 91 Million m³. Therefore, the assumption that the recharged surface water may be temporally stored in the demand areas around Auja village and fully recovered during the dry seasons could not be confirmed by the model simulations.

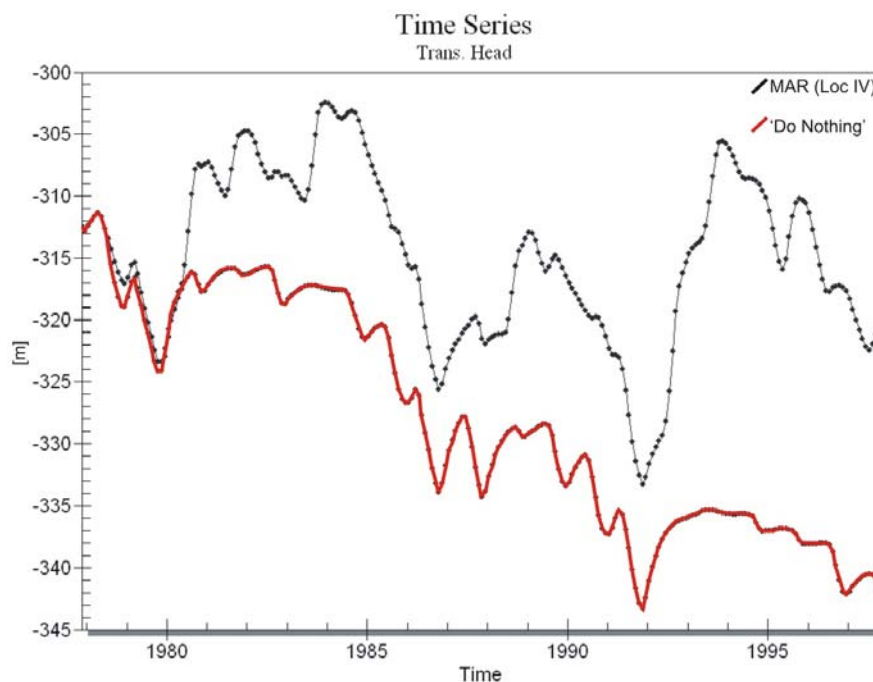


Fig. 4.6: Simulated groundwater head for selected MAR scenario and Do-Nothing-Approach.

5 Sub-basin Nueima–Qilt

Tino Rödiger and Christian Siebert

5.1 Groundwater flow model software - FEFLOW

The software FEFLOW (Finite Element subsurface FLOW system - WASY, 2006)) is usable for simulating groundwater flow, mass transfer and heat transfer in porous media. FEFLOW practices finite element analysis to solve the groundwater flow equation of both saturated and unsaturated conditions. In general, three-dimensional groundwater flow is based on mass balance and Darcy's law according to equation 5.1:

$$\frac{\partial}{\partial x}(k_x \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(k_y \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(k_z \frac{\partial h}{\partial z}) + q_s = S_s \frac{\partial h}{\partial t} \quad (\text{Eq. 5.1})$$

Where h is the hydraulic head, S_s is the specific storage, q_s is a sink or source term and k_x , k_y and k_z are the hydraulic conductivity in x , y and z direction, respectively. The modelling software FEFLOW is able to simulate the groundwater flow by solving equation (1) if specific boundary conditions, initial conditions and spatial distributed hydrogeological parameters are available.

5.2 Study area of Wadi Qilt-Nueima

The catchment of Wadi Qilt-Nueima is located in the central mountainous area of the West Bank, northeast of Jerusalem. The about 200 km² large surface catchment extends from Jerusalem eastward through the Judean Mountains into the plain of Jericho. The subsurface groundwater basin is nearly 760 km² large (Fig. 5.1).

The irregular distribution of annual precipitation ranges from more than 600mm on the top of the Judea Mountains to 50 mm and less in the Jordan Valley. Hence, the recharge area is strong delimited to the high-elevated outcrop areas of the aquifers in the western parts of the study area.

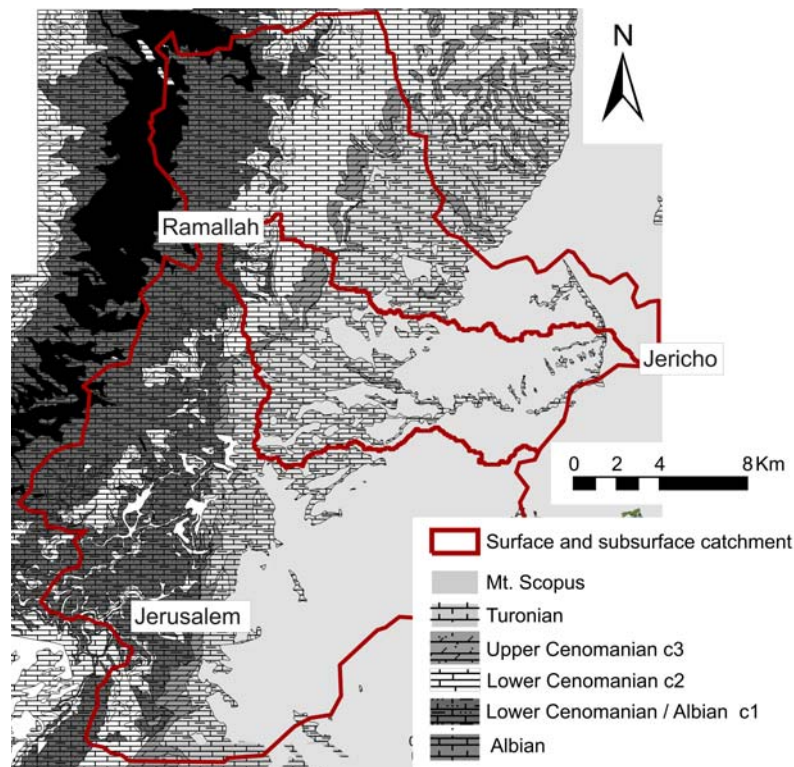


Fig. 5.1: Overview about the geology and the extension of the subsurface and surface catchment area of Wadi Qilt.

Hydrogeological background

The hydrological features of the study area are the aquifers of the Lower (Lower Cenomanian) and the Upper Judea Group (Upper Cenomanian – Turonian). The highest elevated region in the west and the entire western water divide is dominated by a large N-S directed anticline. From there, the strata dip generally towards the east, the reason why the deposits of the Lower JGA crop out in the western part of the catchment area. Towards the Lower Jordan Valley, the layers of the Upper JGA cover the Lower JGA. Close to the Jordan Valley, the base of the Senonian Mount Scopus Group is preserved on the top of the Upper JGA. The drinking water supply is based on both aquifers. In the next passage the stratigraphic units are written in Israeli / Palestinian terminology. The Lower Group consists of limestone and marly dolomite of the Soreq / Upper Bet Kahil (kus) aquitard, the limestone and dolomite of the Kesalon / Upper Bet Kahil (kuke) aquifer and the chalky limestone and chert dolomite of the Bet Meir / Yatta (kubm) aquitard. The Lower and Upper Judea Group are generally hydraulically separated by the aquiclude of the Moza / top of Yatta (kumo) formation. The Upper JGA is built by the dolomite of the Aminadav / Hebron (kua) aquifer, the chalky limestone and marls of the Kefar Shaul / Lower Bet-Lehem (kuks) aquitard, the dolomite of the Veradim / Upper Bet-Lehem (kuw) aquifer and the limestone and dolomite of the Bina / Jerusalem (kub) aquifer. Because of a dense network of tectonical features such as faults, a hydraulic connection between the both aquifer systems is possible (Fig. 5.2).

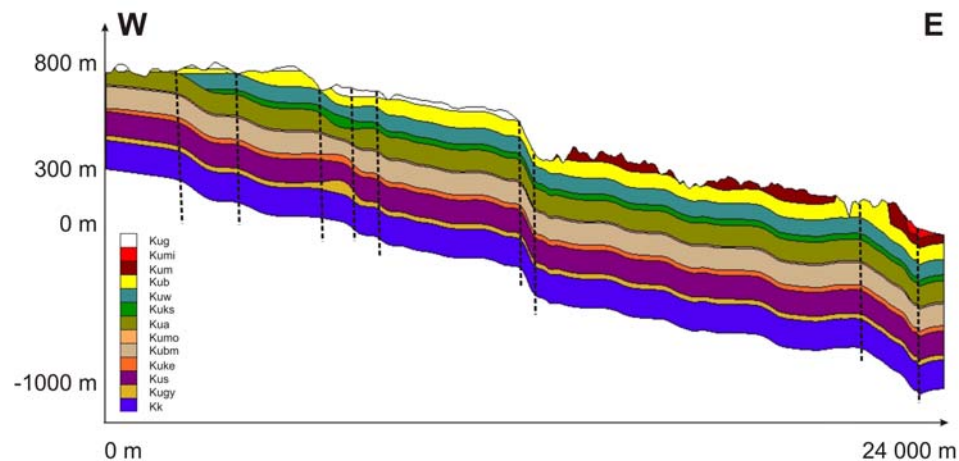


Fig. 5.2: Geological cross-section of Wadi Qilt from W to E

Fractured bedrock and variable karstified rocks represent the Judea Group. The high permeable conditions are controlled by the high tectonics activity of the region and the sedimentary facies and architecture. In the outcrop area both aquifers are characterized as unconfined. Local confined conditions occur where clayey or marly depositions intervene. However, towards the Lower Jordan Valley, the hydrological conditions change from unconfined to confined, forced by the covering low permeable layers. A groundwater contour map was prepared on the base of measured groundwater levels in about 60 wells, tapping the Lower and Upper Judea Group, respectively. The groundwater contours show, the groundwater level decreases in both aquifers as the strata dip to the east. The hydraulic heads fall from above 650 m msl to -50m msl and regional flow directions are eastwards. The groundwater flow patterns show generally no hydraulic connection to wadis.

Conceptual model

The conception of the hydrological model was set in the size of the groundwater flow model. Groundwater watersheds surround the subsurface catchment area. Subsurface outlet of the catchment area is the discharge of the Lower and Upper JGA aquifer to the Jordan Valley. The surface runoff of Wadi Qilt occurs only periodical as the result of rare but heavy rainfall events. Continuous baseflow is only existent in the case of the Ein Perrat and Ein Qilt spring system. The generation of surface runoff is subjected to the known process like infiltration excess, saturation excess and infiltration. The main control parameters of these processes are slope, aspect, land use, soil parameter and percolation rate. Groundwater recharge is only possible about infiltration processes (Fig. 5.3).

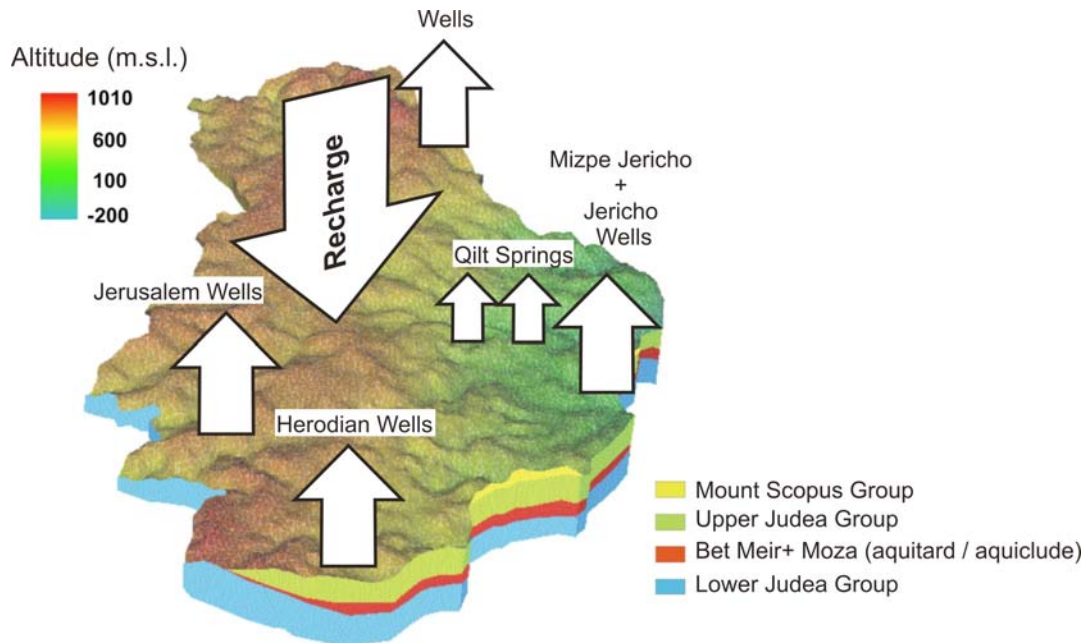


Fig. 5.3: The conceptual model and the set boundary conditions of the study area are shown.

Model set up / Boundary conditions and source terms

The model simulation period was set up for a time series from 1980–2008. In regarding of the conception model the numerical flow model was built up as 4 layers model. The elevation of each boundary was taken by digitizing the constructed cross sections to earn a digital underground surface elevation model of each formation (Fig. 5.4).

The nodes of the surface network were coded by x, y, and z-coordinates. Hence, the layers were imported into the numerical flow model and are the base of the 3D-flow-model. To determine the underground catchment, maps of equipotential groundwater table were performed and compared with the underground-DEM.

The surrounding groundwater watersheds are set as no flow boundary (1st kind boundary). The Graven flanks are defined to be boundaries of fixed heads (2nd kind boundary conditions). At the model surface, the ephemeral streams were not defined as 3rd kind boundary (river/transfer boundary), because they seldom to never show contact to the groundwater table which is mostly far below. Further, the definition of the wadi as 3rd kind boundary would imply errors in the model, because the FeFlow-model gets an additional recharge source during the dry season. Larger spring systems are represented by a 4th kind boundary condition (well). Their average discharge was taken from literature in order to get a sink term. The distribution of the boundary conditions and the set source terms are shown in Figure 5.5.

The mesh generating process is made by triangular prism elements. During that process, observation and abstraction wells with reliable (hydro-) geological information were used as additional locations for mesh-refining nodes. Particularly along important structural features

(e.g. fault systems), the mesh density is increased. The final model body consists of 61808 elements and 39465 nodes.

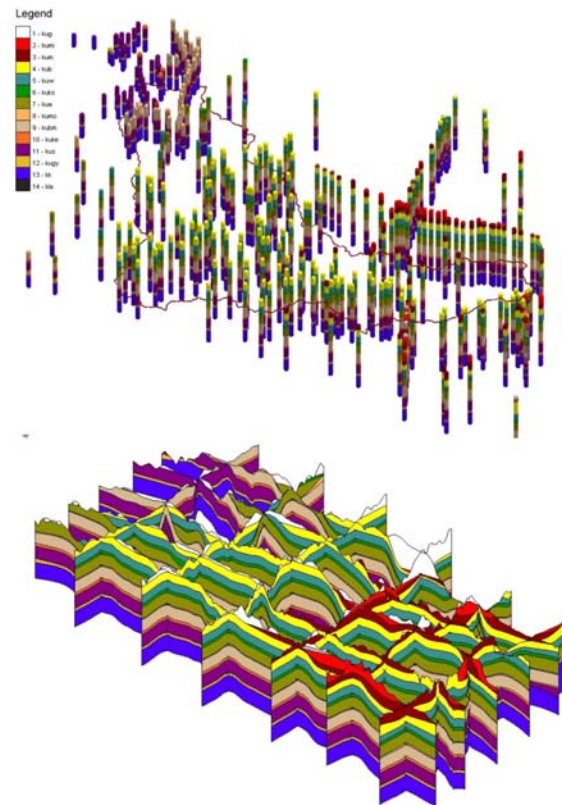


Fig. 5.4: The procedure of construction of geological cross sections is shown. Borehole records were used in order to construct geological cross sections.

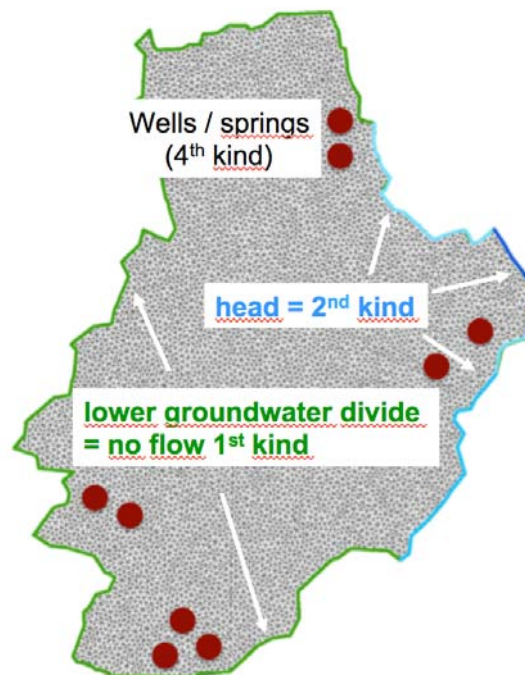


Fig. 5.5: Distribution of boundary conditions and source terms in Wadi al Qilt.

The groundwater recharge as consequence of infiltrating precipitation is set as source terms. In the steady state model the recharge was calculated by the empirical equation of Guttman and Zukerman (1995). The used average amounts of precipitation take the gradient from the mountain range to the Dead Sea and Jordan Valley into consideration. In the transient model, the temporary and spatially variable groundwater recharge is derived from the hydrological model J2000g of Wadi Qilt, which is described in detail in D405. The combination of the process-oriented hydrological model J2000g with the FEFLOW transient groundwater model was used to obtain realistic, spatially and temporally variable groundwater flow scenarios.

Groundwater abstraction from wells

The Israel Mekorot Company and the Palestinian Water Authority share the groundwater abstraction in the Lower and Upper Judean aquifer in the West Bank. It is to emanate from an operating well amount from over 60 wells. But monthly abstraction rates are only given for the wells PWA 1, PWA 2, PWA 3, Jericho 4, Auja4; Mizpe Jericho 6, Jerusalem 3, Shdema 1, El Azaria 1, East Herodian 2, Herodian 2 and Bani Naim 3 (Fig. 5.6).

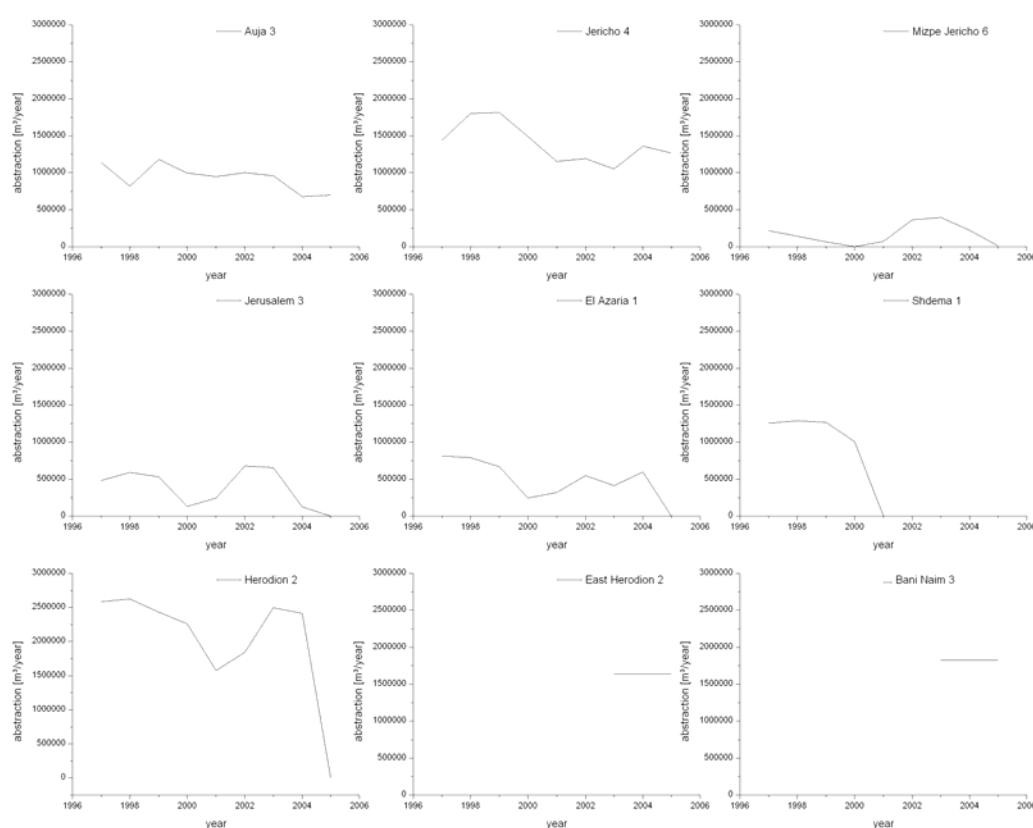


Fig. 5.6: Known abstraction rates for the time period 1996 – 2006.

The annual pumping rates range between 0.5 and 2.5 Million $\text{m}^3 \text{a}^{-1}$ per well. These wells belong to the most productive well fields in the subsurface catchment of Wadi Qilt. These wells fields are the Jericho -, Mizpe Jericho -, the Herodian -, and the Jerusalem well field.

The Jerusalem and Herodian well field are situated in the mountain region and abstracted water mainly from the Lower Judean Group aquifer. Eastward in direction to the Jordan Valley the well pumpage occur from the Judean aquifer through drilling deep wells in the foothills. In the 1970s an important water abstraction start with the construction of the Herodian and Jericho well fields. By further drilling of more production wells the groundwater table drop drastic in the Herodian well field. During the last 30 years the groundwater table decrease between 3 to 80 m in few wells. In fact to scarce detailed information of abstraction rates the total amount are mostly estimated by reference, like SWITCH 2006, PNA & PWA 2010; information from the Palestine Hydrology group and Mekorot Company. The current total abstractions from the Lower and Upper Judean aquifer are estimated with over 50 Mio m³ per year.

5.3 Results and discussion

Steady state model

The objective was to simulate the undisturbed groundwater heads in time for the completion of the well fields in the study area. The calibration of steady state conditions was done with initial heads in 16 wells distributed in the Lower and Upper Judea Group. After preparation of the numerical flow models, an automatic calibration of hydraulic conductivity was realized by using PEST.

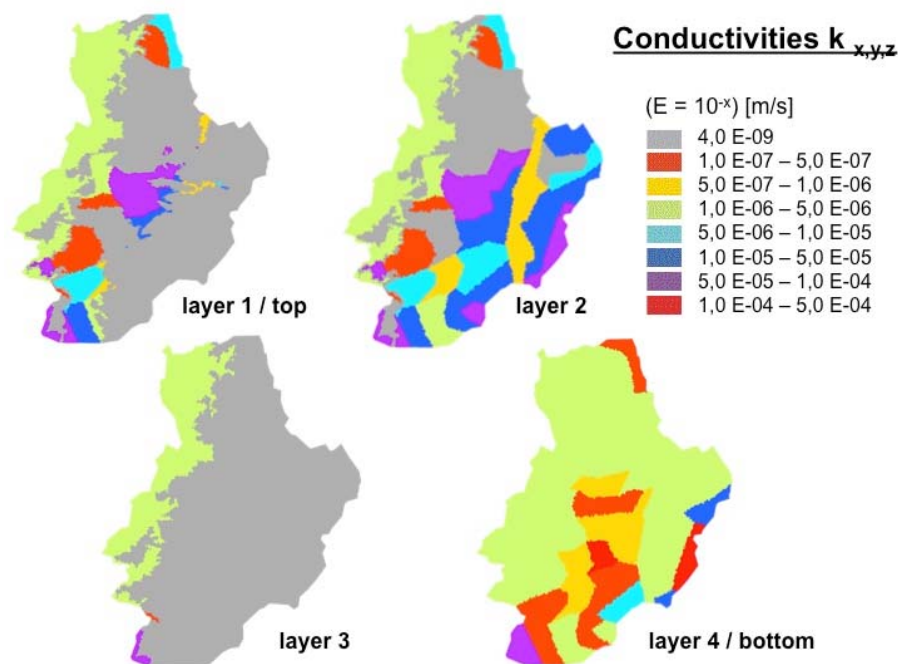


Fig. 5.7: Distribution of the adjusted values of hydraulic conductivity in Layer 1 to 4.

The estimated hydraulic conditions of layers of high permeability (karstified limestone) are 10^{-4} m/s. However, those of silt and clay are mainly between 10^{-7} to 10^{-9} m s⁻¹. The values represent the Moza and Bet Meir formation as aquiclude and aquitard. The median of hydraulic conductivity values lies between 10^{-5} and 10^{-6} m s⁻¹, a range which represents the regional conductivities of limestone very well (Freeze and Cherry 1979), which is proven by pump tests. The adjusted values of hydraulic conductivity are shown in Figure 5.7.

The observed and simulated hydraulic heads for the Lower Judea Group are represented in Figure 5.8. Calculated water levels represent the measured levels under steady state conditions very well.

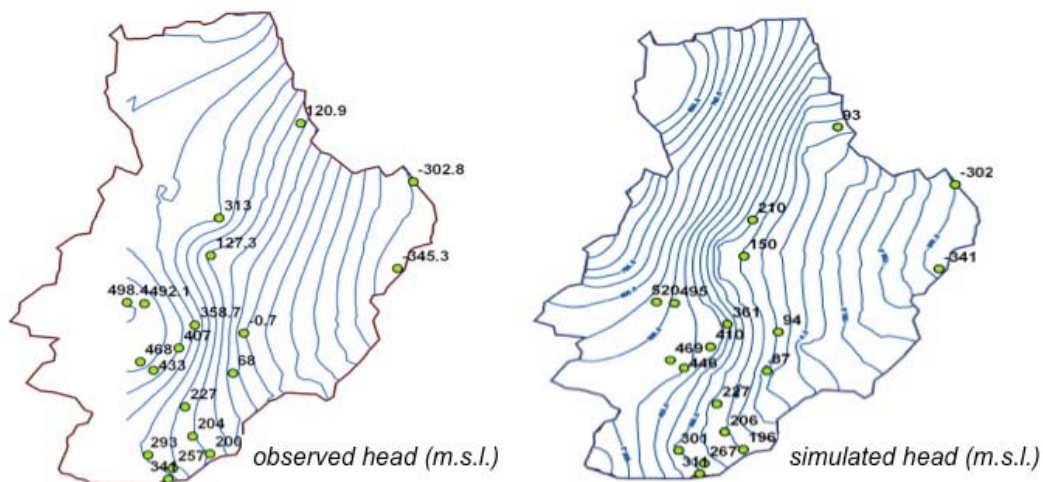


Fig. 5.8: Comparing of observed (left) and simulated (right) hydraulic heads under steady state conditions for the Lower Judea Group.

Transient model

The simulated groundwater recharge by J2000g will be used to complete the transient model in near future.

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