Groundwater resources in Jordan Valley: an integrated approach to the hydrogeological investigation of unconsolidated aquifers

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Abstract

In semi-arid areas groundwater systems are frequently not sufficiently characterized hydrogeologically and long term data records are generally not available. Long-term time series are necessary, however to design future groundwater abstraction scenarios or to predict the influence of future climate change effects on groundwater resources. To overcome these problems an integrated approach for the provision of a reliable database based on sparse and fuzzy data is proposed. This integrated approach is demonstrated in the lowermost area of the Jordan Valley.

The Jordan Valley is part of the Jordan Dead Sea Wadi Araba Rift Valley, which extends from the Red Sea to lake Tiberias and beyond with a major 107 km sinistral strike-slip fault between the Arabian plate to the east and the northeastern part of the African plate to the west. Due to extensional forces a topographic depression was formed. As a result of an arid environment it is filled with evaporites, lacustrine sediments, and clastic fluvial components. A subtropical climate with hot, dry summers and mild humid winters with low amounts of rainfall provide excellent farming conditions. The Jordan Valley is considered as the food basket of Jordan and is used intensively for agriculture. As a result hundreds of shallow wells were drilled and large amounts of groundwater were abstracted since groundwater is the major source for irrigation. Consequently groundwater quality decreased rapidly since the sixties and signs of overpumping and an increase in soil salinity could clearly be seen.

In order to achieve a sustainable state of water resources and to quantify the impact of climate change on water resources a proper assessment of the groundwater resources as well as their quality is a prerequisite. In order to sufficiently describe the complex hydrogeologic flow system an integrated approach, combining geological, geophysical, hydrogeological, historical, and chemical methods was chosen. The aquifer geometry and composition is described with the help of geological, hydochemical, and geophysical methods. As far as the water budget is concerned, the recharge to the considered aquifer is estimated with geological methods and available data sets, while the abstraction from the aquifer is estimated with the help of remote sensing techniques. A historical approach is used to detect the general conditions under which the groundwater system has been in the past. Afterwards this information is implemented into a flow model. On the basis of the findings a numerical 3-D transient model integrating all important features of the hydrogeological system was developed In order to be able to give reliable predictions about the impacts of climate change scenarios on the groundwater system the flow model was tested against stress periods depicted during the historical review of the test area.. These stress periods include periods of intense rainfall, of drought, and of anthropogenic impacts, like building of storage dams and of violent conflicts. Recommendations for future sustainable groundwater abstractions are given.

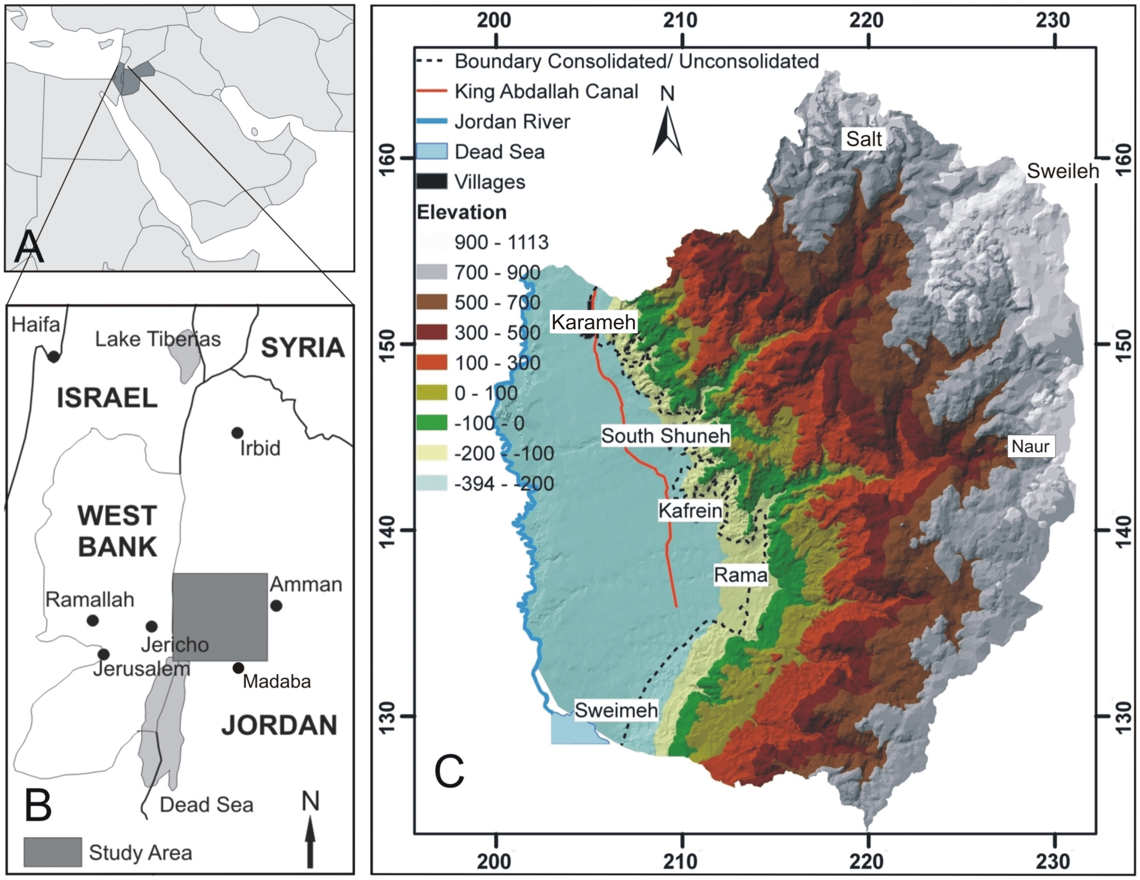

Fig. 1: Location of the study area. **A**: Middles East; **B**: Study area in the regional context; **C**: Study area.

Introduction

In order to achieve a sustainable state of water resources and to quantify the impact of climate change on water resources a proper assessment of the groundwater resources as well as their quality is a prerequisite. Therefore this article contributes to a better hydrogeological understanding of the anthropogenic influence on the groundwater system in the unconsolidated sediments of the Lower Jordan Valley/ Jordan. The area of interest extends from the Dead Sea in the south to the city of Karameh to the north, from the Jordan River to the west up to the margin of the western hills of the East Bank in the east. Nevertheless, the consolidated strata to the East were included in this study because it can be assumed that the major part of recharge to the unconsolidated aquifer originates from this area. In order to sufficiently describe the complex hydrogeologic flow system an integrated approach, combining geological, geophysical, hydrogeological, historical and chemical methods was chosen (Fig. 1). The aquifer geometry and composition is described with the help of geological, hydochemical, and geophysical methods. As far as the water budget is concerned, recharge to the aquifer is estimated with geological methods and available data sets, while the abstraction from the aquifer is estimated with the help of remote sensing techniques (Landsat data sets). A historical approach is used to detect the general conditions under which the groundwater system has been in the past. This information is then implemented into a flow model. This flow model must be able to describe the depicted stress periods on the groundwater systems in order to enable giving reliable predictions about the impacts of climate change scenarios on the groundwater system. The flow model provides the means for testing the consistency of the rather heterogeneous historical data set and allows the simulation of the future impact of management strategies as well as climate change scenarios.

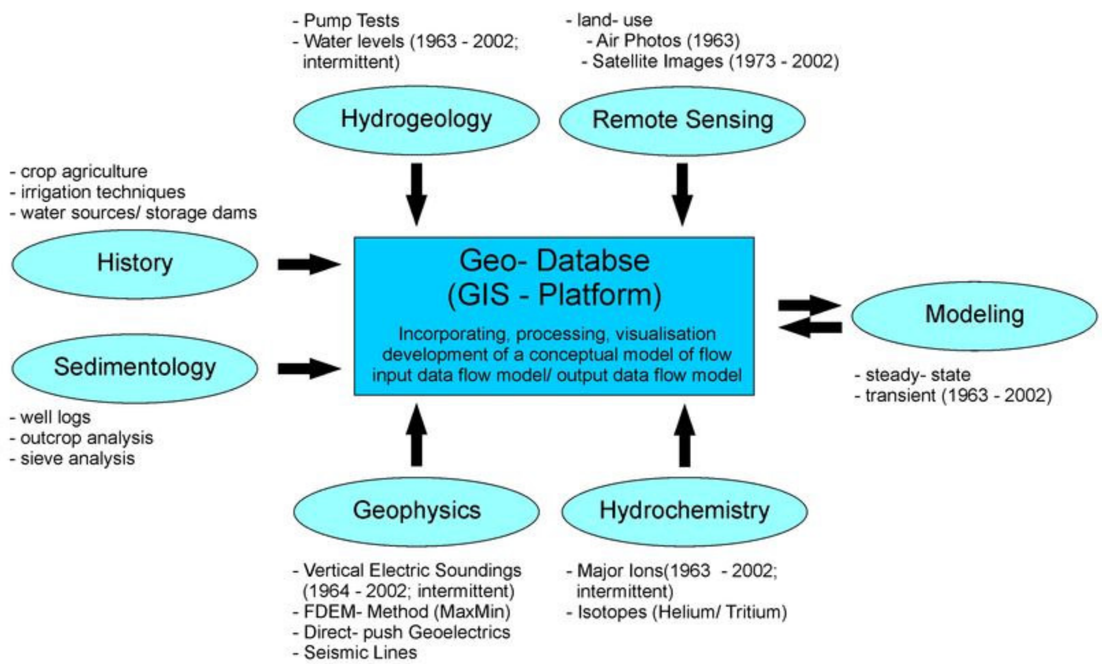

Fig. 2: Integrated approach for the investigation of the unconsolidated aquifers in the study area. The gathered information is stored in a geodatabase. With the help of the information gathered in the geodatabase a flow model is set up. The results of the flow modeling are stored afterwards in the same geodatabase.

The main focus of this paper is on the transient modelling of the studied aquifer system. However, the main findings of the other components of the applied integrated approach used are shortly presented. The characteristics of the aquifer system and the major hydraulic stress periods under which the aquifer system has been in the past are described in detail at Toll (2008a). The major findings will be repeated briefly since they are important for the understanding of the considered flow system.

Only the unconsolidated aquifer is subject to the modeling process. From the geological perspective the study area is characterized by an alternation of alluvial and lacustrine material. The alluvial facies dominates the area close to the East Bank foothills, especially near the outlets of the major wadis. The lacustrine sediments dominate the western part of the study area and the area between the major alluvial fans. The general groundwater flow is from east to west, whereby the groundwater quality, in terms of total dissolved solids, deteriorates along its flow path. The groundwater system of the study area has undergone considerable change since its agricultural development. The present-day flow system is in a transient state and is responding to stresses imposed on it. This is manifested in groundwater heads as well as in groundwater quality. The groundwater flow gradient (high groundwater flow velocities) is small in the area dominated by alluvial material and becomes steeper to the west and southwest of the study area. The steepest gradients (low groundwater flow velocities) can be observed in the vicinity of the Jordan River and the Dead Sea. This behavior was also verified by direct-push drilling along a north-south profile in the vicinity of the Dead Sea (Toll 2008b). This can be attributed to a) a reduction in grain size of the alluvial material in the more distal area and b) to an increase of the lacustrine fraction in the distal fan area. Recharge to the aquifer happens by direct percolation of runoff in the coarse wadi sediments of the major wadis during the winter seasons and by inflow of groundwater from neighboring consolidated aquifers.

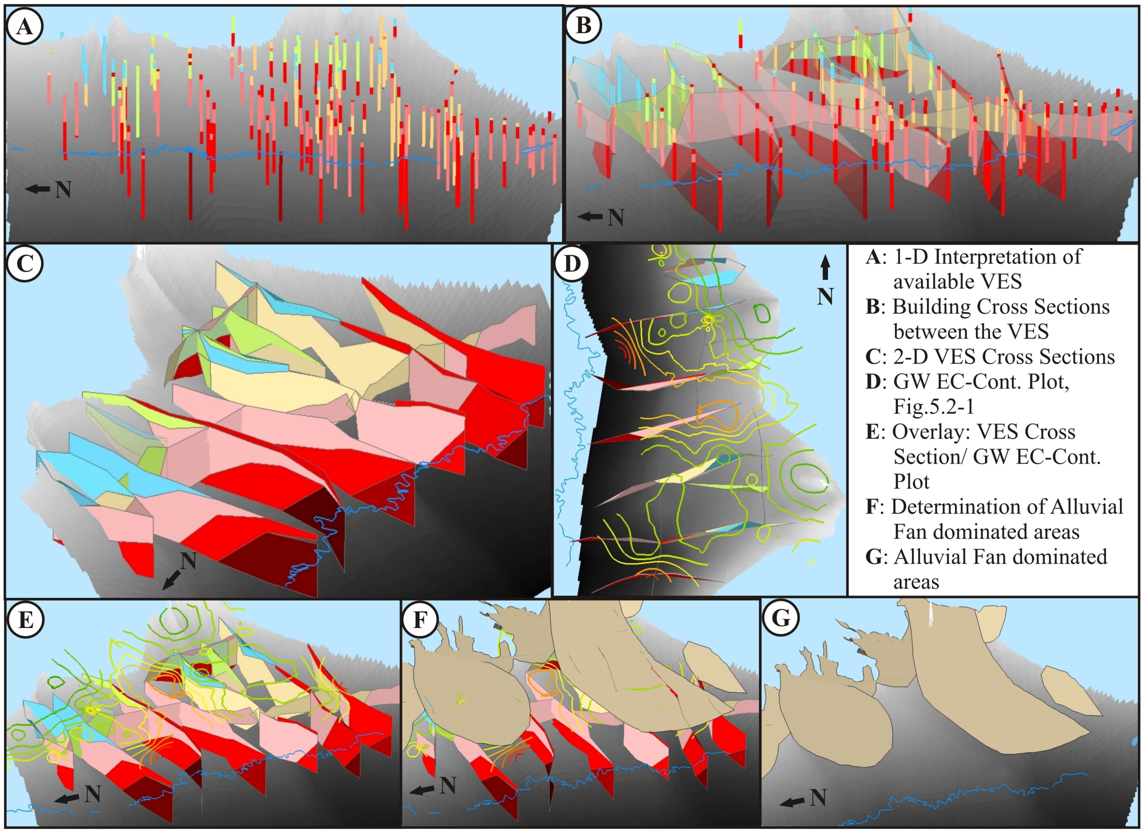

Fig. 3: Assumed influence area of alluvial fan sediments, depicted from the interpretation of VES and EC contour plots.

Model set-up, parameter estimation and steady-state modeling

A considerable amount of input data is required to construct and verify a distributed flow model. The numerical flow model is based on the FEFLOW code (FEFLOW 5.2, WASY Ltd.). Input parameters were pre-processed by ArcGIS 9.2 (ESRI Ltd.).

Two different areas were distinguished for the creation of the supermesh elements: areas dominated by the alluvial fan facies and areas dominated by lacustrine facies. The area dominated by the alluvial fan facies was estimated based on the hydrochemical and geophysical sections (Fig. 3). Due to the active left lateral motion of the Dead Sea Transform Fault the elongated alluvial fans of Wadi Kafrein and Wadi Hisban experienced a north-south displacement. For the Wadi Shueib alluvial fan a semi circular shape was chosen, since most of the alluvial fan is located away from the main displacement fault. A triangular mesh of 29,438 elements with 14,960 nodes was generated on the base of the digitized results of the previous sections. In the influence areas of the surface wadis, the triangular nodes were generated and refined along the drainage line of the different surface wadis. The mesh was refined in areas of high groundwater in- and output, e.g. along the flow course of the different wadis, and manually altered to avoid numerical problems with obtuse angles.

The following boundary conditions were set: No-flow at the northern, southern borders, and, for reasons stated above, in the middle of the eastern border. Fluxes were applied to the upper and lower part of the eastern boundary to simulate groundwater inflow from the adjacent consolidated mountain aquifers. Fixed-head boundaries were applied to the western boundary of the model domain. The recharge to the aquifer by infiltration of surface water was given by flux boundary conditions along the wadi flow path.

The calibration of a model is always crucial. The main problem is non-uniqueness. In order to reproduce observed values, e.g. groundwater elevation contours, unknown or not sufficiently known transmissivity etc. have to be adjusted. Accordingly, an over-parameterized model is unlikely to predict the impacts of a change in the system correctly, no matter how high the correlation between the calculations and the observations are. Just as crucial as the number of calibration parameters is their selection. Highly dependant parameters can produce identical results with different combinations.

The constraints for the hydrogeological model are subject to the following consideration: the groundwater tables should be reproduced correctly. This comparison between predicted and measured data is an important measure for the reliability of the final model. The verified model can afterwards be used to demonstrate impacts on future water abstraction scenarios and climate changes on the groundwater resources.

The transmissivities have been measured at several locations. Pumping test data revealed changes in transmissivity between the upper fan area and the lacustrine dominated area (in an area that solely is made up of lacustrine formations in the distal fan area, no pumping tests were performed) are more than one order of magnitude. The information gathered for the setup of the conceptual flow model with regard to the flow materials was applied insofar, that the concentric zones of hydraulic conductivity (onion layers) were adjusted to the respective alluvial fan shapes (Fig. 4 left), where highest hydraulic conductivities were applied to the alluvial dominated areas in the upper fan area and lower transmissivity values in the lower to distal fan area. Lowest transmissivity values were applied to areas dominated by lacustrine sediments.

No recharge from rainfall was attributed to the model for reasons stated above. Recharge to the model domain were applied by flux boundary conditions either on the upper and lower eastern boundary or along the flow course of the different wadis (Wadi Hisban and the minor wadis southwest of it). The flux conditions on the eastern model boundary reflect the inflow of groundwater. The recharge to the unconsolidated aquifer from the infiltration of runoff and baseflow surface water is reflected by the flux conditions applied to the different wadi flow courses. An infiltration of 50% of the runoff water, that flows in the different wadis was assumed. However, infiltration into the unconsolidated aquifer will be, due to the coarser nature of the sediment material, higher in eastern part. Therefore it was assumed, that 60% of the infiltration water infiltrates in the first third, 30% in the second third, and 10% in the last third of the different wadi courses. The only exception is Wadi Shueib, here 60% infiltrates in the first one third and 40% in along the remaining two thirds of the wadi flow. Therefore 12 different flux, two for the groundwater influx in the area east of South Shuneh and the area east of Rama and ten for the different wadi sections, were assigned to the model (Fig. 4 right).

Extraction zones were created since no information regarding pumping amounts and duration of the wells in the study area exists. The basis of the these extraction zones are well locations (Fig. 4 right). Around the well locations polygons were drawn (Fig. 4 right) and its area calculated with the help of the ArcGIS 9.2 software (ESRI Inc.). These areas were later imported into FEFLOW and used as sinks and represent the pumping activity in the area (extraction of water per area of the polygon). However, variations in groundwater heads measured in single observation wells cannot always fit the calculated heads, because groundwater extraction in the model averages over a wider area (the whole area of a polygon) than the groundwater extraction that takes place through individual wells. But this method should be able to represent seasonal trends.

The goal of calibration is to obtain an optimal fit between the calculated and the measured data. In this approach, data consists of average groundwater heads (1987 – 2002) of available well data. The remaining parameters, like the transmissivity distribution, the inflow of groundwater from the adjacent mountain aquifers, the outflow through the western and southern boundaries, and the evaporation rate has been used for calibration. Fig. 5 right shows the result of the steady-state simulation.

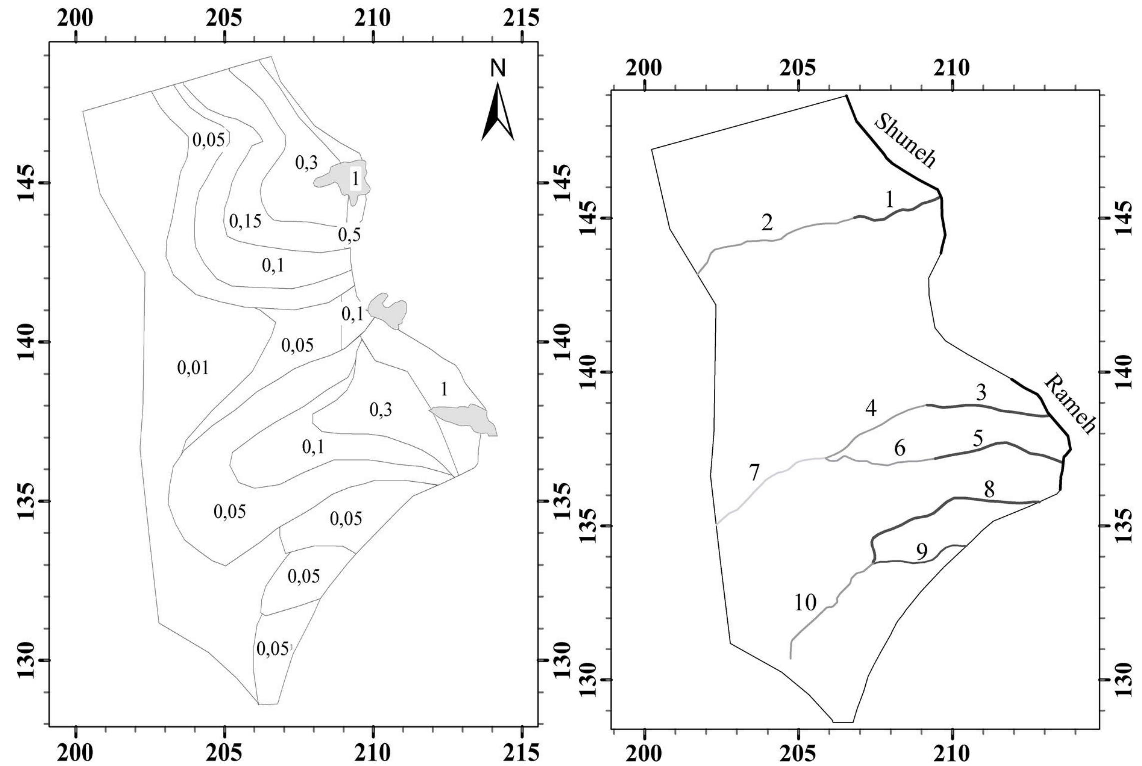

Fig. 4: Left: Hydraulic conductivity values assigned to the different zones of the model domain [10E-04 m/s]. **Right:** Fluxlines assigned to the model domain. 1 through 10 represent inflow along the different wadis section and Rama and Shuneh represents the inflow of groundwater into the model domain.

Transient Model

The steady state calibration was constructed to estimate the hydraulic parameters of the subsurface and the amount of groundwater inflow into the study area. In order to simulate the influence of pumping activities over time, a dynamic model was constructed. The basic geometric set-up and material parameters of the aquifer is analogous to the set-up used for the steady state simulations. The aquifer top elevations were taken from the 1: 25,000 topographic map (Royal Geographic Center) and aquifer bottom elevations were taken from Toll (2008b). The hydraulic conductivity values are shown in Fig. 4 left. The transient model was set up for unconfined flow. Additional input data required for transient simulations are (estimated values are given in brackets): the initial conditions and storativity (0.1). Moreover, the discretization of the variable time has to be defined (time steps were adapted automatically by FEFLOW). The dynamic model simulates the influence of irrigation on the groundwater household in the study area in two different steps. First, yearly variations of pumping activities and yearly variations of groundwater inflow into the model domain had to be estimated. Therefore a dynamic calibration was applied to the model domain. Second, the dynamically calibrated model is applied to two different time periods: 1955 – 1970 and 1975 - 2001. These periods were limited by data availability. No information (hard or soft) for the period 1970-1975 was available. No data was available for the period end 2001 onwards. The main difference between this steady state model and the model used for calibration starting from the 60ies onward is the modified discharge.

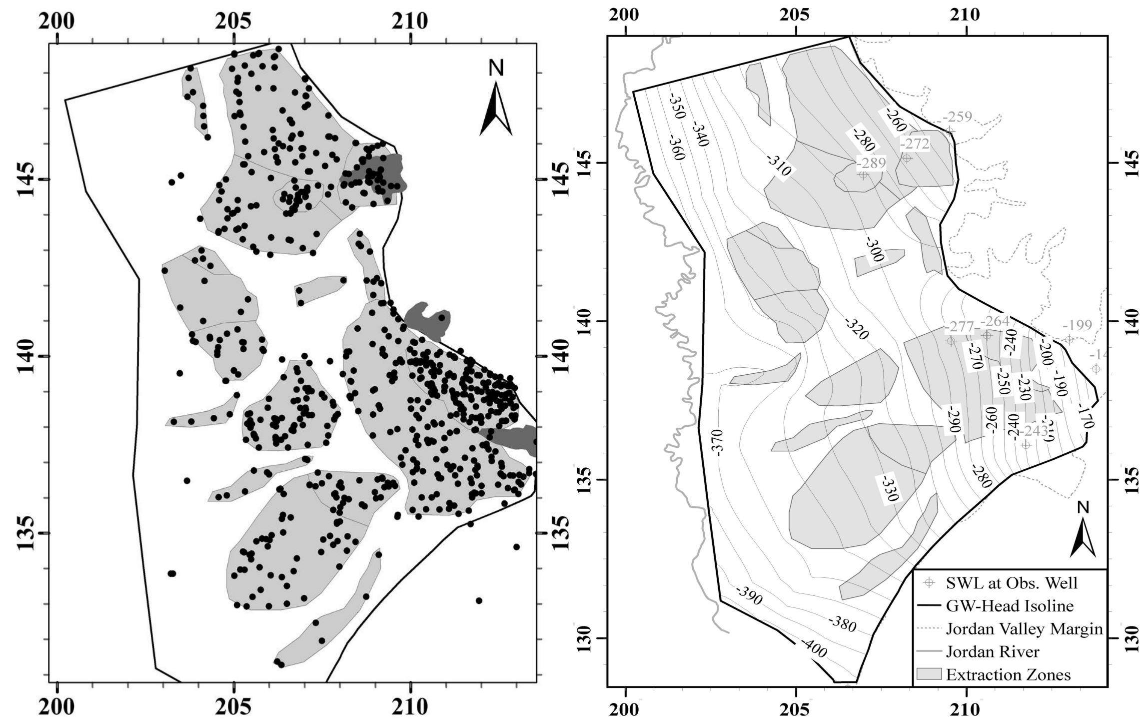

Fig. 5: Left: Well locations and groundwater extraction zones. **Right:** Hydraulic conductivity values assigned to the different zones of the model domain [10E-04 m/s].

In order to adjust the yearly variations of inflow and outflow into the model domain and to fine adjust the flow material parameters, a dynamic calibration for a period of 120 years have been undertaken. As far as the inflow and outflow of groundwater into the model domain is concerned, average values for the period of 1956 to 1968 were entered. Monthly stream flow data was taken from the Water Master Plan Vol. III prepared by the GTZ (1977). An infiltration of 50% of the surface stream flow amount was assumed along its flow from the east towards the west. As in the case of the steady-state model a 60, 30, 10% estimation was made. The total recharge to the model domain was estimated by Tleel to be 3.7 in the area of Shunat Nimreen and 13.1 million cubic meters in the area of Kafrein and Rama. In order to reach a balance between inflow and outflow, the extraction zones, described above, were used. Two different pumping periods were assumed: a winter (first 200 days, no pumping activity) and a summer pumping period (the remaining 166 days). The difference between the recharge estimated by Tleel (1963) and the amount of the infiltrated surface stream water was assigned as groundwater inflow through the eastern flux boundary conditions near Shuneh and near Rama.

The results of the dynamic calibration were used for the first modeling period. The modeling period began in October 1955 and lasted until September1970. In the mid fifties intensive well drilling began in the study area and subsequently groundwater abstraction increased until it reached its peak in the mid sixties (Toll 2008a). Unfortunately groundwater heads of different wells existed only from the period of 1962 to 1970.

Like in the case of the dynamic calibration, infiltration of half of the surface water coming from the eastern catchment area was assumed along the major wadis in the area. Along its flow towards the west the same assumption about infiltration rates were made. The monthly surface water flow was taken from the Water Master Plan GTZ (1977). Groundwater abstraction rates increased from the 1950ies and at the beginning of the sixties until the political conflict in 1968 and its aftermath the abstraction amount was kept constant. The same pumping seasons as used during the dynamic calibration were used. During the events of 1968 pumping activities seized for most of the study area and were reduced significantly up until the beginning of the 70ies due to the reasons stated Toll (2008a). The inflow of groundwater into the study area is constant for the whole period.

The water budget of the transient model run can be seen in Tab. 1. It can be seen, that except for the events of 1968 and their aftermath the water balance is always negative. Even the rainfall intensive season 1966/67, which lead to an increase in the water table in the study area had a negative balance. Fig. 6 shows the measured versus calculated groundwater levels. A fairly good match between the calculated and measured groundwater heads was achieved. The continuous decrease during the rain poor season 1965/66 and the sharp increase of the groundwater levels during the rain intensive season 1966/67 could be represented correctly. The continuous increase of groundwater heads from 1967 until 1970 however, cannot be explained only by variations of drier or wetter years. Therefore, the assumption, that effects of the events of 1968 and their aftermath lead to no or only few pumping activities was validated, since this effect would only explain the behavior of the groundwater table in the study area. It should be noted, that the calculated groundwater heads in the area of Shunat Nimreen do not match as good as in the case of the area around Rama. This can be attributed to usage of sinks instead of single well extractions for simulating groundwater extraction.

The second model period ranges from October 1975 until September 2001. Here groundwater extraction rates are based on the findings of Toll (2008a), where the minimum water requirements for the study area was estimated with the help of remote sensing data (Landsat data). Since the commissioning of two earth filled dams at the outlets of Wadi Shueib and Wadi Kafrein, both located close towards the east of the study area, infiltration of surface water seized along the course of these two wadis. No information regarding surface water flow in the hinterland of the major alluvial fans and the storage of water in the dams was available. Since the inauguration of the third extension of the KAK another irrigation water sources is added to the area of Shunat Nimreen.

Tab. 1: Water budget for the period of 1962/63 to 1969/1970 of the transient model run; Surf. Inf = Inflow of water along the different wadi sections (infiltration of surface water), Border = Inflow/outflow of groundwater through the flux boundaries (groundwater inflow/outflow), Pumping = Sink through the different extraction zones (groundwater pumped out for irrigation purposes).

	Flux in			**Flux out**			**IN - OUT**
Year	**Surf. Inf.**	**Border**	**Total**	**Border**	**Pumping**	**Total**	**Total**
[-]	**Mass [m3]**	**Mass [m3]**	**Mass [m3]**	**Mass [m3]**	**Mass [m3]**	**Mass [m3]**	**Mass [m3]**
1962/63	3,61E+06	1,25E+07	1,61E+07	-2,94E+06	-2,77E+07	-3,06E+07	-1,45E+07
1963/64	6,55E+06	1,25E+07	1,91E+07	-2,95E+06	-2,25E+07	-2,55E+07	-6,42E+06
1964/65	8,40E+06	1,25E+07	2,09E+07	-2,90E+06	-2,77E+07	-3,06E+07	-9,65E+06
1965/66	5,77E+06	1,25E+07	1,83E+07	-2,87E+06	-3,54E+07	-3,83E+07	-2,00E+07
1966/67	1,32E+07	1,25E+07	2,57E+07	-2,80E+06	-2,33E+07	-2,62E+07	-4,37E+05
1967/68	9,06E+06	1,25E+07	2,16E+07	-2,76E+06	-1,90E+07	-2,18E+07	-1,95E+05
1968/69	8,41E+06	1,25E+07	2,09E+07	-2,72E+06	-1,64E+06	-4,36E+06	1,66E+07
1969/70	8,38E+06	1,25E+07	2,09E+07	-2,66E+06	0,00E+00	-2,66E+06	1,82E+07

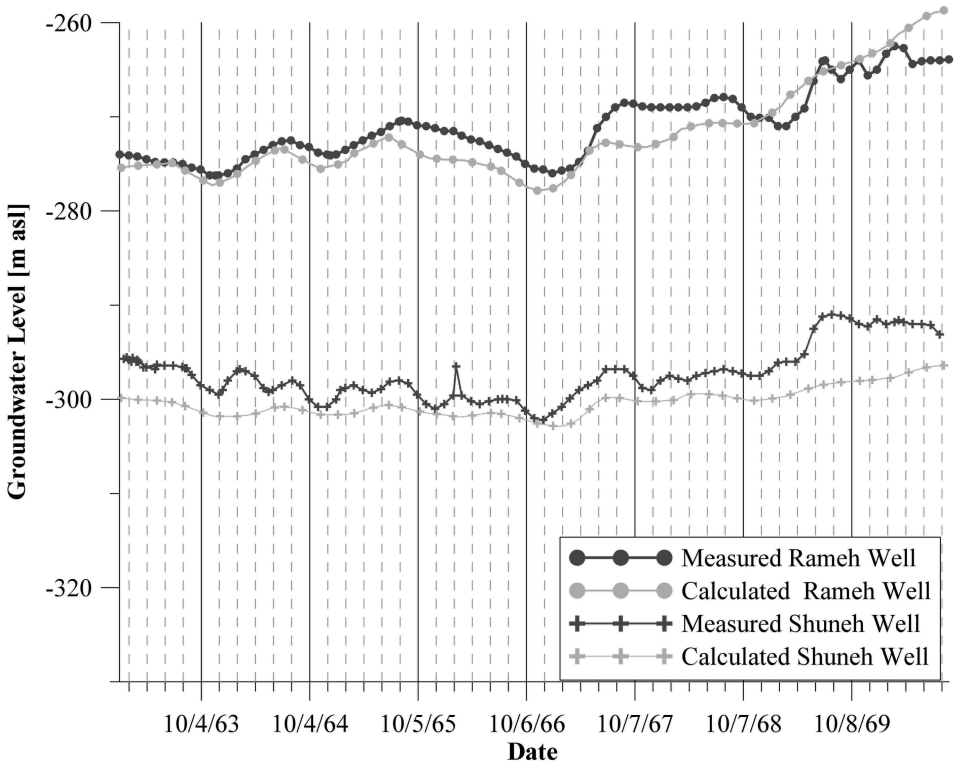

Fig. 6: Calculated versus measured groundwater heads for the period of 1963 to 1970.

First, the field water requirement of the study area was determined with the help of the method described in Toll (2008a). Different Landsat scenes were used to determine the irrigated area in the study area. In order to estimate the yearly water requirement of the irrigated culture in the model domain, the Landsat scenes taken on 2nd March 2002, on 21st of May 2000, and on 14th of August 1987 were used. These classified areas were allocated to the different extraction zones and their field water requirement (for drip irrigation) calculated according to the procedure described in Toll (2008a). Land use (vegetables or banana planting) for the different areas of the study area were considered as well as their respective growth stages. Taking the different planting and harvesting seasons under consideration, the yearly field water requirement, based on the classification results of the different Landsat scenes, was calculated. The calculation revealed that a total of around 38 million cubic meter of irrigation water is needed to irrigated the farmland in the model domain. Since no other information regarding planting activities exist for the study area this water demand is kept constant for the whole modeling period.

For the second considered period, no data regarding surface flow in the different wadis was available. Therefore, the next parameter to be estimated is the amount of surface water available for irrigation in the study area. The best fit straight line method described Toll (2008a) were used to estimate surface flow for the considered period.

The next step is to estimate the amount of pumped water for the model domain. Since the water stored in the different dams and the water flowing in Wadi Hisban is exclusively used to irrigated farmland within the study area, the deficit between the estimated field water requirement and the surface water flow represents the amount of groundwater that is necessary to irrigate the farmlands. The only exceptions are years with intensive precipitation. Usually direct precipitation on the irrigated farmlands can be neglected. However, rainfall intensive years (e.g. 1991/92) do contribute to the irrigation of the farmlands and also contribute recharge to the groundwater system. The last step in preparing the transient model was estimating different pumping periods for each year. Four different pumping periods were chosen to represent the extraction of groundwater for each season: 15th of December until 15th of March, 15th of March until 31of May, 01st of June until 31st of July, and 01st of August until 15th of December. These periods were chosen according to the planting and harvesting season in the area (Toll 2008b). Since the rainy season is usually not very intensive until the mid of December and decreases usually by the end of March, very low to no pumping activities can be assumed for the first pumping season, low to very low pumping activities in the second pumping season, medium pumping activities in the third, and high to very high pumping activities in the last pumping season. These assumptions were applied to all extraction zones, which were labeled with shared irrigation sources (well plus surface water). For the different irrigation water sources see Toll (2008a). All extraction zones that have well water as their only irrigation water source, pumping activities throughout the whole planting season were applied. The last assumption to the transient model is related to the commission of the King Abdullah Canal in 1987. After its inauguration it serves a sole irrigation water source for most of the area north of South Shuneh. Therefore, starting with the commission of the canal pumping activities in its influence area seized.

Fig. 7 shows the measured versus calculated groundwater heads. A good fit between calculated was achieved. However, the groundwater level fluctuations of the measured wells cannot be calculated exactly. This can be explained for the reason stated above (the usage of sinks instead of single well extractions for the simulation of groundwater extraction). During the model run it became obvious, that groundwater inflow into the study area cannot be constant, as assumed during the model run for the sixties. In order to achieve a good results of calculated versus measured groundwater heads more groundwater inflow into the study area must take place during rain intensive seasons and less in rain poor seasons.

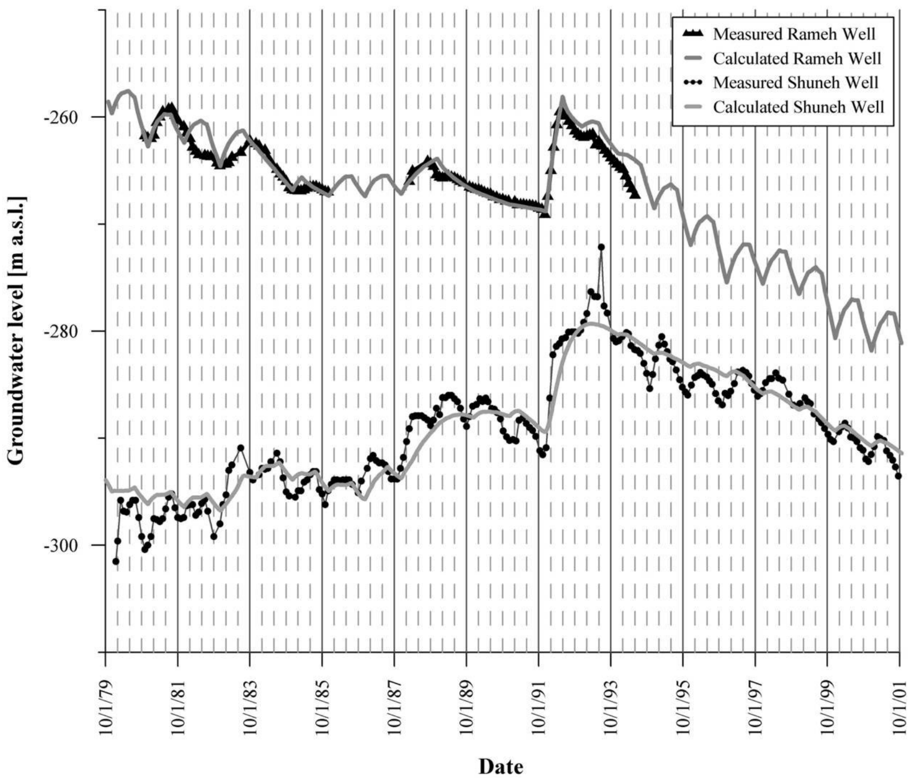

Fig. 7: Calculated versus measured groundwater heads for the period of 1980 until 2001.

Implications for groundwater management

The groundwater resources of the unconsolidated aquifer should be used intensively, since high groundwater levels lead to steady- state evaporation of groundwater in the distal fan area. However, the extraction of groundwater should happen in a sustainable manner. Overexploitation, as practiced during the 1960ies, leads to groundwater quality deterioration. Groundwater should be extracted in the upper to mid-fan area, since the salinity of the groundwater increases along the flow path to the west. In the mid-fan to more distal fan areas groundwater can be used to irrigated salt tolerant crops, like e.g. tomatoes or squash. Groundwater extraction between the major alluvial fans should be avoided, since inflow to these areas can only occur from the major alluvial fans. In addition, these areas are dominated by the saline Lisan Formation. Furthermore, wells drilled in these areas will yield only small quantities of groundwater, since these areas are dominated by clays to silts. In general, groundwater should be extracted rather from many wells pumped with medium pumping rates, than from few wells with high pumping rates. Increased pumping activities from single wells leads to a serious increase in groundwater salinity. Once the salinity increases, it is a rather long process to reduce the increased salinity. It should be noted, that in the upper to uppermost areas pumping activities can be high. Due to the high amount of groundwater entering from the neighboring consolidated aquifers, and, more important, from leakage of the earth filled dams, increased salinity in these wells can be reversed quickly. In areas were the inflow from neighboring consolidated aquifers is the only source of recharge, pumping rate should be medium, since increased pumping activities in the unconsolidated aquifer might lead to increase in salinity in the consolidated aquifers, which can only be reversed slowly.

In general the questions must be raised, if it is wise to plant crops with high water demand in an arid area. This is insofar important, that large areas in the upper fan areas are planted with banana plants, which demand large quantities of low saline irrigation water. Jordan faces today and even more in the future a severe water crisis, therefore all available resources should be used in the most efficient manner.

Acknowledgements

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