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Integrated investigation of Stressed Groundwater Resources in Brackish Unconsolidated Aquifers

Toll, M.[1], Salameh, E.[2], Sauter M.[1]
1. Applied Geology, University of Göttingen, Göttingen, Germany
2. Department of Applied Geology, University of Jordan,
Amman, Jordan

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. Therefore 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.

Keywords: Integrated Approach, Jordan Valley, 3-D Flow Model, Jordan

Introduction

Today, Jordan, already among the ten water poorest countries in the world, faces a severe water crisis. It was estimated, that only 20% of the renewable water resources can be used. The rest is lost through evaporation (Salameh and Haddadin 2006). Because of the inflow of refugees from neighboring countries, which took place over the last 66 years, the population grew 11.5 fold (Salameh and Haddadin 2006). This population increase along with the rapid socio-economic development put stress on the water demand. Groundwater resources are overused at a rate of 104 Mm^3/y and this rate is still increasing despite the government's efforts to reduce overexploitation (Salameh and Haddadin 2006). Despite the overuse of blue water resources, the per capita share of water in Jordan (2004) is only 396 m^3/y (Salameh and Haddadin 2006). The overexploitation of groundwater resources has degraded water quality, which resulted in the abandonment of many water wells (Chebaane et al. 2004, Al-Kharabsheh-Atef 1999) and which endangers a future use of the limited groundwater resources (Salameh 1996; Dottridge and Abu-Nizar 1999).

In the light of the report on world climate, published in early 2007 by the Intergovernmental Panel on Climate Change (IPCC), a bigger challenge regarding water management awaits Jordan in the future. The discovery that global warming is man made and that an increase in global temperature is inevitable even when immediate measurements are taken, has consequences for the future water availability in the region. Climate models of the Mediterranean Basin for the end of this century show a decrease in the total amount of yearly precipitation (up to –57 mm/y for the whole Mediterranean basin) and an increase in evaporation rates (Ulbrich et al. 2006). Less rainfall however has direct influence on soils and vegetation and therefore on human and animal life.

Although the current and future water crisis in Jordan cannot only be overcome by using more blue water resources, it is however an integral part of the solution. 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 demanded. Groundwater systems in semi-arid areas are frequently not being sufficiently characterized hydrogeologically and long term data 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 combines geological, geophysical, hydrogeological, historical, and chemical methods and is demonstrated using the lowermost area of the Jordan Valley.

A historical approach is used to detect the general conditions under which the groundwater system has been in the past. These conditions include the natural flow conditions, the impact of the rapid development of the Jordan Valley from the 1950s onward, as well as the influence of periods of drought and of intensive rainfall on the groundwater system. The aquifer geometry and composition is described based on field investigations and intensive literature studies on the depositional environment and its sedimentological and hydraulic characteristics. Information about soil and groundwater salinization and their spatial distribution are acquired by the application of hydrochemical and surface geophysical methods (resistivity measurements). A water budget is calculated by the application of direct and indirect information. A minimum water demand for the test area is estimated with the help of fuzzy information and remote sensing techniques. This type of fuzzy information includes, information about irrigation techniques, about cultivated crops, and about growing seasons. The area under cultivation was identified for different periods by the classification of Landsat images. This paper combines the findings of Toll (2007), Toll et al. (2008), Toll (2008). The findings are implemented into transient flow model. In order to be able to predict the impacts of climate change scenarios on the groundwater system, this flow was tested against the depicted stress periods on the groundwater systems for a period of 48 years. The flow model provides the means for testing the consistency of the rather heterogeneous quality of the historical data set and would allow the simulation of the future impact of management strategies as well as climate change scenarios.

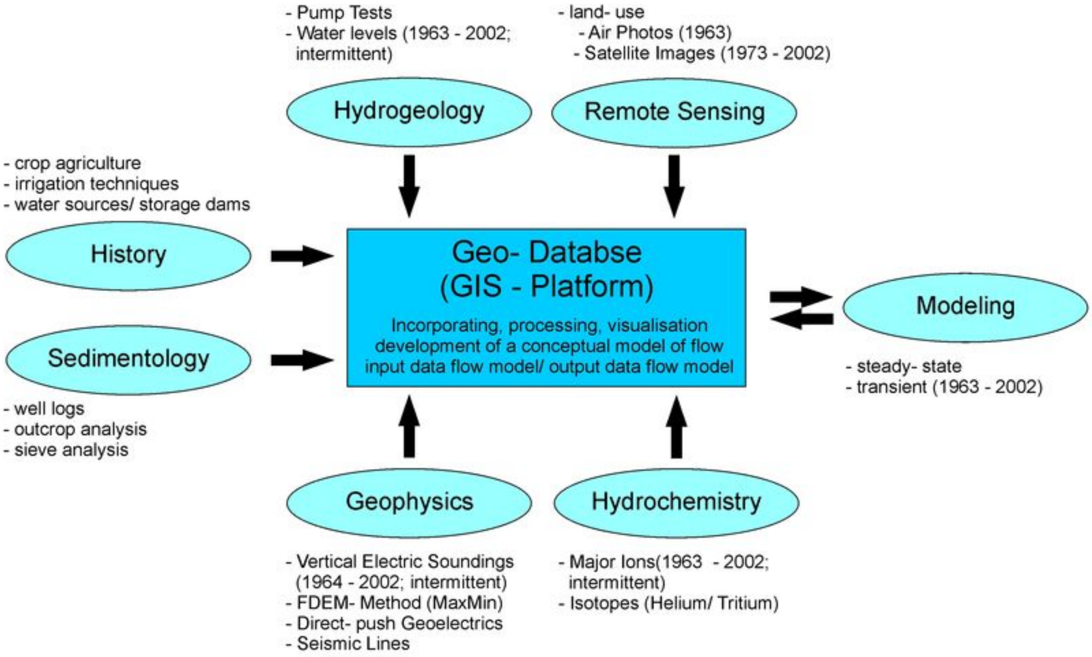

Fig. 1: Integrated approach for the investigation of the unconsolidated aquifers in the study area. The gathered information is stored in a geodatabase. With the help of the information gathered in the geodatabase a flow model is set up. The results of the flow modeling are stored afterwards in the same geodatabase (Toll 2008).

The main focus of this paper is on the transient modelling of the studied aquifer system. 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 (2008). 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 et al. 2007). 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. 4).

Geography

The study area lies in a geographical unit commonly known as the Jordan Valley (in Arabic called ‘Al Ghor’). The Jordan Valley and its adjacent areas lie on the western margin of the Asian continent (Fig. 2) and belong geographically to the Eastern Mediterranean Basin. The research area is located in the lower Jordan Valley/ Jordan. The centre is located at WGS84 coordinates 31° 52’ N and 35° 36’ E, and has an area of 150.66 km^2, and an average elevation of 270 metres below mean sea level (b.m.s.l.), and, compared to the bordering area to the east, a very smooth average slope of one to two degrees. The lowest point is located at the Dead Sea shore in the south with an elevation of 420 m below mean sea level (2006; the elevation depends on the water level of the Dead Sea), and the highest point at the fan apex of Wadi Hisban with 160 m b.m.s.l. The detailed study area includes the unconsolidated strata of lower Jordan Valley and extends from the Dead Sea in the south to the town of Karameh in the north, from the Jordan River in the west until the margin of the western hills of the East Bank in the east. The maximum extension is 14 km in east- west and around 20 km in north- south direction.

The Jordan Valley, often referred to as the “food basket” of Jordan, is the most important area for agriculture and therefore it is intensively used. However, farming activities in the middle and the northern part of the Jordan Valley exceed by far the production of the lower Jordan Valley. Farmers in the Jordan Valley generally refer to three different zones along the Valley: the Zor, Qatar, and Ghor areas. These zones represent different morphological features.

The Zor (Arabic for ‘throat’) area represents the flood plain of River Jordan. The Jordan River cut itself into a 30 to 60 m deep gorge and eroded the soft lacustrine sediments of Lake Lisan, the predecessor of the Dead Sea (e.g. Kaufman et al. 1992). The slopes ascending to the smooth alluvial plain are called the Qatar (Arabic for ‘badland’) area. They are characterized by steep slopes (20 to 50°). The Ghor area is the alluvial plain that ascends smoothly until the mountain slopes of the East Bank. The mountain slopes are known as Djebel (Arabic for ‘mountain’).

Villages in the lower Jordan Valley are situated close to the western border of the western slopes (from north to south): Karameh, South Shuneh, Kafrein, Rama, and Sweimeh (Fig. 2). Seminomadic Bedouins who live in tents are scattered randomly mostly around the middle to western part of the study area.

These seminomads descend to the Jordan Valley in winter because of its warm temperatures.

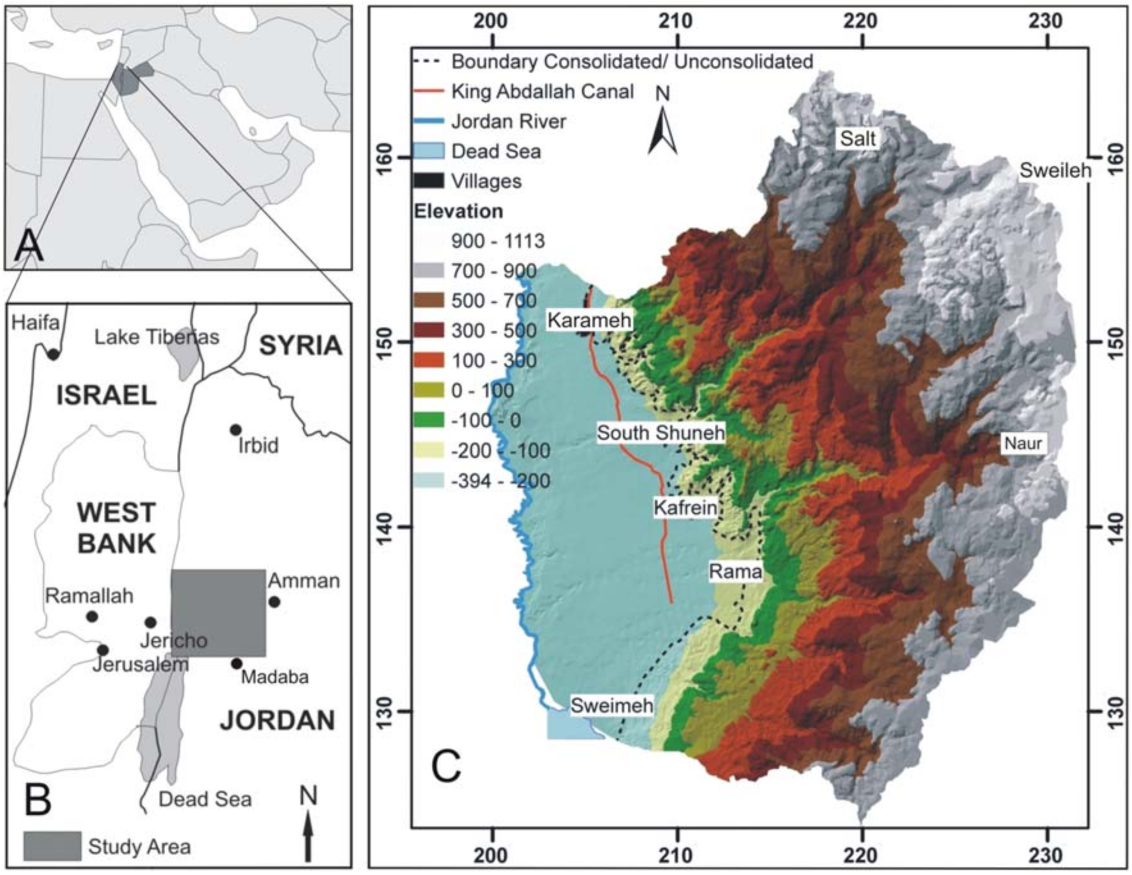

Fig. 2: Location of the study area. A: Middles East; B: Study area in the regional context; C: Study area (Toll 2008).

Traditionally, many of these seminomads farm plots of land in the valley. In summer they move their herds up into the hills to avoid the intense heat. In addition to these people farm workers, mostly Pakistanis, Palestinians, and Egyptians live in small huts near the farm sites. No industrial activities are found in this area. Farming is mostly restricted to the east of the Jordan Valley. Towards the west soil salinity increases and only salt tolerant crops can be planted. The eastern part is intensively used for agriculture, mostly banana plantation and some vegetables like tomato, zucchini, and egg plant. As a result of the favourable climatic hot conditions three harvesting seasons are planted: autumn, winter, and spring. But due to the lack of precipitation large amounts of water are used for irrigation. Irrigation water comes from dam storage water, from the King Abdullah Canal, and, unlike the middle and northern Jordan Valley area, to a large extent from groundwater.

Some touristic activities exist near the Dead Sea shore in the south and at the Baptism Site of Jesus in the west, near the Jordan River.

Climate

According to Köppen (1931) the wider area of interest can be classified as a Group B Dry (arid and semiarid) climate, since precipitation is less than the potential evaporation, but further subdivisions can be made. Morphology has the largest influence on the prevailing climate. Following the morphological division, a subdivision into three different climatic zones can be made: the

Highlands area, the Western Slopes of the East Bank, and the Jordan Valley. The climate in the Highlands is of Mediterranean type. It is characterized by long, hot, dry summers and short, cool, rainy winters. Towards the west, the climate undergoes a rapid change to semi-arid and arid climate in the Jordan Valley. The western Slopes act as a transition zone between the Mediterranean climate along the Highlands in the east and the arid climate in the Jordan Valley in the west.

Rain falls only during the winter months. Then the climate changes abruptly from dry hot summer conditions to humid, cold, and stormy conditions. Usually it starts to rain in November and rainfall continues until the end of April, whereby 70 % of the annual precipitation falls between November and February. Snow falls once to twice a year in the Highlands. A strong correlation with altitude and climate data for the area exists. Strong variations regarding total annual amounts of rainfall is visible in Fig. 3. For the plotted period, the highest amount of annual rainfall for the Highlands is 1,135 mm/y in the hydrologic year 1991/92, whereas the lowest recorded amount was 234 mm/y in the hydrologic year 1988/89 (a difference of factor 4.85). This important nature of semi-arid areas is also one of the major challenge for water engineers. The water demand of the population increases or decreases constantly with time, while the water supply or input by rainfall is highly variable, both spatially as well as temporally.

The variability of annual rainfall and the necessity of long term records is addressed in Fig. 3 (data kindly provided by the Hashemite Kingdom of Jordan, Ministry of Water and Irrigation). The longest record for the wider area of interest was available for the Naur Station. Annual precipitation amounts are plotted for the period from the hydrologic year 1942/43 until 2002/03. Mean average values for time periods of 5, 10, 30, and 60 years are displayed. In order to undertake future water budget calculations long- term mean averages of at least 30 years should be used. A short period of only five years might lead to considerable over- or underestimations regarding water availability.

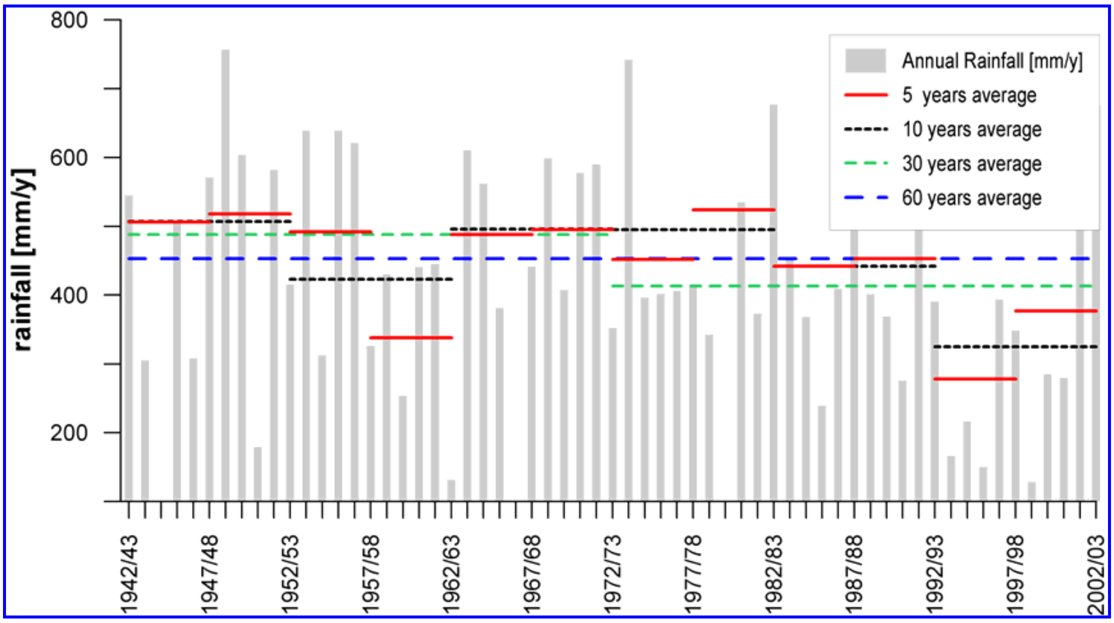

Fig. 3: Annual rainfall 1942/43 – 2002/03 for the meteorological station in Naur with short (5 years) to long term (60 years) averages (MWI open files).

Aquifer Geometry

Unconsolidated rocks - Jordan Valley Group

The lower Jordan Valley is a part of the Jordan Dead Sea Wadi Araba Transform Valley, which extends from the Red Sea to Lake Tiberias and beyond with a major 107 km sinistral strike-slip fault movement between the Arabian plate to the east and the northeastern part of the African plate to the west. Due to extensional forces a deep depression, which is often called Jordan "Graben" (for historical reasons), has formed. As a result of the arid environment it is filled with evaporites, lacustrine sediments, and clastic fluvial components (Niemi at al. 1997).

Three different continental depositional environments have played a major role since the development of the Jordan Valley basin. These environments are terrestrial/fluvial, deltaic/limnic, and limnic/brackish environments.

Upper Pliocene to lower Pleistocene Unit

As stated above, the early history of the Jordan Valley Group is not fully known. In the study area the above described Shagur Formation is believed to be the oldest formation deposited in the Jordan Valley (Upper Pliocene – Lower Pleistocene). The Shagur Formation consists of massive, crudely bedded fluvio-limnic conglomerates that alternate with crudely bedded travertine and marl or claystone. This unit overlies unconformable older consolidated rocks. Clasts are angular to subangular and siliceous cemented. In the type localities in the east and south the terrestrial to fluvio- limnic Shagur Formation has a thickness of approximately 75 m. However, thickness changes significantly within the different facies types (Bender 1968). While the Shagur Formation crops out in the east and southeast of the study area, it was not reported, neither in the deep oil wells Jordan Valley 1 and 2, nor in the wells drilled by the Ministry of

Water and Irrigation. No outcrop of the Ghor al Qatar Formation exists in the study area.

Pleistocene Unit

During Pleistocene times, three members can be distinguished. The three members (the coarse clastic, the silt and the lacustrine) are a vertical and lateral facies succession from terrestrial/fluvial, to deltaic/limnic and limnic/brackish lake environments. As stated above, Bender (1968) divided these different depositional environments into two members: Samra and Lisan. But in order to avoid confusion with the word Samra, the term Pleistocene Aquifer will be used for the coarse clastic and the silt member henceforward. The “Pleistocene aquifer” consists of the coarse clastic and the silt member. However, exploitable water resources are principally restricted to the coarse clastics member. The lacustrine member (Lisan Formation) consists of marl, gypsum and silt, and is generally considered an aquiclude, void of exploitable water. It crops out mainly in the west of the study area. Since the Lisan Lake reached an elevation of –180 m above mean sea level its sediments can be found in incised channels of the major wadis up to the margin of the Jordan Valley. Its total thickness is around 40 m. The coarse clastic member consists of gravel, interbedded with clay, sand and marl horizons. Both, the coarse clastic and the silt member underlie, overlie, or interfinger with the Lisan Formation .

Holocene or sub-recent Unit

This unit is built up of sub-recent terrigenous sediments deposited along the outlets of major wadis. These alluvial fans are still accumulating as a result of large floods. They consist of debris from all neighbouring lithologies and are deposited according to their transport energy. The biggest components are found close to the apex and the smallest close to the fan margin. The transport normally takes place along alternating channels or after very heavy rain storms as sheet, or debris flow. Thus permeable horizons alternate with less permeable lithologies within these deposits. It is believed that the thickness maximum is near the valley margins, thinning out towards the centre of the basin. Well depth is rarely beyond several tens of metres. Often the alluvial aquifer directly overlies the Pleistocene gravel aquifer and because of that is hydraulically interconnected with this aquifer.

Subsurface contacts between consolidated rocks and unconsolidated Jordan Valley Group sediments

Due to the spatial variability of the hydraulic potential and the multilayer nature of aquifers and aquitards in the consolidated rock sequence hydraulic contacts with the unconsolidated valley sediments play a major role in the hydraulic budget.

At the foothills of the highlands near Al Karameh, South Shuneh, Kafrein, Sweimeh the base of the Jordan Valley Group sediments (bJVG) crops out at an altitude of ca. –200 m b.s.l. A preliminary analysis of reflection seismics in combination with the deep wells JV1 and JV2 shows that the late Cretaceous structures continue beneath the younger Jordan Valley Group sediments (Heinrichs et. al 2004; AlZoubi et al. 2006). The same data reveal a drop of the bJVG along the Wadi Shueib composite anticline from –200 m at the surface to about –500 m b.s.l. at 4 to 5 km distance WSW of the outcropping contact. This dip corresponds roughly to the dip of the Cretaceous strata E of the contact. It can therefore be concluded that up to this location on this anticline Naur and Kurnub Formations are directly overlain by unconsolidated sediments. Further W and toward SW seismic data suggest that higher stratigraphic levels of the Cretaceous are preserved and in contact with the unconsolidated sediments in spite of the bJVG dipping steeply toward W and toward the Dead Sea in the south. A similar inference can be made for the Wadi Shueib Syncline where the Wadi as Sir Formation should be continuous for some distance under the base of the unconsolidated sediments. At the moment low density of seismic information does prevent tracing the major faults into the subsurface of the Jordan Valley.

Conceptual and long-term (period of 48 years) numerical modelling of the stressed groundwater system

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 finite element grid: 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 findings described in Toll (2008). 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.

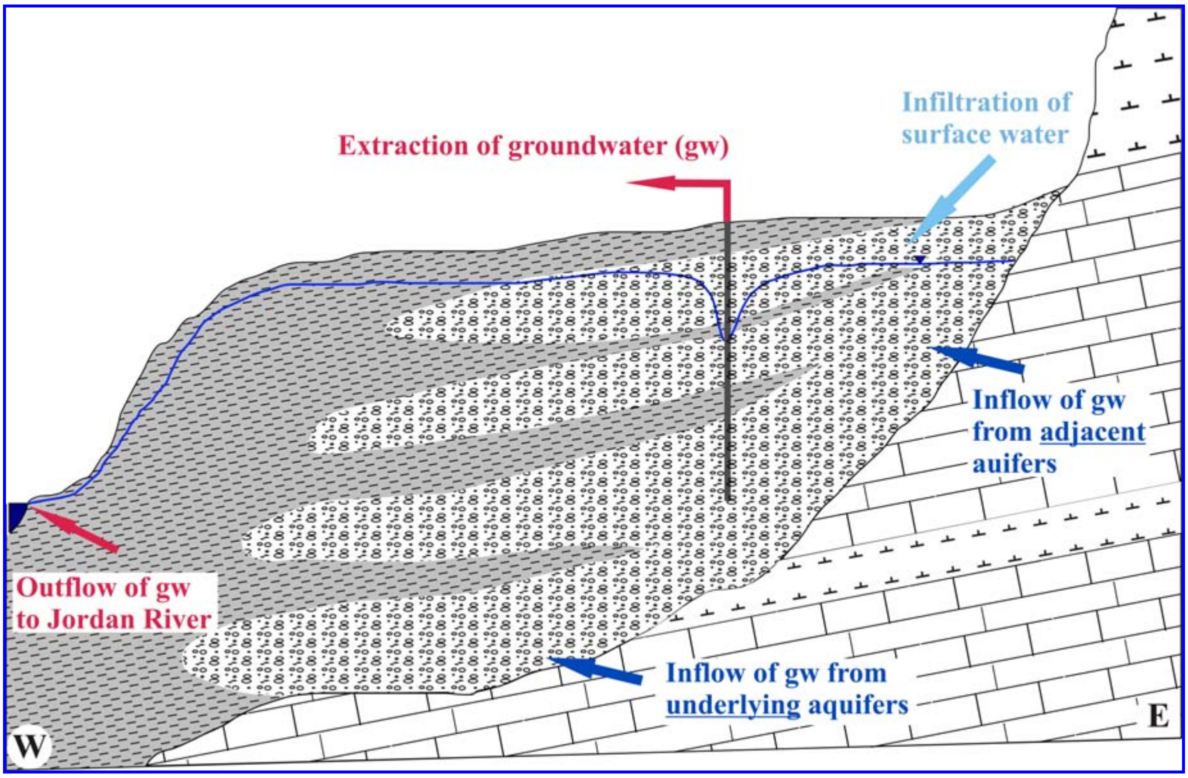

Fig. 4: Conceptual model of flow of the unconsolidated aquifer in the study area

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. 5 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. 5 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. 6 left). Around the well locations polygons were drawn (Fig. 6 left) 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.

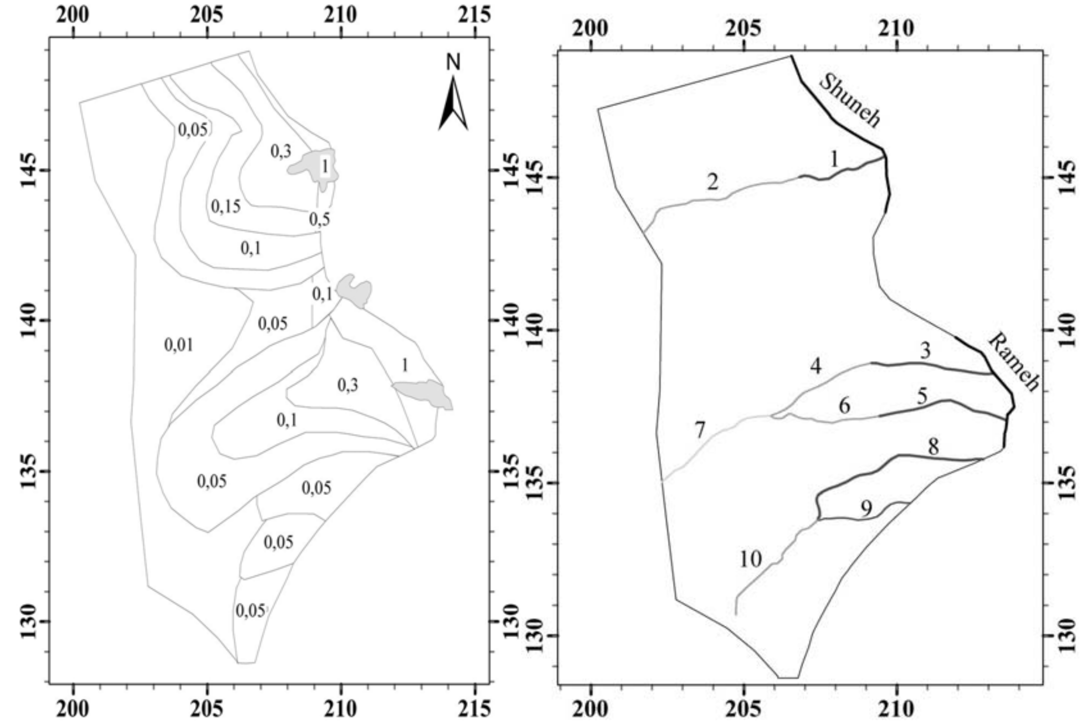

Fig. 5: Left**:** Hydraulic conductivity values assigned to the different zones of the model domain [10E-04 m/s]. Right**:** Fluxlines assigned to the model domain. 1 through 10 represent inflow along the different wadis section and Rama and Shuneh represents the inflow of groundwater into the model domain.

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 (Fig. 6 right). 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.

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 (2007). The hydraulic conductivity values are shown in Fig. 5 left. The transient model was set up for unconfined flow. Additional input data required for transient simulations are: 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.

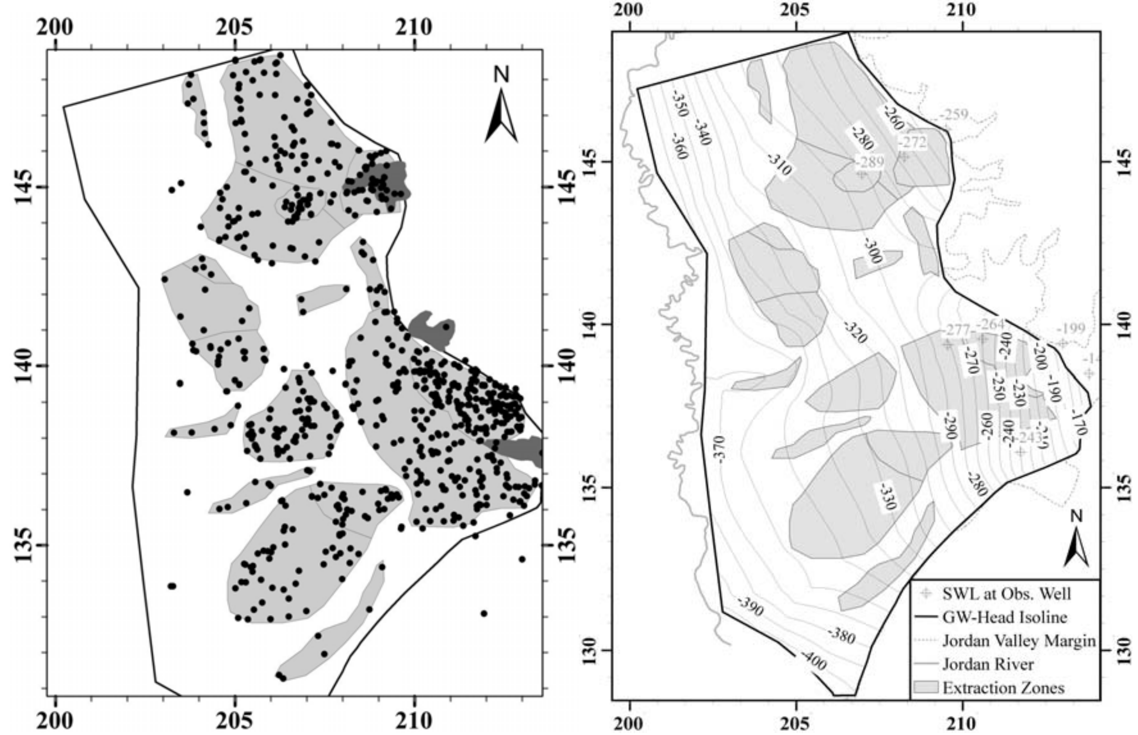

Fig. 6: Left: Well locations and groundwater extraction zones. **Right:** Hydraulic conductivity values assigned to the different zones of the model domain [10E-04 m/s].

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 September 1970. 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 et al. 2008). 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 (“six days war”) 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 et al. (2008). 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 Fig. 7. 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. 8 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 (2008), 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.

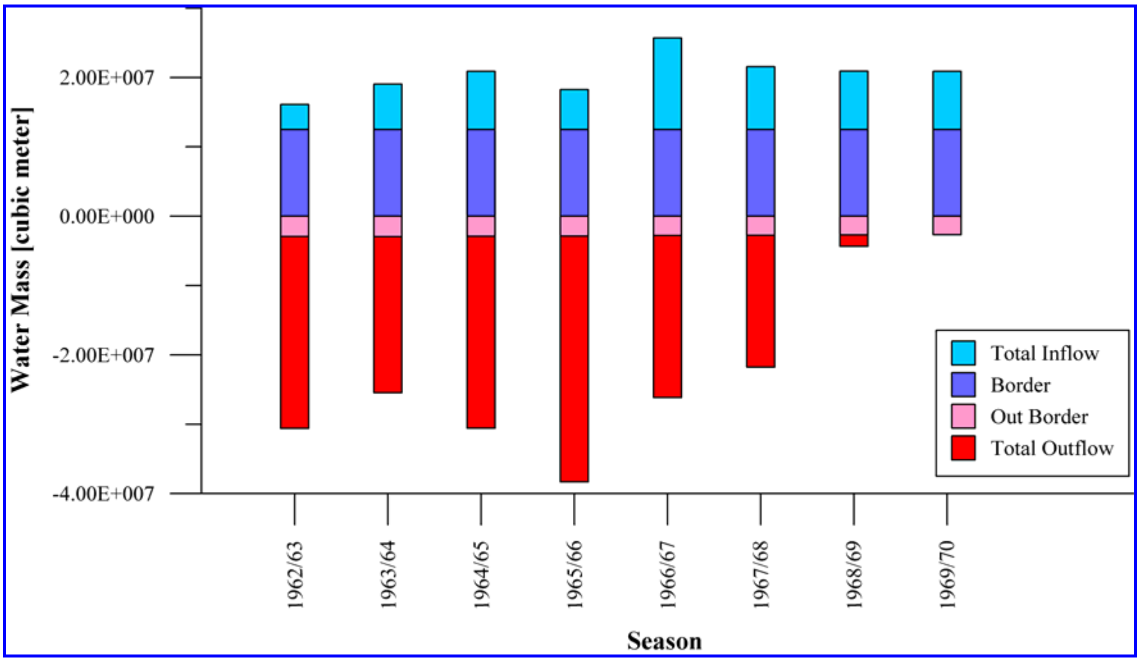

Fig. 7**:** Water budget for the period of 1962/63 to 1969/1970 of the transient model run; Total Inflow = Inflow of water along the different wadi sections (infiltration of surface water) together with flux through the eastern flux boundaries, Border = Inflow of groundwater through the flux boundaries (groundwater inflow), Out Border = Outflow of groundwater through the western flux boundaries (effluent groundwater to the Jordan River); Total Outflow = Out Border together with groundwater pumped from the different extraction zones.

Fig. 9 shows the water budget for the period of 1980/81 until 2000/01. It can be seen that rain poor season lead to a negative water budget and rain intensive years to a positive one. Fig. 10 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.

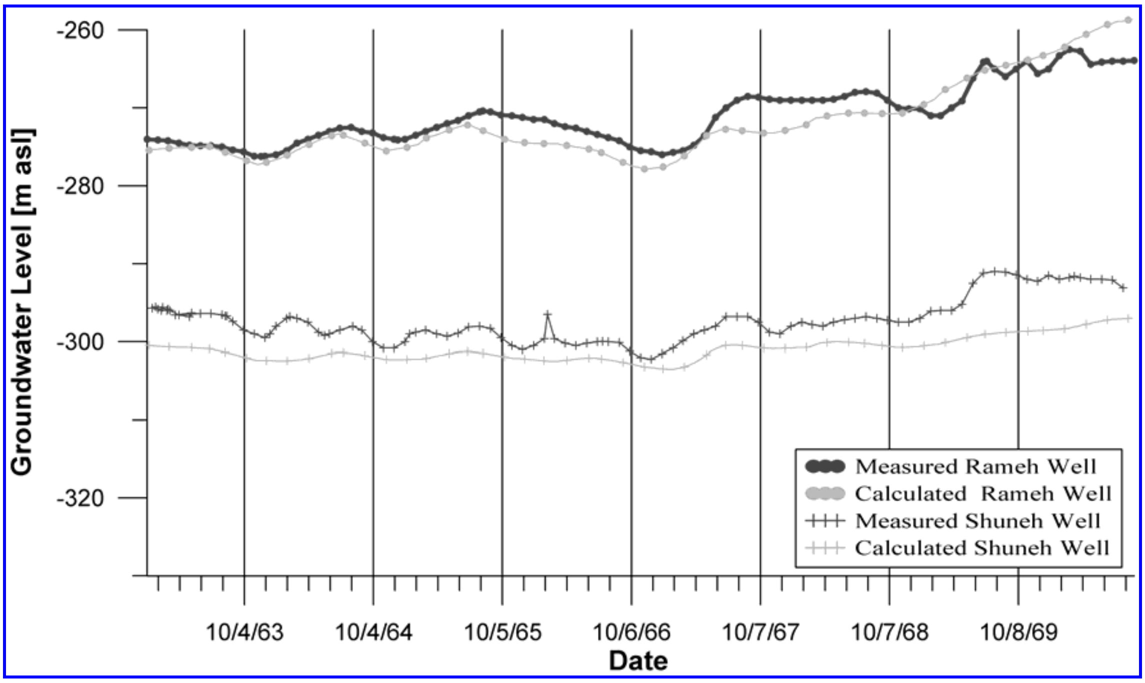

Fig. 8: Calculated versus measured groundwater heads for the period of 1963 to 1970.

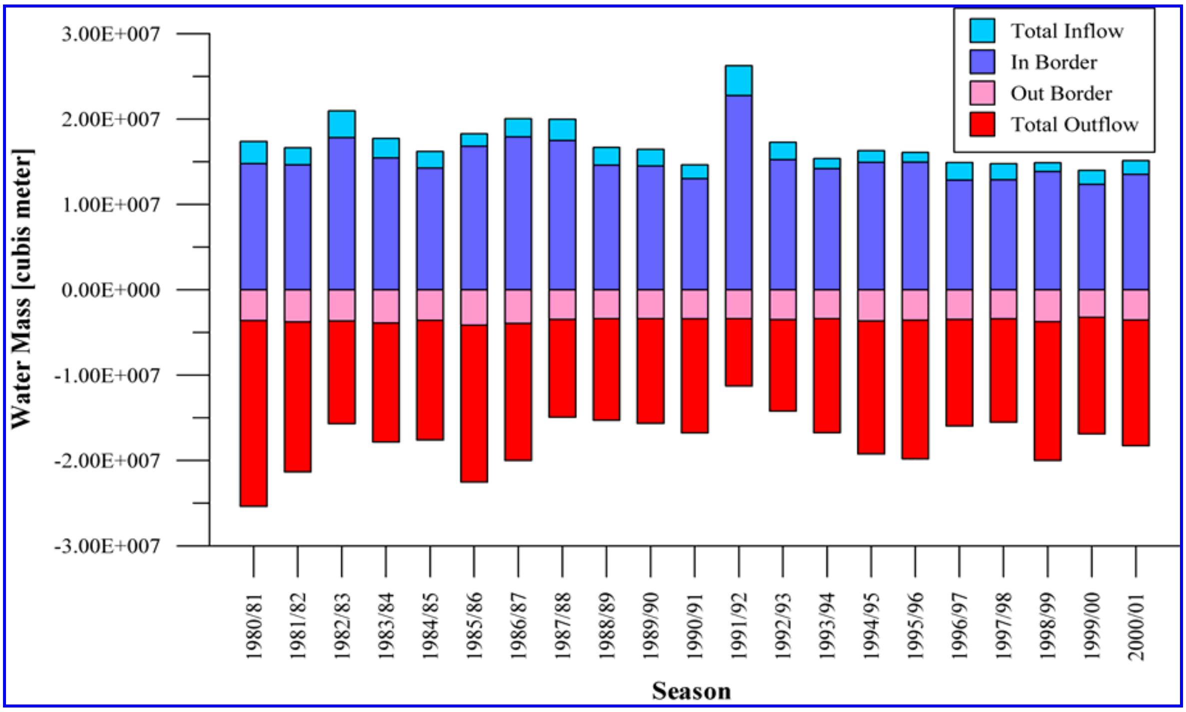

Fig. 9: Water budget for the period of 1980/81 to 2000/01 of the transient model run; Total Inflow = Inflow of water along the different wadi sections (infiltration of surface water) together with flux through the eastern flux boundaries, Border = Inflow of groundwater through the flux boundaries (groundwater inflow), Out Border = Outflow of groundwater through the western flux boundaries (effluent groundwater to the Jordan River); Total Outflow = Out Border together with groundwater pumped from the different extraction zones.

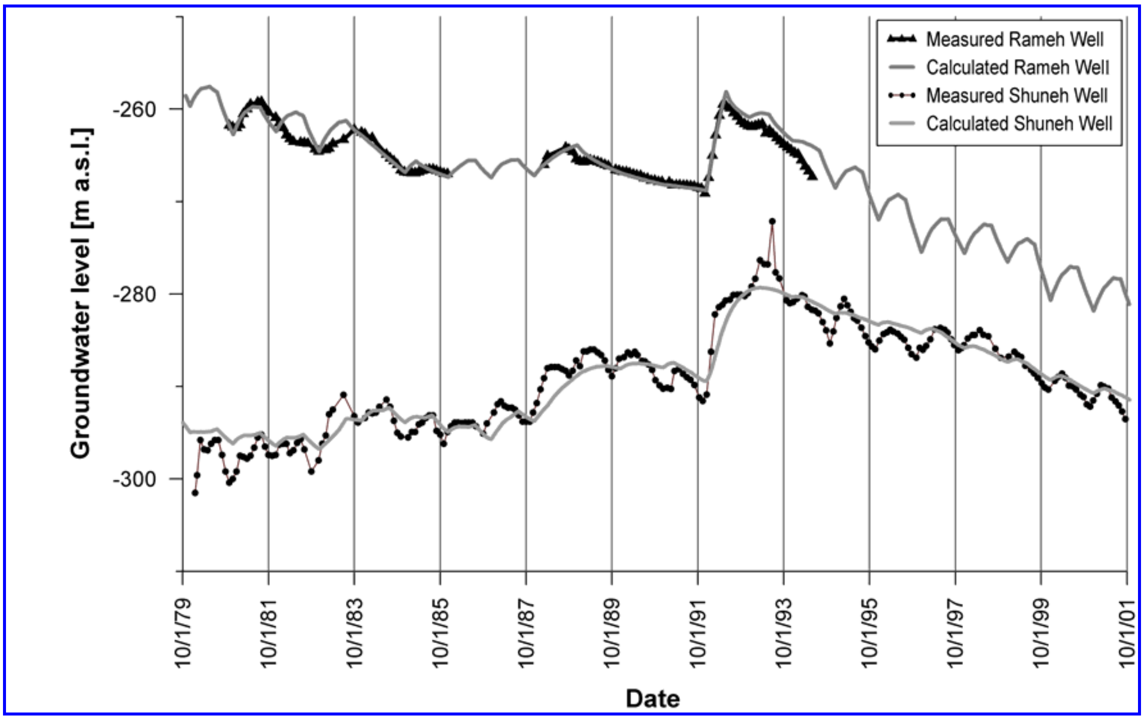

Fig. 10**:** Calculated versus measured groundwater heads for the period of 1980 until 2001.

Summary and Conclusions/ Implications for Groundwater Management

In this work an integrated approach is proposed that combines different types of available data and therefore overcomes data gaps common in many arid regions. This approach was demonstrated for the unconsolidated aquifer in the lowermost area of the Jordan Valley/ Jordan.

The conceptual model of flow was set up based on geological, hydrochemical, and geophysical methods. Geological methods were employed to determine the geometry of unconsolidated sediments, including the most important structural features of the study area. A numerical 3-D flow model was set up by using the FEFLOW (Wasy Ltd.) software code. The geometrical and water budget information gathered with the integrated approach (Toll 2008) was incorporated into a steady- state model. This numerical flow model simulates the average flow conditions between 1987 and 2002 and was calibrated with available groundwater heads.

This numerical steady- state model was transformed into an unconfined 3-D transient model. After dynamic calibrating the model for 120 years, the model successfully simulated two different time periods: the first time period ranged from the first development phase until after the hostile event at the end of the sixties (1955-1970) and the second time periods ranged from the second development phase until the new millennium (1975-2001). The model was successfully able to simulate all extreme constraints that were put on the aquifer. These stress constraints included: periods of aquifer overexploitation during the sixties and the response of the aquifer to the stop of all pumping activities during the “six day war” and their aftermath, periods of drought, and one of the most intense rainfall season ever recorded in the study area (rainfall season 1991/92). Especially these extreme constraints deliver valuable information about the vulnerability of the studied aquifer system. The developed model should be able to successfully simulate future impacts on groundwater abstraction strategies or the impact of climate change scenario on the studied groundwater system. It should however be noted, that the model was developed for the whole study area. While it is evident that hydraulic properties are highly variable in space, the location and characteristics of the alluvial material is not known so that they cannot be adequately included into a groundwater model. Further field investigations are therefore necessary to develop a groundwater model, that would be applicable to small scale areas. Desirable investigations are especially:

- pumping tests with observation wells to assess the specific yield
- installing water meters in all wells to further validate the model
- a complete well survey to assess operating and non-operating wells, including measurements regarding well depth, depth of the pump, pump discharge, etc.
- gamma-ray depth profiles at all available well locations, in order to be able to subdivide the unconsolidated aquifer into further subunits
- permeability test of the lacustrine material
- a more precise investigation about the subsurface contact between the unconsolidated/ consolidated aquifers (shallow reflections seismic) to further enhance the knowledge about aquifer geometry
- investigating the “artificial recharge” of the surface dams at the outlet of the major wadis
- long-term pumping tests at wells close to the surface dams to investigate the interconnectivity between the dams and the unconsolidated aquifer
- groundwater hydrograph recording at high timely resolution

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 practised 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 abstraction 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 abstracted 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 neighbouring 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 neighbouring 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.

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