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ORIGINAL ARTICLE

# Artificial groundwater recharge to a semi-arid basin: case study of Mujib aquifer, Jordan

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**Abstract** Mujib watershed is an important groundwater basin which is considered a major source for drinking and irrigation water in Jordan. Increased dependence on groundwater needs improved aquifer management with respect to understanding deeply recharge and discharge issues, planning rates withdrawal, and facing water quality problems arising from industrial and agricultural contamination. The efficient management of this source depends on reliable estimates of the recharge to groundwater and is needed in order to protect Mujib basin from depletion. Artificial groundwater recharge was investigated in this study as one of the important options to face water scarcity and to improve groundwater storage in the aquifer. A groundwater model based on the MODFLOW program, calibrated under both steady- and unsteady-state conditions, was used to investigate different groundwater management scenarios that aim at protecting the Mujib basin. The scenarios include variations of abstraction levels combined with different artificial groundwater recharge quantities. The possibilities of artificial groundwater recharge from existing and proposed dams as well as reclaimed municipal wastewater were investigated. Artificial recharge options considered in this study are mainly through injecting water directly to the aquifer and through infiltration from reservoir. Three scenarios were performed to predict the aquifer system response under different artificial recharge options (low, moderate, and high) which then compared with no action (recharge) scenario. The best scenario that provides a good recovery for the groundwater table and that can be feasible is founded to be by reducing current abstraction rates by 20% and implementing the moderate artificial recharge rates of 26 million(M)m$^3$/year. The model constructed in this study helps decision makers and planners in selecting optimum management schemes suitable for such arid and semi-arid regions.

**Keywords** Artificial recharge · Injection wells · MODFLOW · Mujib basin, Jordan

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## Introduction

The shortage of water in arid and semi-arid regions of the world is a major limiting factor in the development of sound economic and social structures. In such regions, where groundwater is often the major water source, almost any development of the aquifers constitutes over abstraction conditions. The erratic nature of precipitation in arid countries such as Jordan exerts a profound influence upon the accumulation and replenishment of groundwater.

The rainfall in Jordan is the main source of water for surface and subsurface water resources. It is relatively scarce and varies considerably with location due to the variable topographic features and climatic conditions. This makes Jordan suffers from the limited water resources. Groundwater contributes a significant portion of the water supply in Jordan. Increased dependence on groundwater needs improved aquifer management with respect to understanding recharge and discharge issues (Tompson et al. 1999). Furthermore, due to the increasing demand, the withdrawal from most of the Jordan's aquifers is almost double that of the safe yield. This will eventually lead to the depletion of water resources and deterioration in the water quality according to the National Water Master Plan of Jordan (NWMP 2001).

Therefore, a good and comprehensive management for the water system should be applied on both sides, either demand or supply, in order to ensure an adequate water supply for the increasing demand on water. Among methods and solutions used to improve the water resources management, the artificial groundwater recharge can be considered. This method had been used since the eighteenth century and began to be used widely recently as a new non-conventional water resource (Asano 1985). According to the NWMP of Ministry of Water and Irrigation of Jordan, artificial recharge is one of the management options aiming at bridging the gap between the very limited available water resources and the increased water demand resulted from the expanding economy (NWMP 2001). Consequently, artificial recharge in arid and semiarid countries such as Jordan can play an important role in conserving its water resources and avoiding the depletion of the existing aquifers.

Groundwater modeling is an effective tool that can be used to get interpreted understanding of groundwater flow and aquifer management. By using MODFLOW computer code (Chiang and Kinzelbach 1993), this work presents a mathematical model for the study area for predicting, with reasonable accuracy, the response of Mujib aquifer to different scenarios of future abstractions and artificial recharge. This paper is a continuity of the work presented in Abdulla and Al-Assa'd (2006) study on developing a groundwater flow model for Mujib aquifer.

## Methodology

The methodology followed in this research can be summarized as follows:

- Collection of data, which includes the physical parameters such as hydraulic conductivity, aquifer thickness, recharge and pumping rates, geological boundary, distribution of geologic formation, topographic maps, and groundwater flow directions maps.
- Identification of the geological and hydrological setting of the study area.
- Dividing the study area into a grid mesh. The size of the grids was irregular, depending upon the location and density of the wells and the gradient of the water table. The MODFLOW was applied to simulate three-dimensional groundwater flow for the study area.
- Estimation of the model parameters by manual adjusting until a good match between computed and observed water levels is obtained.
- Performing statistical analysis on the calibrated results.
- Conducting sensitivity analysis to test the effect of uncertainty in aquifer parameters and boundary and initial conditions on the model outputs.
- Verifying the model results using the observed data.
- Analyzing different scenarios which include future stresses such as groundwater artificial recharge rates and pumping rates based on projected demands.

### Study area

Mujib basin is located between 205 and 297 east and 10 and 146 north (according to Palestine grids) (Fig. 1) and covers an area of about 6,600 km$^2$. It consists of two major catchment areas: Wadi Mujib catchment of about 4,500 km$^2$ and Wadi Wala catchment of about 2,100 km$^2$. It is bounded westward by the Dead Sea catchment, northward by the Zarqa basin, eastward by Azraq basin, and southward by Hasa and Jafr basins.

Riverbed slopes are gentle in the eastern area due to sediment transportation by wind and scarce rainfall. While in the downstream area the slopes are steep due to the flush flood erosion and comparatively more rainfall occurrence. Both drainage systems of Wala and Mujib have perennial flow only in downstream reaches where elevations are lower than 400 m above mean sea level (a.m.s.l.). The elevation in Mujib basin is ranged from about 1,200 m a.m.s.l. southern the Karak city to the mean sea level at the outlet of Wadi Mujib. Three distinctly physiographic provinces are recognized in the study area, which are the desert in the eastern part, the highlands in the northern part to the south of Amman (Jordan capital) and in the southwestern part, which is a part of Karak Mountains, and the deep wadis in the western part. The main Wadis and cities in the study are illustrated in Fig. 2.

### Groundwater aquifer system

Figure 3 shows the simplified conceptual model of the hydrogeological setup of the Mujib basin. Two major aquifer systems were recognized in Mujib basin: B2/A7 and Kurnub. The B2/A7 aquifer consists of massive limestone, dolomitic limestone, marl chalk, and Chert beds. It is considered to be a uniform aquifer unit with hydraulic connections, which is widespread throughout the study area with a thickness of 100–300 m. The B2/A7 formation is an excellent aquifer with high permeability due to joints, fractures, and karstification of the limestone (JICA/WAJ 1987). The B2/A7 aquifer outcrops in the western and

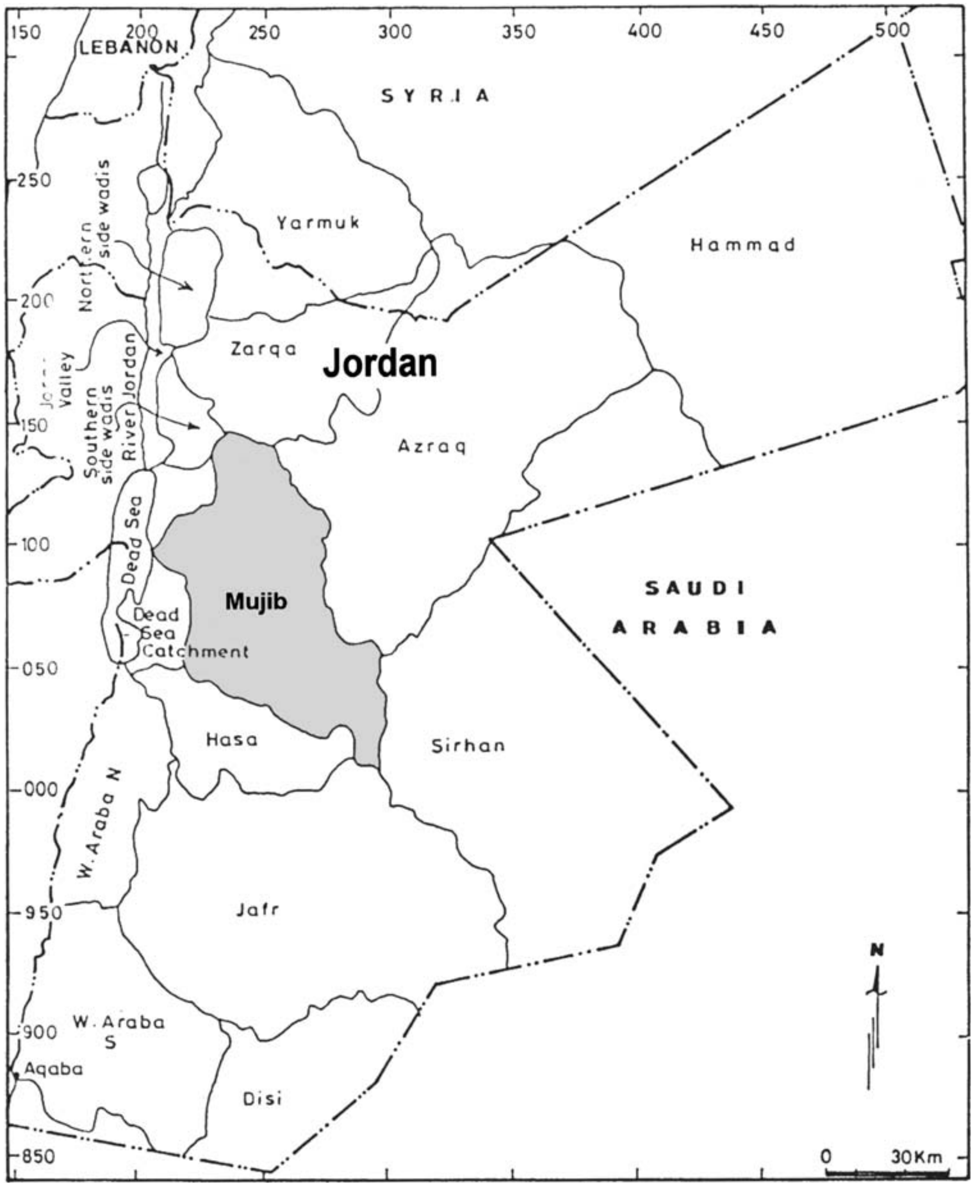


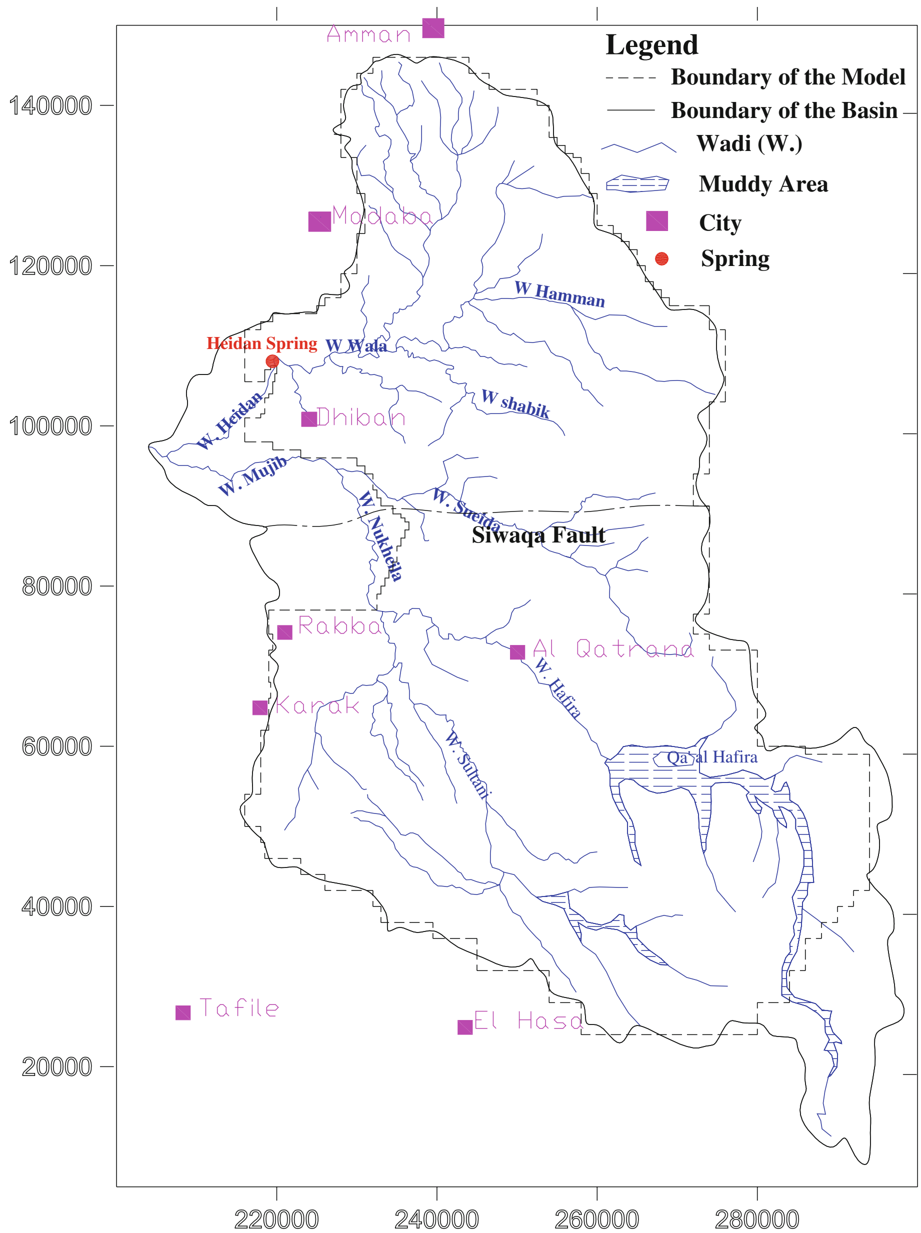

**Fig. 1** Study area location (JICA/WAJ 1987)

central parts of the Mujib basin, and is overlaid by the B3 aquiclude in the eastern part. The B3 aquiclude which consists of marl, chalk, and chalky marl is dry over the Mujib basin. It is also overlaid by the dry B4/5 aquifer in a minor area in the northeastern part of Mujib. So, natural recharge almost occurs in the western and central parts of Mujib basin while a small quantity of precipitation could recharge in the eastern part of the basin. The Kurnub aquifer is deep and consists of medium- to coarse-grained sandstone with some intercalations of siltstones and clay stones.

The B2/A7 aquifer and Kurnub aquifer are separated by the A1/6 Aquitard which is formulated from six layers (A1–A6) and mainly consists of series of alternating limestone, siltstone, marlstone, and nodular limestone. Historically, all the groundwater abstractions are from the B2/A7 aquifer. Kurnub aquifer is not utilized till 2002 because it is deep in most of its parts. Moreover, there is no observation well available in the Kurnub aquifer to be used in calibrating and validating the model. Therefore, the study is performed only on the B2/A7 aquifer.

The water table elevation of the B2/A7 layer is lower than the base elevation of the B3 layer, thus the B2/A7 is considered as an unconfined aquifer. The depth of water in the Mujib basin varies from less than 10 m to more than 300 m. The A1/6 Aquitard is assumed to be an impervious layer in the model even though there are some leakages happen to the Kurnub aquifer. The lack of information on the Kurnub aquifer led to set this assumption as well as limiting the study to the B2/A7 aquifer system.

Fig. 2 Main cities and Wadis in Mujib basin



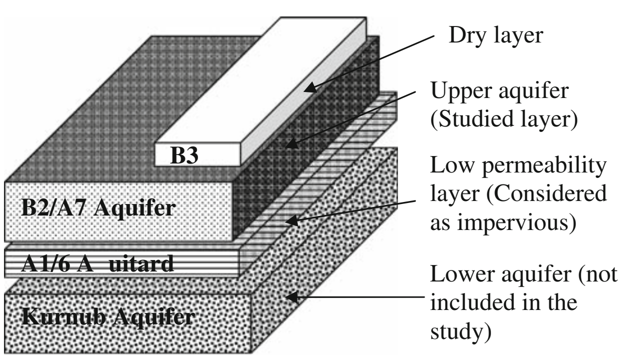




Fig. 3 Conceptual model of Mujib basin

## Model characteristics

In order to investigate the efficiency of the groundwater artificial recharge in the Mujib basin, a verified groundwater model is required. The MODFLOW program, which simulates groundwater flow in the aquifer system using an implicit iteration solution, has been used in developing a groundwater flow model for Mujib basin. Detailed description of the model was presented by Abdulla and Al-Assa'd (2005, 2006). Guidelines and practical tips are mainly adapted from Spitz and Moreno (1996) and Anderson and Woessner (1992) throughout the model development. In the following sections, brief description of the main features of the model is presented.

Model grid

The model domain was selected to cover 5,760 km$^2$ of the Mujib watershed. The model domain is divided into 129 rows and 99 columns forming rectangular cells. This discretization produces 12,771 cells in the model layer. The width of the cells varies along rows (in $x$-direction) between 250 and 2,000 m and along columns (in $y$-direction) between 250 and 4,000 m based on the location and concentration of wells and springs.

Aquifer parameters

Topographical and hydrogeological contour maps obtained from the Ministry of Water and Irrigation were used to determine the top and bottom of the B2/A7 layer for each cell. The B2/A7 aquifer system has a wide range of hydraulic conductivities due to karst features, enlarged joints, sink holes, caves, and solution breccias that developed in and around the fault zones. The measured transmissivities from the pumping tests provide values ranging from $5.8 \times 10^{-6}$ to 0.3 m$^2$/s (JICA/WAJ 1987). The high transmissivities are located along the zone of the major Wadi systems in the Wala Mujib catchments. The hydraulic conductivity values of the study area vary from $1.0 \times 10^{-8}$ to $5.0 \times 10^{-3}$ m/s. The bulk of the conductivity values obtained from pumping tests lies between $1.0 \times 10^{-6}$ to $1.0 \times 10^{-4}$ m/s (BGR/WAJ 1987).

There are 14 springs in the Mujib basin, which are grouped into five groups. Most of them are located in the valley's outcrop areas in Wadi Wala, Wadi Heidan, and Wadi Mujib. The largest spring group that discharges regional flow from the B2/A7 aquifer is located in Wadi Heidan (Fig. 2) with annual average discharge of 15.3 Mm$^3$.

The groundwater abstraction rate was increased significantly since 1970s due to the continuous development occurred in Jordan including Mujib area. The overall annual abstraction was around 5.2 Mm$^3$ for 1976–1979, and around 10.8 Mm$^3$ for 1980–1984. Starting from 1985 further groundwater wells had been drilled in order to provide Amman with additional water quantities where abstraction rates reached around 29.5 Mm$^3$. Another jump was occurred in 1993 when further wells were drilled to supply Amman, Madaba, and Karak with additional water. The abstraction rates recorded about 55.5 Mm$^3$. Currently, there are more than 350 wells that abstract annually about 58 Mm$^3$ of groundwater.

Boundary and initial conditions

The groundwater flow pattern of the B2/A7 aquifer and the locations of the groundwater wells are used to identify the location and the type of the boundary conditions for the Mujib basin. Figure 4 illustrates the proposed boundary conditions where numbers refer to the site specification as following: (1) Amman Mountains in the northern side are considered as a physical boundary (recharge side) defined as a constant head boundary, where groundwater flow comes from this side. (2) The southwestern side is also defined as a constant head boundary and groundwater flow comes from Karak Mountains recharging the Mujib basin. (3) Further important recharge side to the Mujib basin is in the northwestern side above the Heidan springs, where groundwater flow comes from Madaba hills. This is also defined as a constant head boundary. (4) The middle western part of the Mujib basin around Wadi Wala and Wadi Mujib is considered as a constant head boundary as groundwater flows out toward these Wadis. (5) Northeastern side and lower middle eastern side of the Mujib basin are also major outflow boundaries toward Azraq basin, where they are defined as a constant head boundary. (6) Inactive cells are assigned to the area beyond Qatrana city where no groundwater exists as a result of the B2/A7 aquifer uplifting. The proposed boundary conditions for points 1–5 are assumed to be constant head because these boundaries are far enough from the abstraction wells which will not significantly affect the groundwater levels at these boundaries. Figure 4 shows the groundwater level map for Mujib basin created in 1984 through using the initial water level recorded in the groundwater wells as well as the available observation wells during the 1970s when the extraction quantities were still minor. This represents the initial head distribution for Mujib basin (JICA/WAJ 1987).

Steady-state calibration

Hydraulic conductivities estimated from previous studies and from pumping tests were used as initial values for the steady-state simulation. The steady-state heads (initial heads) created in 1984 for the aquifer were matched with the hydraulic heads simulated by MODFLOW to achieve the steady-state calibration. This is done by trial and error calibration, where horizontal hydraulic conductivity was adjusted during many sequential model runs until the match between the observed and simulated groundwater heads were obtained (Spitz and Moreno 1996). Also minor adjustments were done on the boundary conditions that are firstly used in the initial runs. A comparison of measured and calibrated (simulated) water level contours of the B2/A7 aquifer is presented in Fig. 4. It clearly shows that

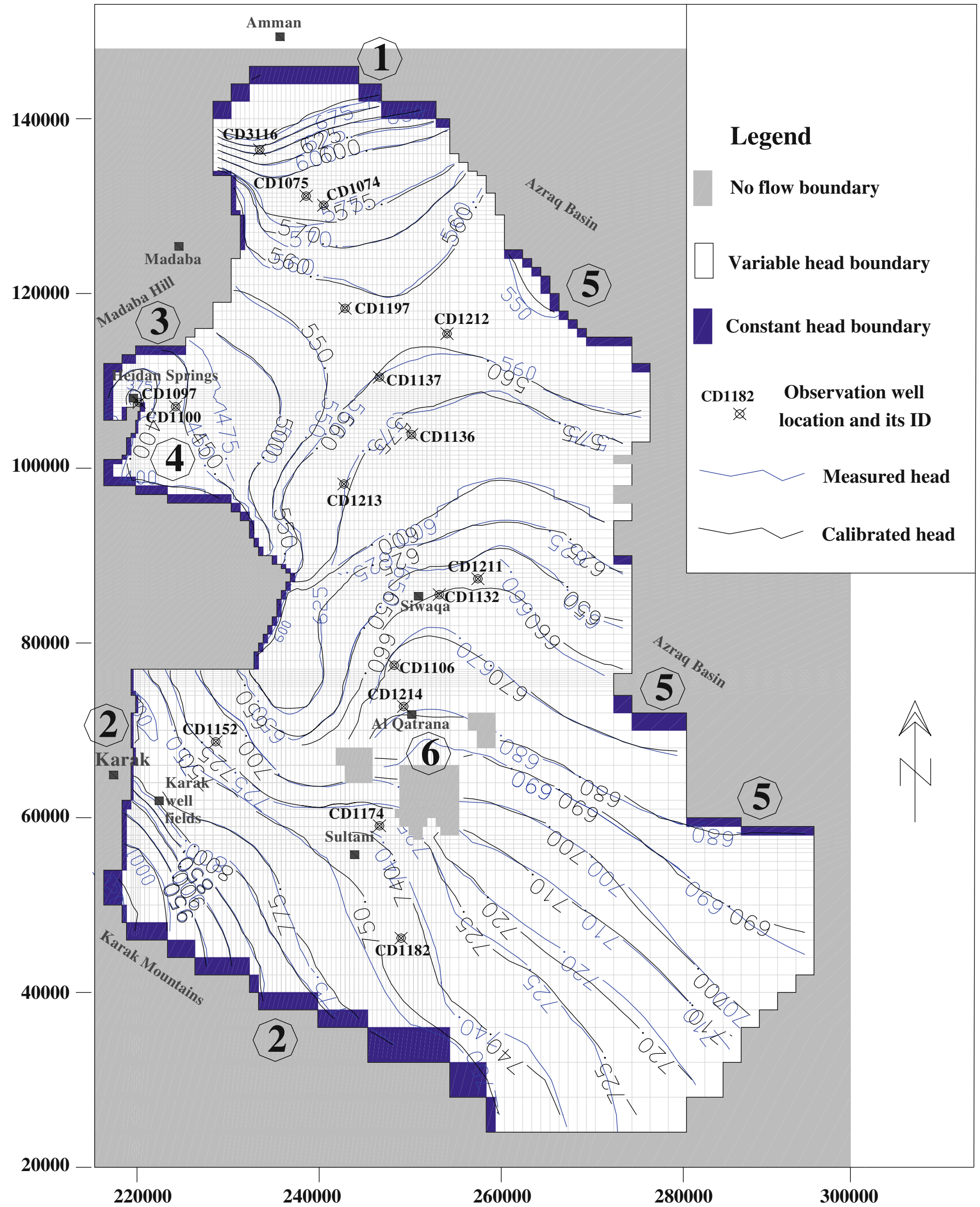



**Fig. 4** Flow model boundaries, grid, and the measured and simulated water levels for Mujib basin (B2/A7 aquifer)

there is a good agreement between the calibrated and measured heads.

Most values of the hydraulic conductivity are ranged between $1.16 \times 10^{-6}$ and $3.47 \times 10^{-5}$ m/s. The maximum value of the calibrated hydraulic conductivity occurred around the Heidan springs with a value of $4.63 \times 10^{-4}$ m/s, while the minimum value reached $1.16 \times 10^{-8}$ m/s to the east of Wadi Mujib. The distribution of the values of the calibrated horizontal hydraulic conductivity is shown in Fig. 5. There is no vertical hydraulic conductivity required for calibration since the simulation was done on one layer with an impermeable bottom assumption. The presence of Siwaqa Fault (Fig. 3) creates sharp changes in the hydraulic conductivity in some areas around its path. Table 1 lists the statistical summaries of the model inputs used in the steady-state calibration.

Table 2 shows the water balance for the B2/A7 aquifer system in Mujib basin at steady-state condition with a discrepancy of −1.91% where the calibrated outflow is exceeded the inflow by 0.64 $Mm^3$. The overall underground inflow is estimated to be around 13.03 $Mm^3$ while the overall underground outflow is estimated to be 18.73 $Mm^3$. The major inflows come from Amman Mountains at the north of Mujib basin which is indicated by number (1) in Fig. 4 with about 4.1 $Mm^3$, from Madaba hills (indicated by number (3)) with about 5.2 $Mm^3$ and from Karak mountains (indicated by number (2)) with about 3.5 $Mm^3$. On the other hand, the major outflows

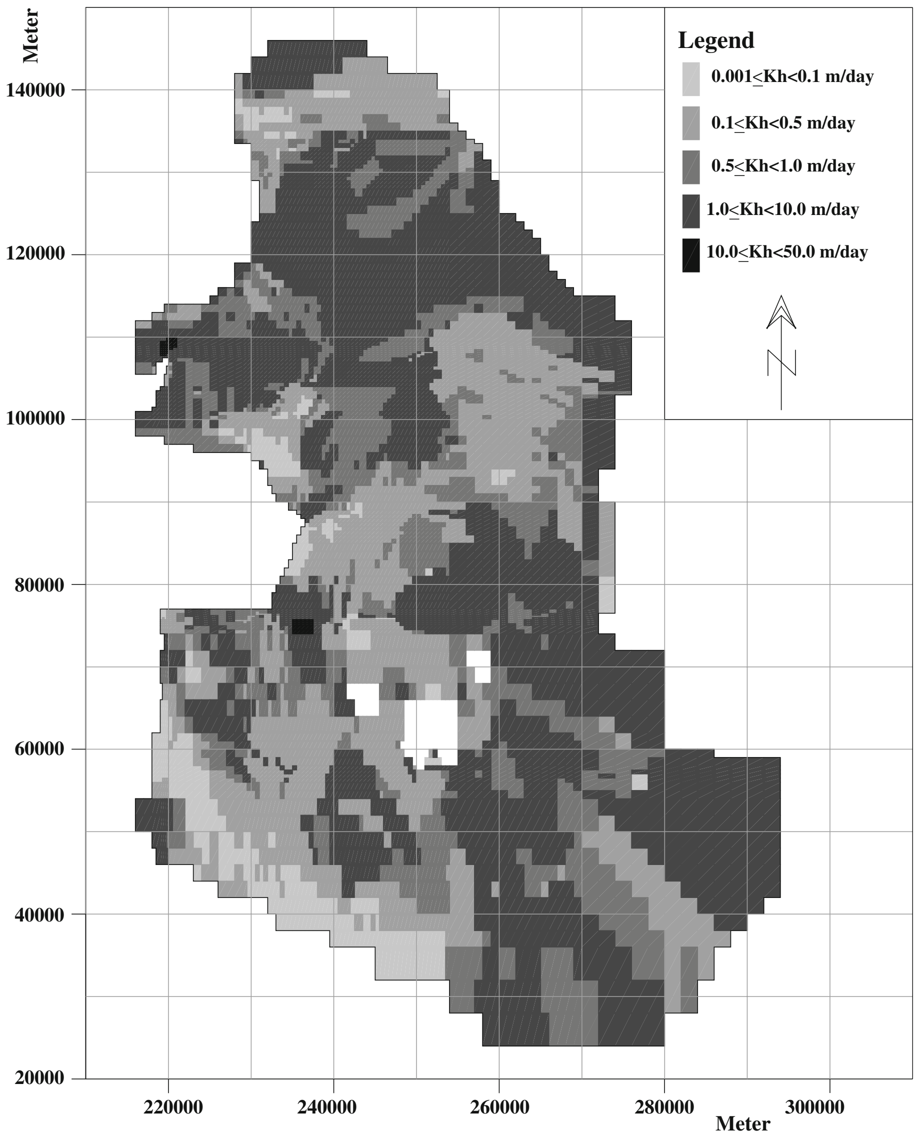



**Fig. 5** Distribution map of the calibrated horizontal hydraulic conductivity of the B2/A7 aquifer system

**Table 1** Statistical summary of calibrated model inputs for the Mujib basin (steady-state stage)

| Input | Min. | Max. | Mean | Standard deviation |
|---|---|---|---|---|
| Horizontal hydraulic conductivity (m/s) | $1.16 \times 10^{-8}$ | $4.63 \times 10^{-4}$ | $1.48 \times 10^{-5}$ | $2.23 \times 10^{-5}$ |
| Water level (m) | 363.3 | 1021.9 | 622.5 | 103.7 |
| Saturated steady-state thickness (m) | 57.2 | 382.0 | 148.1 | 47.8 |
| Transmissivity ($m^2$/s) | $1.16 \times 10^{-6}$ | $3.72 \times 10^{-2}$ | $2.19 \times 10^{-3}$ | $2.74 \times 10^{-3}$ |
| Annual natural recharge (mm) | 0.96 | 17.66 | 4.48 | 4.45 |
| Elevation of the bottom layer (m) | 179.6 | 964.0 | 474.5 | 127.5 |

**Table 2** Groundwater balance computed for steady-state condition ($Mm^3$)

| | |
|---|---|
| Outflow | 18.73 |
| Inflow | 13.03 |
| Spring flow | 15.3 |
| Recharge | 20.43 |
| Simulation error (%) | −1.9 |

from the B2/A7 aquifer system are toward Wadi Mujib and Wadi Wala (indicated by number (4)), and toward Azraq Basin (indicated by number (5)) with about 9.3 and 7.6 $Mm^3$, respectively. In addition, the spring discharges estimated by the model were close to the actual steady-state quantities of about 15.3 $Mm^3$. It is important to

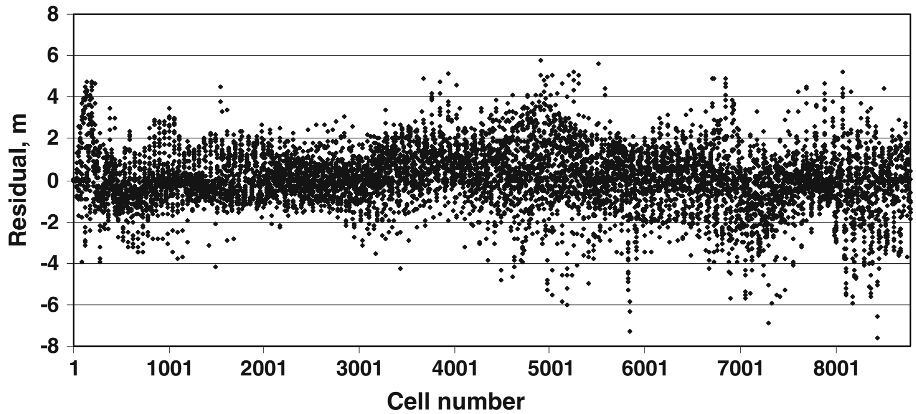



**Fig. 6** Plot of residual heads of model cells

address that the resulted water balance is influenced by the proposed boundary conditions.

## Model evaluation

Contour map of measured and simulated heads (Fig. 4) provides a visual, qualitative measure of the similarity between patterns, but it also includes errors introduced by contouring and therefore should not be used as the only proof of calibration. Figure 6 is another way of showing the calibration fit, which shows a scatter plot of residual heads of all model cells. There is a balanced distribution of residuals around zero and most of the residual heads are located between 2 and −2 m. Table 3 lists the summary of the goodness-of-fit of the steady-state calibration of the model at selected observation wells. The mean absolute error (MAE) ranges from 0.58 to 1.12 m. The maximum residual is about 4.2 m at the observation well CD1213. The coefficient of determination ($R^2$) ranges from 0.36 to 0.97.

## Transient calibration

Successful transient calibration depends mainly on the good estimation of hydraulic conductivities and boundary conditions obtained from the steady-state calibration. Generally, specific yield for unconfined aquifers and storage coefficient for confined aquifers are the main parameters that are changed during the transient calibration. In this study, specific yield was evaluated since the B2/A7 aquifer system in the Mujib basin is unconfined. The variation in the annual natural recharge quantities due to the rainfall fluctuation was taken into account during the transient calibration period.

The year of 1976 was considered as the year in which significant groundwater abstraction started. One stress period from year 1976 until 1979 with 48 time steps and constant wells discharge of 5.2 $Mm^3$/year was considered. Another stress period from 1980 until 1984 with 60 time steps and constant wells discharge of 10.8 $Mm^3$/year was considered. The natural recharge during 1976 and 1984 was assumed to be constant and equal to the average annual natural recharge. This is assumed due to the lack in groundwater levels data during that period. The period from year 1985 to year 2002 was divided into 36 stress periods, in which each year was split into two stress periods of 5 and 7 months. The natural recharge is assumed to occur only in the first stress period of 5 months (groundwater recharge season), while no recharge is occurred in the second stress period of the 7 months (no groundwater recharge season). It was assumed that well discharges have the same rates over the year.

The transient state model was calibrated using water level data from 12 observation wells. The groundwater level data for each observation well are divided into two sets: The first set for the period 1985–1995 is used for the calibration process while the second set for the remaining period (1996–2002) is left for the validation process. These 12 wells were selected from the 17 observation wells existing in Mujib basin because there are sufficient and suitable water level records. The remaining five wells have loose and interrupted records. The transient calibration was firstly done by assigning initial values of the specific yield to the groundwater model layer. These values are taken

**Table 3** Summary of some measures of fit between observed and computed groundwater heads for transient state (calibration period)

| ID | Residual max. | Residual min. | ME | MAE | RMS | $R^2$ |
|---|---|---|---|---|---|---|
| CD1097 | 0.062 | −2.167 | −0.632 | 0.640 | 0.844 | 0.419 |
| CD1106 | 1.421 | −1.601 | 0.139 | 0.681 | 0.826 | 0.986 |
| CD1132 | 2.893 | −3.628 | −0.012 | 0.981 | 1.313 | 0.716 |
| CD1136 | 2.518 | −0.836 | 0.588 | 0.668 | 0.985 | 0.441 |
| CD1212 | 1.497 | −0.920 | 0.230 | 0.583 | 0.700 | 0.360 |
| CD1213 | 4.232 | −1.611 | 0.876 | 1.121 | 1.523 | 0.950 |
| Ideal value | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |

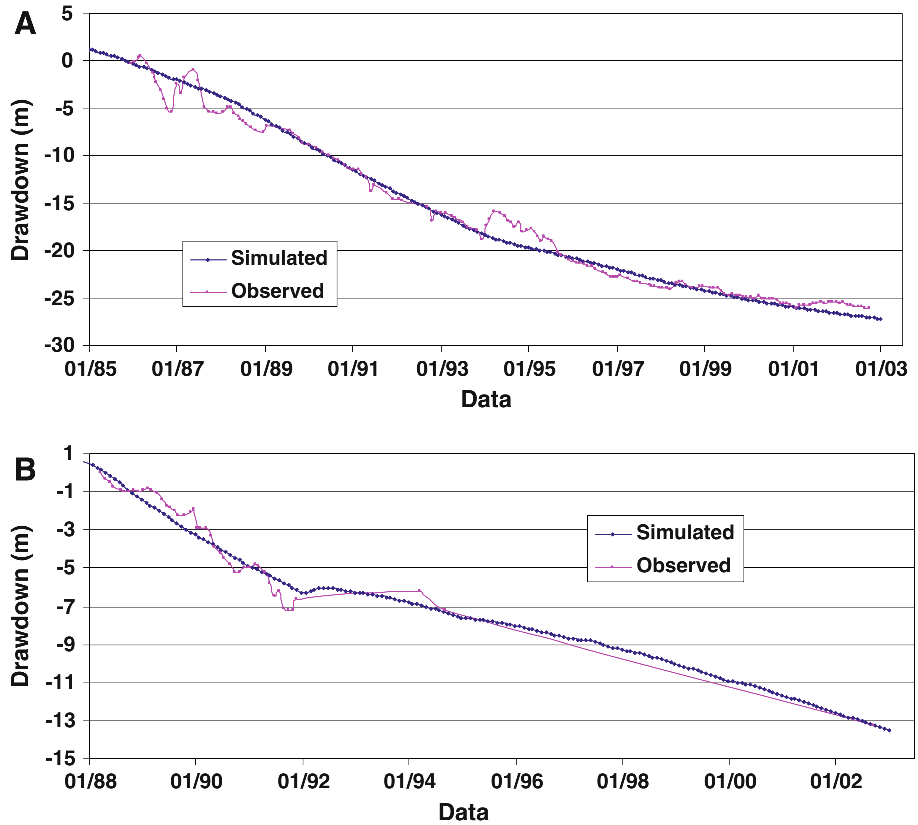



**Fig. 7** **a** Comparison between observed and simulated drawdowns of CD1132 calibration period (1985–1995), and validation period (1995–2002). **b** Comparison between observed and simulated drawdowns of CD1213 calibration period (1985–1995) and validation period (1996–2002)

from previous studies. Then, the initial values of the specific yield were changed several times by performing several computer runs until acceptable matches were obtained between the observed and simulated groundwater drawdown levels. The range of the resulted specific yield after the final calibration of the transient state was found to be varying from 0.0001 to 0.15 and averaged at 0.0283. However, the majority of the specific yield values were ranged from 0.01 to 0.04.

Figure 7a and b shows the comparison between observed and calculated drawdowns in the observation wells CD1132 and CD1213, respectively. Their drawdowns are highly affected mainly by the groundwater withdrawals and slightly by the natural recharge variation resulted from rainfall fluctuation. It can be seen that there is good agreement between the observed and simulated drawdowns. Table 4 presents summary statistics of the goodness-of-fit for the transient state calibration of the model for a selected set of the observation wells. The results indicate good agreement between the observed and simulated groundwater levels at these observation wells.

**Table 4** Summary of some measures of fit between observed and computed groundwater heads for transient state (validation period)

| ID | Residual max. | Residual min. | ME | MAE | RMS | $R^2$ |
|---|---|---|---|---|---|---|
| CD1075 | 12.603 | −18.695 | 1.312 | 5.816 | 7.083 | 0.568 |
| CD1097 | 2.289 | −7.985 | −1.210 | 2.059 | 3.039 | 0.453 |
| CD1174 | 3.210 | −0.914 | 0.186 | 0.837 | 1.158 | 0.668 |
| CD1211 | 0.808 | −0.207 | 0.332 | 0.388 | 0.447 | 0.485 |
| CD1214 | 4.232 | −1.611 | 0.876 | 1.121 | 1.523 | 0.950 |
| CD3116 | 0.567 | −9.556 | −5.238 | 5.272 | 5.785 | 0.345 |
| Ideal value | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 1.0 |

## Groundwater management considerations in arid region

Groundwater plays an important role in alleviating water scarcity problems in arid regions such as Jordan due to its inherent physical and storage characteristics. Aquifers can be used to store water especially in the wet seasons and have a much larger storage capacity compared to surface water reservoirs (Pereira et al. 2002). Groundwater in Mujib basin has been extensively exploited during the last 20 years which led to significant drawdown in groundwater table. Therefore, effective and sustainable management of groundwater resources is essential to save Mujib basin.

Non-conventional steps can be implemented to improve the storage of groundwater in the aquifers. Artificial groundwater recharge is one of these effective non-conventional methods that can be used to increase the aquifer productivity (Pereira et al. 2002). In this method, surface water is conveyed from lakes, reservoirs, wastewater treatment plants (WWTPs) or is being diverted from flowing streams to suitable areas where it is made to infiltrate to the groundwater through basins, trenches, pits, injection wells, etc.

### Proposed artificial recharge methods and water sources

In this paper, well injection and surface dams are the proposed methods for doing artificial recharge. The reasons of selecting these methods are explained in Table 5. Flood water is the main source used to artificially recharge the groundwater aquifer. The collected flood water in the surface dams will be used to directly allow water to infiltrate into the groundwater aquifer as well as for recharging into the aquifer through well injection method at well fields close to the dam sites. The dams will act as sediment retention reservoir and as water storage tank. However, collected flood water will mostly require preliminary treatment before injecting it to the B2/A7 aquifer. Treated wastewater can also be used for recharging which will be available in study area by constructing two new mechanical WWTPs. It is important to address that the quality of the treated wastewater used for artificial recharge assumed to meet the related Jordanian standard No. 893 of 2006 (JISM 2006).

The natural and artificial recharges are weighing up against the high losses of evapotranspiration occurred in relatively hot weather such as Jordan. If the flash floods during the rainy season may not have sufficient opportunity to infiltrate into the aquifers, such water will be lost through discharging it to the Dead Sea which then will be lost by evaporation. Furthermore, storing the water in the surface dams for long periods increases the water losses through evaporation as a result of the high temperatures and dry weather in Jordan. These losses are estimated to reach up to 25% of the water stored in the surface dams. Thus, the conjunctive use of surface and groundwater storage has big advantage in this case. Among a number of management interventions that could help improving the water situation in Jordan is artificial groundwater recharge. This aims to increase the groundwater recharge potential by artificially inducing increased quantities of surface water to infiltrate into the groundwater.

## Artificial groundwater recharge scenarios

The artificial groundwater recharge scenarios proposed in this study focused on injecting water directly to the aquifer from the existing and the proposed dams in the Mujib basin (Table 6), and from the future WWTPs that are planned to be constructed in the northern part of the Mujib basin (Fig. 8). In addition, infiltration from dams' reservoirs was taken into consideration.

According to the JICA study (1987), there are 20 conceivable dam sites in the Mujib basin which are illustrated in Fig. 8. The features of these dams are summarized in Table 6. Some of these dams were already built while the others are proposed as possible sites to make best use of the valuable surface flow. Most of these conceivable dam sites are located in limestone geological layers. There is thick low permeability layer on the ground surface at some of these dam sites. The ground surface of Hamman, Sadir, and Qatrana (existing) dams is overlaid by B2 formation (good permeability), while Mujib and Nukheila are overlaid by A3 formation (low permeability). However, only Wala and Sueida 2 dam sites are located in a region of shallow groundwater table.

Eight out of 20 dams proposed were not included in the management scenarios for the Mujib basin. These dams are shaded in Table 6. Rumeil and Nukheila dams were not

**Table 5** Artificial recharge methods selected for the study area

| Artificial recharge method | Advantages | Disadvantages | Rational behind method selection |
|---|---|---|---|
| Injection wells | Preference to use in case of (Pereira et al. 2002)<br>Presence of a thick and low permeability layer<br>Land scarcity<br>Deep groundwater | Clogging problems and difficult cleaning operations (Huisman and Olsthoorn 1983)<br>Pretreatment of recharged water (Asano 1985) | Most of the B2/A7 aquifer system is overlaid by a low permeable layer (B3)<br>Groundwater table depth of 10–300 m<br>To reduce evaporation losses estimated at around 25% of water injected |
| Surface dams | Good to use in case of shallow groundwater and existence of high permeability layer | High evaporation rates | Dams located at a ground of high infiltration rate<br>To reduce the cost of constructing water transfer pipelines and injection wells |

**Table 6** Principle features of proposed dams sites (JICA 1987)

| No. | Dam | Catchment area ($km^2$) | Average flood runoff ($Mm^3$/year) | Most frequent flood runoff (2-year return) ($Mm^3$/year) |
|---|---|---|---|---|
| 1 | Wala | 1,770 | 21.52 | 19.31 |
| 2 | Rumeil | 1,620 | 18.99 | 16.99 |
| 3 | Zeinab | 490 | 11.23 | 9.86 |
| 4 | Halq | 720 | 5.13 | 4.59 |
| 5 | Hammam | 340 | 2.15 | 1.91 |
| 6 | Sadir | 140 | 1.53 | 1.35 |
| 7 | Shabik | 240 | 1.67 | 1.44 |
| 8 | Mujib | 4,340 | 29.85 | 24.12 |
| 9 | Nukheila | 3,560 | 26.15 | 20.75 |
| 10 | Sueida 2 | 520 | 1.66 | 1.39 |
| 11 | Sueida 1 | 460 | 1.4 | 1.17 |
| 12 | Siwaqa (existing) | 440 | 1.32 | 1.10 |
| 13 | Siwaqa N | 90 | 0.23 | 0.19 |
| 14 | Siwaqa S | 280 | 0.76 | 0.63 |
| 15 | Qatrana | 1,640 | 2.51 | 1.96 |
| 16 | Qatrana (existing) | 1,490 | 2.28 | 1.78 |
| 17 | Dabb'a | 1,430 | 11.77 | 8.96 |
| 18 | Khabra | 290 | 9.01 | 6.12 |
| 19 | Sultani | 1,010 | 3.39 | 2.15 |
| 20 | Sultani (existing) | 950 | 3.19 | 2.02 |

selected because they are close to the existing Wala and Mujib dams. Sueida 2 is selected in favor of Sueida 1 since the catchment area of Sueida 2 is larger and its groundwater table is shallow. Siwaqa N, Siwaqa S, and Qatrana dams were not selected because Siwaqa and Qatrana existing dams were already built and they have enough capacity to fulfill the recharged water quantity required. Khabra dam was taken away as it is close to the proposed Dabb'a dam site which is located downstream from the proposed Khabra dam site, and because Dabb'a dam is closer to the well fields than Khabra dam. Sultani (existing) was not selected since its reservoir is full with sediments and so it cannot be used to store water.

Table 7 summarizes the water infiltration rates and quantities from the reservoirs as well as the capacity of the dams considered in the artificial recharge scenarios. Part of the stored water in these dams was considered to be injected directly to the B2/A7 aquifer system. The infiltration rate quantities were calculated based on the infiltration rate per day (Table 7) by assuming that the infiltration was occurring only during the rainy season (5 months) and that the dams' reservoirs were half full with water. Based on these assumptions, the overall annual quantities infiltrated from the selected dams were estimated at about 1.9 $Mm^3$. It is worth to address that dams' reservoirs will lose around 7.7 $Mm^3$/year through evaporation if they are assumed to be half full with water during the year. This also supports recharging water option artificially into the B2/A7 aquifer instead of losing significant amount of water through evaporation.

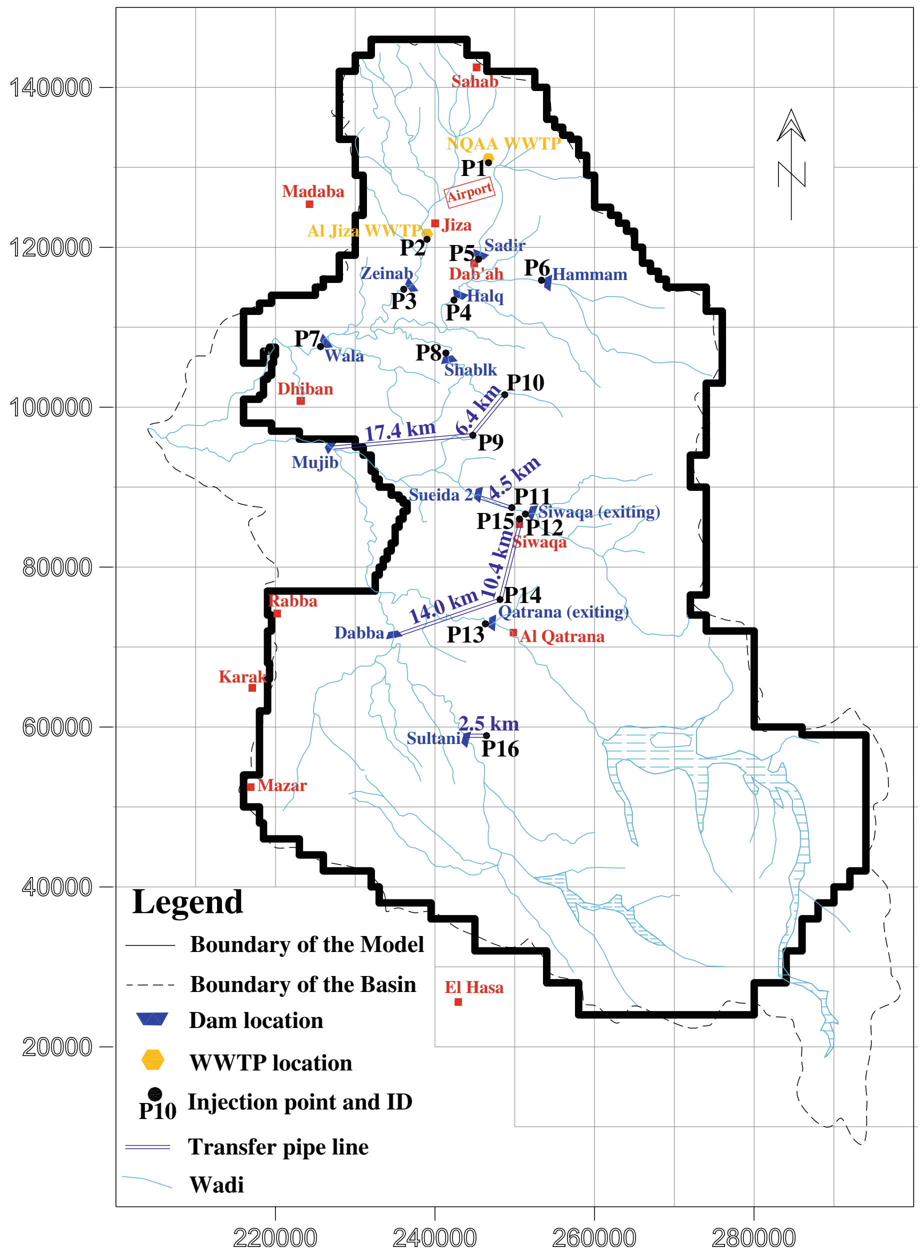
Two mechanical WWTPs are planned to be constructed in Mujib basin: Al Jiza WWTP and North Queen Alia Airport WWTP (NQAA WWTP). According to the investment program of the Ministry of Water and Irrigation (MWI 2002), the operation of these plants will be started in the mid of 2009. The capacities of Al Jiza WWTP and NQAA WWTP were estimated to be 2.7 and 8.4 $Mm^3$/year, respectively. It is expected that these two plants will produce treated wastewater of good quality that meets the Jordanian standards for groundwater artificial recharge purposes.

In this paper, it was assumed that the artificial recharge implementation will take place at the beginning of year 2010 through 16 injection points illustrated in Fig. 8. The proposed locations of these points were selected depending on the degree of groundwater table drawdown and on the distance of water transferring. The areas of relatively high groundwater drawdown, which are mostly close to the well fields, are selected so as to help recovering the deteriorated groundwater aquifer and increase the wells productivity in these areas. The distance of water transferring between its sources (dams and WWTPs) and the proposed injection points was considered to be minimized as possible in order to reduce the cost of the pipeline construction. It can be seen that most of the selected locations are close to the dams and WWTPs except for Mujib, Sueida 2, Dabba'a, and Sultani Dams, where transfer pipelines are needed to convey water from dams to the proposed points. The lengths of these pipelines are shown in Fig. 8. The overall length is about 55.2 km. Three scenarios for artificial recharge will be introduced (scenarios 2–4) and compared with scenario 1 that assumes the continuity of the current pumping rates (no artificial recharge).

Scenario 1: Continuity of the current pumping rate (57.9 $Mm^3$/year) without artificial recharge.

This is assumed that the pumping rates of year 2002 remain constant for 8, 18, and 28 years. The model results show that the maximum drawdowns would be concentrated in the well field areas, and reached about 71.5, 90.3, and 104.9 m in the years 2010, 2020, and 2030, respectively. According to this scenario, the model predicted that in 2030 there would be some dry areas at Siwaqa well field where the drawdown exceeds 100 m. In addition, Heidan spring would dry before year 2010 and most of the northern part of Mujib basin (southern Amman city) would have

Fig. 8 Proposed injection points location and their ID




high groundwater drawdown by 2030 ranged from 20 to 50 m as a result of continuing the current extensive pumping rates.

Scenario 2: High artificial recharge rate (35.9 $Mm^3$/year) and no reduction of current pumping rate (57.9 $Mm^3$/year).

In this scenario, it was assumed that current abstraction rates are constant and about 1.9 $Mm^3$ is infiltrated from dams' reservoir, 30.0 $Mm^3$ is injected from dams' water storage and 4.0 $Mm^3$ from the reclaimed wastewater (3.0 $Mm^3$ from NQAA WWTP and 1.0 $Mm^3$ from Al Jiza WWTP). This means an overall recharged quantity of about 35.9 $Mm^3$/year. However, achieving such high artificial recharge rate may not be guaranteed due to the fluctuating behavior of rainfall in Jordan. Detailed injected quantities at each point are summarized in Table 8.

The model results show that the groundwater levels at Wala injection wells would increase by about 15.2, 19.9, and 22.5 m in 2010, 2020, and 2030, respectively, above the steady-state groundwater levels. Under this scenario, the overall recharge quantity (artificially and naturally of 58.3 $Mm^3$/year) would exceed the abstracted quantity by groundwater wells of 57.9 $Mm^3$/year. Moreover, the Heidan spring would discharge around 5–6 $Mm^3$/year, and the groundwater table in the upper stream area of Heidan spring would recover fast and would reach higher levels than computed steady-state groundwater levels. Qatrana

**Table 7** Proposed and existing dams selected for the artificial recharge scenarios

| No. | Dam | Proposed (existing) capacity (Mm$^3$) | Reservoir area (km$^2$) | Infiltration[a] (mm/day) | Infiltration quantity (Mm$^3$) |
|---|---|---|---|---|---|
| 1 | Wala | (9.3) | 0.70 | 5 | 0.37 |
| 2 | Zeinab | 6.0 | 0.71 | 5 | 0.38 |
| 3 | Halq | 2.0 | 0.51 | 5 | 0.27 |
| 4 | Hammam | 1.5 | 0.51 | Negligible | 0.00 |
| 5 | Sadir | 1.5 | 0.57 | Negligible | 0.00 |
| 6 | Shabik | 1.5 | 0.33 | 5 | 0.17 |
| 7 | Mujib[b] | (35.0) | 1.92 | 0.5 | 0.10 |
| 8 | Sueida 2 | 1.5 | 0.22 | 5 | 0.12 |
| 9 | Siwaqa (existing) | (2.5) | 0.60 | 1 | 0.06 |
| 10 | Qatrana (existing) | (2.0) | 0.75 | Negligible | 0.00 |
| 11 | Dabb'a | 6.0 | 0.62 | 5 | 0.33 |
| 12 | Sultani | 2.5 | 1.72 | 1 | 0.18 |

[a] Infiltration rates are taken from JICA study (1987)

[b] Mujib dam is out of the modeled area

**Table 8** Injected quantity at each proposed point for different scenarios

| Point ID | Injected quantity (Mm$^3$) | | | Sources name | Point ID | Injected quantity (Mm$^3$) | | | Sources name |
|---|---|---|---|---|---|---|---|---|---|
| | Scenario 2 | Scenario 3 | Scenario 4 | | | Scenario 2 | Scenario 3 | Scenario 4 | |
| P1 | 3.0 | 0.0 | 1.5 | NQAA WWTP | P9 | 2.5 | 1.25 | 2.0 | Mujib dam |
| P2 | 1.0 | 0.0 | 0.75 | Al Jiza WWTP | P10 | 2.5 | 1.25 | 2.0 | Mujib dam |
| P3 | 4.0 | 2.0 | 3.0 | Zeinab dam | P11 | 1.0 | 0.5 | 0.75 | Sueida 2 dam |
| P4 | 1.5 | 0.75 | 1.0 | Halq dam | P12 | 1.0 | 0.5 | 0.75 | Siwaqa (existing) dam |
| P5 | 1.0 | 0.5 | 0.75 | Sadir dam | P13 | 1.5 | 0.75 | 1.0 | Qatrana (existing) dam |
| P6 | 1.0 | 0.5 | 0.75 | Hammam dam | P14 | 2.0 | 1.0 | 1.5 | Dabb'a dam |
| P7 | 7.0 | 3.0 | 5.0 | Wala dam | P15 | 2.0 | 1.0 | 1.5 | Dabb'a dam |
| P8 | 1.0 | 0.5 | 0.75 | Shabik dam | P16 | 2.0 | 1.0 | 1.5 | Sultani dam |

and Siwaqa well field areas also would benefit of good recovery.

Scenario 3: Low artificial recharge rate (15.5 Mm$^3$/year) and no reduction of current pumping rate (57.9 Mm$^3$/year).

Low recharge quantity was assumed to be injected and infiltrated under this scenario. About 1.0 Mm$^3$/year was assumed to be infiltrated from dams' reservoir, 14.5 Mm$^3$/year to be injected from dams' storage and no reclaimed wastewater is injected, while the abstraction rates were also assumed to be constant to the current rates (57.9 Mm$^3$/year). Table 8 shows the detailed injected water at each proposed point. In this scenario, the deficit between recharge quantity and wells abstraction would exceed 20 Mm$^3$/year, and consequently the drawdown of the groundwater table would increase significantly.

Scenario 4: Moderate artificial recharge rate (26.0 Mm$^3$/year) and 20% reduction of current pumping rate (46.3 Mm$^3$/year).

This scenario was judged as the most feasible scenario. The present abstraction rates of about 57.9 Mm$^3$/year were assumed to decrease by 20–46.3 Mm$^3$/year and about 26 Mm$^3$/year of moderate artificial recharge will be applied. The recharged quantity is divided into 22.25 Mm$^3$ injected water from dams' storage, 2.25 Mm$^3$ injected reclaimed wastewater and 1.5 Mm$^3$ infiltrated quantity from dams' reservoir. Detailed injected quantity at each proposed point from dams and WWTP is summarized in Table 8. Under this scenario, the total amount of recharged water both artificially and naturally would exceed the suggested abstraction amount. This management scenario would result in a better recovery for groundwater table than previous artificial recharge scenarios.

Fig. 11, it can be noticed that groundwater levels at Wala injection wells would increase and reach about 9.8, 12.8, and 14.3 m above the steady-state groundwater levels in the years 2010, 2020, and 2030, respectively. A good recovery for groundwater table under artificial recharge scenarios is noticed when enough water is injected while abstraction rates are reduced, which is the case of scenario 3.

The last three scenarios present possible management options using artificial groundwater recharge in which high, low, and moderate artificial rates are proposed in scenarios 2–4, respectively, accompanied with no reduction in abstraction rates for scenarios 2 and 3 and with 20% reduction in scenario 4. It is likely that the groundwater abstraction rates will decrease through the existing plans of WAJ to further activate the Underground Water Control By-Law of 2002 (WAJ 2002). This By-Law sets increasing block fees on the groundwater quantity abstracted by wells' owners. Moreover, the aquifer productivity is decreasing as a result of the groundwater table decline. Taking into account the fluctuating behavior of rainfall in Jordan, a high recharge rate as foreseen in scenario 2 would be mostly not achievable. Therefore, scenario 4 is practically considered the most feasible management scenario.

The model prediction shows that scenario 4 would produce the best results in most observations wells followed by scenario 2 then by scenario 3. Sample of the results are presented in Figs. 9, 10, 11, which illustrate the change on the groundwater table drawdown during the 2003–2030 period in CD1097, CD1132, and CD1212. Figures 9 and 11 show that scenario 2 would be able to achieve almost the same results of scenario 4. In fact, the model prediction shows that scenario 2 has a better impact on the groundwater table only in wells CD1213 and CD1174 (2 out of 15 wells). The figures also compare the artificial recharge scenarios (2–4) with scenario 1 (current pumping rate without artificial recharge). The figures clearly show that there are good recovery rates of the groundwater table under all the artificial recharge scenarios compared with scenario 1. However, the recovery rates differ between the wells as illustrated in Figs. 9, 10, 11.

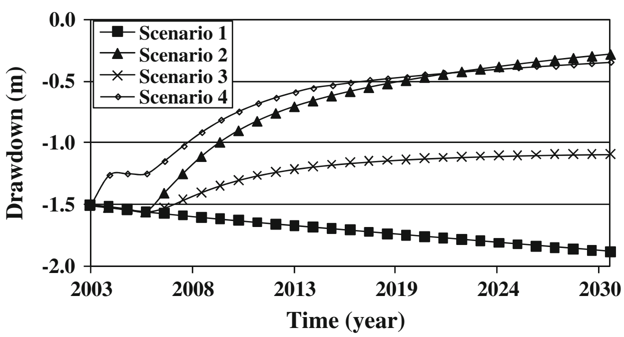



**Fig. 9** Model prediction for the four scenarios at the observation well CD1097

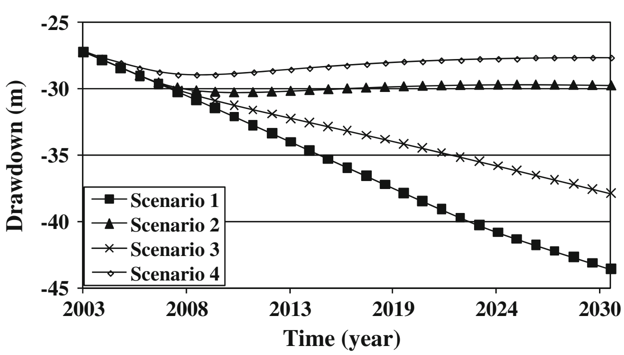



**Fig. 10** Model prediction for the four scenarios at the observation well CD1132

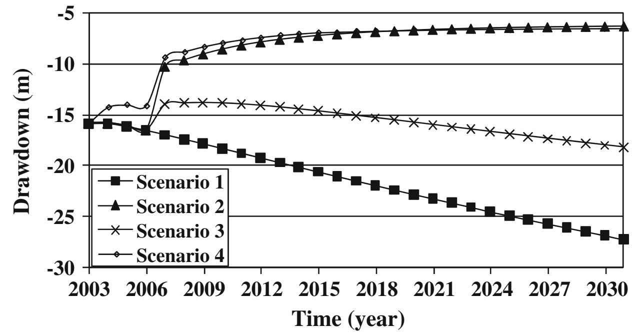



**Fig. 11** Model prediction for the four scenarios at the observation well CD1212

## Conclusions

Processing MODFLOW version 5.0 (PM5) is used in this study to simulate the groundwater flow for the B2/A7 aquifer system in Mujib basin for both steady and transient conditions, and to simulate the future changes occurred on the groundwater table under different scenarios of artificial recharge. The model is a one layer and the aquifer type is unconfined with low permeability bed considered as impervious.

Model calibration for steady-state conditions showed a very good agreement between observed and simulated steady-state groundwater levels and statistical evaluation of the model ensures that agreement. Transient state calibration also showed a good agreement verified using the drawdown data of the 1996–2002 period. Agreement of the validation period was less good than for the calibration period but it gives also good and acceptable agreement for most observation wells.

Results of the calibrated flow model (steady and transient states) indicate that the horizontal hydraulic conductivity of the B2/A7 aquifer system in Mujib basin ranges between $1.16 \times 10^{-8}$ and $4.63 \times 10^{-4}$ m/s. The majority of the calibrated specific yield values range between 0.01 and 0.04. The water balance of the model for steady-state conditions is as follows: the total annual direct recharge to the B2/A7 aquifer system is 20.4 $Mm^3$; the total annual inflow (base flow) is 13.0 $Mm^3$; springs discharge is 15.3 $Mm^3$/year; and total annual outflow is 18.7 $Mm^3$.

Three scenarios to predict aquifer system responses under different artificial recharge options and one scenario without artificial recharge and at the same current pumping rate have been performed. The following results were obtained:

- Continuity of the current pumping rate would lead to further groundwater drawdown and create dry areas at several locations including the drying up of Heidan spring by 2010.
- Applying high artificial recharge rates (35.9 $Mm^3$/year) in addition to the natural recharge quantity would create some kind of balance in facing the current abstraction rates (57.9 $Mm^3$/year), and good recovery for groundwater table would be occurred in many areas in the basin.
- Applying low artificial recharge rates (15 $Mm^3$/year) with the current abstraction rates would not allow producing good recovery in groundwater table except in some areas.
- With moderate artificial recharge rates of about 26 $Mm^3$/year and with applying small reduction of 20% in the current abstraction rate, a good recovery in groundwater table could be achieved. This scenario could be considered as the most feasible one where (1) activating the Underground Water Control By-Law of 2002 to reduce the current abstraction rates could be achieved and (2) moderate amount of water could be recharged annually with acceptable cost and water availability.

Mujib basin has been highly over-exploited during the last 15 years. It would face a serious problem leading to increase its groundwater table drawdown and to reduce its groundwater quality, if no measures are taken. Such measures include reducing the current groundwater abstraction rates and applying artificial recharge to increase the aquifer yield. It is recommended to make further investigation on the feasibility of artificially recharging aquifers with reclaimed wastewater in order to obtain deeper understating of the reclaimed wastewater impact on the groundwater quality.

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