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ORIGINAL ARTICLE

Conjunctive use of groundwater and surface water resources with aquifer recharge by treated wastewater: evaluation of management scenarios in the Zarqa River Basin, Jordan

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Abstract We study the effects of treated wastewater (TWW) discharge into the Zarqa River in Jordan and the underlying unconfined limestone Hummar Aquifer. The main objectives were to develop a conceptual model of the aquifer, to gain better understanding of water dynamics in the basin and to investigate different management scenarios of conjunctive use of groundwater and surface water. The model using MODFLOW 2005 code was developed over a selected part of the Zarqa River Valley of area 387 km^2, including the As Samra wastewater treatment plant (WWTP). The annual TWW discharge of 110 million m^3 significantly augments the groundwater storage and allows for expansion of agricultural practices in the area, providing large reserve during dry spells. On average, the water table rises by 29 m following the inception of the WWTP. The results indicate that the aquifer will be able to accommodate extra discharge of TWW when the plant will operate at full capacity as planned and upon increase in the abstraction rate for irrigation by 30 %, based on farming land availability. This abstraction will result in an average water table drawdown of 0.3 m. Because around 20 % of the discharged TWW only reach the aquifer, we recommend direct use of river water, especially during drought periods to reduce the stress on the aquifer storage and its associated depletion. The simulated conjunctive use and MAR utilizing both TWW and the groundwater present a salient case study of intricate management of water resources in arid zone. Augmentation of groundwater resources by both banking of the TWW and management of water use will allow more agricultural activities that would result in a better income for farming communities and social stability in the MENA region, where water is a precious commodity.

Keywords Groundwater–surface water interactions · Zarqa River · As Samra wastewater treatment plant · Jordan · Conjunctive water use · MODFLOW 2005

Abbreviations

BC	Base case scenario (current situation)
BG	Background scenario
C	River conductance (m^2/day)
D	Recharge rate (m^3/day)
Depth	Soil depth (m)
Depth_min	Depth of the horizon above the horizon with the lowest hydraulic conductivity (m)
ET	Evapotranspiration (mm/year)
GIS	Geographical information system
H	Stream depth at the gauging station (m)
H_{BC}	Average river water depth for base scenario (m)
H_S	Average river water depth for a given scenario (m)
IDW	Inverse distance weighing method

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J2000	Hydrological and physical processes-based model of the water balance of large catchment areas
kf_max	Maximum coefficient of hydraulic conductivity (m/day)
kf_min	Minimum coefficient of hydraulic conductivity (m/day)
k_s	Hydraulic conductivity of streambed sediments (m/day)
l	Length of the river reach (m)
MAR	Managed aquifer recharge
MENA	Middle East and North Africa
ModelMuse	A graphical user interface for MODFLOW-2005
MODFLOW	Finite-difference groundwater flow model
m_s	Thickness of the streambed sediments (m)
MWI	Ministry of Water and Irrigation of Jordan
NE	North East
NRA	Natural Resources Authority, Amman, Jordan
P	Precipitation (mm/year)
Q	River discharge
Q_{TWW}	River discharge changes among various scenarios
RIV	River MODFLOW package
R_{off}	Runoff (mm/year)
SCS	Soil Conservation Service, the United States Department of Agriculture
SID	Soil type ID
STP	Sewage treatment plant
SW	South West
TWW	Treated wastewater
USA	United States of America
USAID	United States Agency for International Development
USGS	US Geological Survey
w	Width of the river reach (m)
WAJ	Jordan Water Authority, Amman, Jordan
WWTP	Wastewater treatment plant
ΔS	Change in soil water storage in the soil column (mm/year)

Introduction

Studies of groundwater–surface water interactions are a subject of interest to hydrologists, leading to a better conjunctive use of water from two different sources: surface water and groundwater, for consumptive purposes. Proper conjunctive use can mitigate water shortages in irrigated agriculture (Singh 2014) and increase the water use efficiency and improve regional environmental conditions in irrigated areas (Cheng et al. 2009; Liu et al. 2013). Khare et al. (2007) developed the conjunctive water use plan (allocation of surface water and groundwater) and suitable cropping patterns to meet present and future requirements of the studied canal command area, India. Montazar et al. (2010) evaluated various scenarios of conjunctive use in a semiarid region, the northwest of Iran. Several studies report conjunctive use of TWW and groundwater. Ejaz and Peralta (1995) developed a simulation–optimization model to determine the use of reclaimed water in conjunction with river and groundwater and considering the water quality constraints. Surapaneni and Olsson (2002) proposed the conjunctive use of channel water, groundwater pumping and treated municipal industrial water in the Shepparton Irrigation Region, northern Victoria, Australia. Al Khamisi et al. (2013) explored direct use of reclaimed water from a sewage treatment plant (STP) without Aquifer Storage and Recovery, as a source of irrigation water in conjunction with groundwater in Al Batinah Region, Oman. Results show that the conjunctive use of reclaimed water with groundwater can increase the irrigated area by 323 %.

Managed aquifer recharge (MAR) is defined as the intentional recharge of water into an aquifer either by injection (including treated wastewater) or infiltration and recovery by planned extraction (Hayder Consulting 2006). MAR, also called subsurface water banking (O'Geen et al. 2015), offers a promising practice to alleviate water shortage during high-demand seasons. However, implementing the MAR using TWW has adverse environmental effects as TWW may contain pathogens, heavy metals, pharmaceuticals among other undesirable constituents (Abdel-Raouf et al. 2012). Therefore, most of the MAR studies in connection with TWW focused on small-scale laboratory experiments only (e.g., Ko et al. 2016; Im et al. 2016) or mathematical modeling (e.g., Rahman et al. 2013). The investigated site of the current study, the Zarqa River Basin in Jordan, offers an optimal opportunity to assess a long-term aquifer recharge at a field scale, where the TWW discharged into the river interacts with the groundwater.

More than 90 % of Jordan area has arid and semiarid climate. Strains on limited surface and groundwater resources due to the population growth, agricultural development and influx of refugees are among the major reasons forcing planners in the Ministry of Water and Irrigation of Jordan (MWI) to use and extend managed aquifer recharge (MAR) in their water management and development strategies. One of the sources already in agricultural practice is use of treated wastewater (TWW). In Jordan, there are 31 TWW plants ("Appendix 1"), and As Samra plant is the largest, with a designed maximum capacity of 364,000 m^3/day (MWI 2013) or about 60 % of entire TWW volume in Jordan, and serving the two major cities: Amman and Zarqa. This plant is situated in the upper part of the Zarqa River Basin that accepts all TWW discharges. The Zarqa River is the most important source of surface water in Jordan, and more than 78 % of its current is composed of TWW (WAJ 2006). River's total length is 65 km, with the topographical drop of more than 1 km from the source to the mouth at the confluence with the Jordan River; the annual discharge varies from 112 million m^3/year in the upper course to 65 million m^3/year in the middle course. Downstream, the middle and lower courses are gaining sections that receive baseflow. While the TWW component is relatively stable with slight decrease on weekends due to the drop of urban sewage generation, the baseflow has strong seasonal fluctuations determined by the local arid climate.

Before construction of the plant in 1985, two hydrological periods characterized the upper reaches of the river. In the 1950s and earlier, the river and underlying aquifer were in hydrological homeostasis: the Zarqa spring served as the origin of the river, which was gaining groundwater along its whole course (Al-Wer 2009). Since 1960s, tube wells and irrigation-fed farms proliferated in the catchment, resulting in the water table drop, and the spring dried out. The first tens of kilometers of the river became ephemeral, where water appeared as flash floods after torrential rainfalls only. The stable discharge of TWW resuscitated the upper section of the river as a perennial watercourse. Intensive groundwater withdrawal had, however, continued and even increased over the interlocking river reaches. Consequently, the upper course of the river became a losing section, where TWW seeps through the riverbed that formed a large groundwater mound in the last two decades. Remarkably, with the USAID-sponsored improvement in technologies of water treatment in STP, the quality of water discharged into the river also improved (Al-Abdallat 2011).

Currently, the farms get water from both the wells tapping the mound and directly from the river [see Bouwer (1970) and Feigin et al. (1991) for a similar experience in the USA and Israel, where the practice of the MAR by TWW was used for half a century]. In the middle and lower courses of the river, the water quality, however, drops because of more return flow from drainage with pesticides and fertilizers, as well as untreated industrial wastes, which continuously exfiltrate with the baseflow and are carried into the river by occasional runoff.

Historical records from the Zarqa River in the 1960s indicated a baseflow of 2.0 m^3/s, which decreased to less than 0.2 m^3/s in the early 1980s due to over-pumping and agricultural activities (MWI 2015). Starting by mid-1980s, the discharge recovered due to the effluent of TWW, which was released after secondary treatment directly to the river ("Appendix 2").

Today, the hydrological regime of the Zarqa River is strongly affected by the substantial discharge of TWW effluents from As Samra, which became a vital resource of water in the Zarqa River Basin: As Samra plant contributed about 76 % of the annual discharge of the Zarqa River, while the baseflow is limited to 24 % (Margane et al. 2002). The TWW is used mainly for irrigation activities in the basin, which is considered the most important in Jordan, because about 65 % of the Jordan population lives along the Zarqa River Basin (Al-Wer 2009). As Samra TWW plant services Amman and Zarqa cities (See Service Governorate in Appendix 1: Wastewater treatment plants in Jordan). In total, about 62 % of the population in the Amman-Zarqa area is serviced with sewerage systems, currently producing about 110 million m^3/day of secondary treated effluent. This discharge is expected to rise to 135 million m^3/year (MWI 2009) in 2016.

Due to the anthropogenic impacts, the Zarqa Basin is still facing many agroecological challenges. They include secondary salinization of soils that are continuously irrigated for several decades, depletion of groundwater in the parts of the river basin not positively affected by the mentioned MAR in the upper course of the river, siltation and water quality degradation in the reservoir of the King Talal Dam in the middle course of the river. Overall, the groundwater abstraction exceeds the average sustainable limits (MWI 2009). Therefore, TWW discharge augments both surface and groundwater.

The conjunctive use of groundwater with adjoining streams, canals and drains is a common aspect of many hydrogeological–hydroengineering systems. The effluent from treatment plants in Jordan, used mainly for agriculture, is discharged into the dry wadis or stored by the dams such as the mentioned King Talal Dam, Shuieb Dam and Wadi Kafra Dam. TWW can supply all of the Jordan agricultural needs in the future if production of TWW continues to increase (Altz-Stamm 2012). Considering the increasing TWW rates and expanding areas with sewerage services and groundwater use for agriculture, amalgamation of natural and MAR inputs, dynamic multi-criteria management, including protecting surface and groundwater against over-pumping and pollution, is a critical issue for the Zarqa River Basin, which can serve as a role model for the whole country.

Models [analytical and numerical, stochastic and deterministic, comprehensive and parsimonious, physical and empirical, see Giacomelli et al. (2001)] are widely used in studying interactions between surface water and groundwater (e.g., Winter et al. 1998; Woessner 2000; Kalbus et al. 2006; Barlow and Leake 2012). While analytical methods are easier to implement for diagnostic "back-of-an-envelope" assessments when input data on aquifers and surface flow are limited (Barlow and Moench 1998; Barlow et al. 2000), the numerical models are more effective in accommodating vast and different hydrological datasets. In addition, surface water modules are available in the commonly used groundwater flow models, including the MODFLOW (Harbaugh et al. 2000; Harbaugh 2005) for studies of stream–aquifer systems.

Hydrogeology, groundwater hydrology and water management of several catchments of the Jordan Valley are well investigated, including MODFLOW-based modeling which extends the recent work by Al Mahamid (2005), Abdulla and Al-Omary (2008), Hötzl et al. (2009), Al-Omari et al. (2009) and Al Kuisi et al. (2014). However, a crucial area of the upper course of the Zarqa River near the As Samra plant needs more detailed studies.

Al Mahamid (2005) provided a list of relevant projects in the area and developed a groundwater flow model for the upper (limestone B2A7) and deep (Kurnub) aquifers in the Amman-Zarqa Basin, which covered more than 3918 km^2, neglecting the intermediate Hummar Aquifer. This model considered the upper limestone (B2A7) aquifer in the highland which is eroded along the Zarqa River and covering the northern highlands of the basin making Hummar Aquifer as the upper aquifer in the river basin. The model considered the study area as dry cells as it was composed of Hummar Aquifer with the absence of B2A7 in the river basin, which is the upper aquifer in the northern highlands, while Kurnub is the third aquifer. Abdulla and Al-Omary (2008) evaluated the impact of the climate change in the monthly runoff and actual evapotranspiration of the Zarqa River Basin in Jordan. Al-Omari et al. (2009) developed a water management support system for Amman-Zarqa Basin in Jordan for water resources evaluation and planning for year 2025. The results showed that the agricultural demand could only be satisfied under the advanced wastewater treatment and the optimistic scenarios: both consider the advanced wastewater treatment option for the As Samra plant effluent. Al Kuisi et al. (2014) generated a groundwater vulnerability map for the Amman-Zarqa Basin using remote sensing information and laboratory analyses, to assist in the implementation of land use planning and groundwater management strategies to prevent degradation of groundwater quality. Nevertheless, data with appropriate spatial and temporal resolution are limited, and our work significantly utilizes general data provided by MWI (2014).

The aim of this paper is to incorporate new data, evaluate groundwater–surface water interactions and provide insights into the effects of water resources management in the part of the river basin adjacent to the sewage treatment plant. This area is characterized by unique anthropogenic impacts and rapid MAR-induced aquifer changes. We assess several forthcoming factors: a well-projected increase in the TWW discharge from the As Samra plant to the Zarqa River, less certain increase in water extraction from irrigation wells (if the water quality remains adequate) and potential reduction in groundwater extraction due to deterioration of water quality in some wells. This model is the first attempt to investigate conjunctive use in the catchment under a strong influence of MAR at such important spatial scale. The analyses of aquifer response to various scenarios of TWW discharge and well abstraction will contribute to the proper development of irrigated agriculture in the river basin.

Study area

Geography

Amman-Zarqa Basin covers an area of about 4025 km^2, where 89 % are located in Jordan and 11 % in the Syrian territory (Fig. 1b). The climate varies from semiarid in the western highlands of the study area to arid in the eastern parts, with different land use patterns and various socioeconomic practices such as agriculture, power generation and oil refining (Al Mahamid 2005).

The Zarqa River is located in the central parts of the Amman-Zarqa Basin with discharge at a rate 110 million m^3/year of a secondary TWW from the As Samra plant, located 50 km East of Amman. The studied portion of the Zarqa River extends from the discharge site of Khirbet As Samra through Al-Hashimiya Village and the cultivated areas along the banks of the Zarqa River to Tawaheen Al Adwan area representing the first 22 km of the river (Al-Abdallat 2011) (Fig. 1c).

Water resources and their use

The Zarqa River is one of the most important sources of surface water in Jordan, which carries more than 78 % of the TWW quantities (WAJ 2013). With the increasing demand for agriculture in the downstream areas, future impacts on Zarqa River will be critical to the water resources of Jordan.

Water resources in the study area are limited to conjunctive use of groundwater and surface TWW. Groundwater pumping is taking place from 72 groundwater wells for agricultural activities abstracting 6.9 million m^3/year. Since the establishment of the As Samra plant, no wells are used for domestic supply within the vicinity of the river. Industrial pumping is limited to one well (steel pipes factory), which extracts around 120,000 m^3/year. This well was counted in the balance with agricultural wells. TWW is the biggest share in water resources with 110 million m^3/year. Springs are present in the river area with no direct measurements due to their low discharges (MWI data bank 2015).

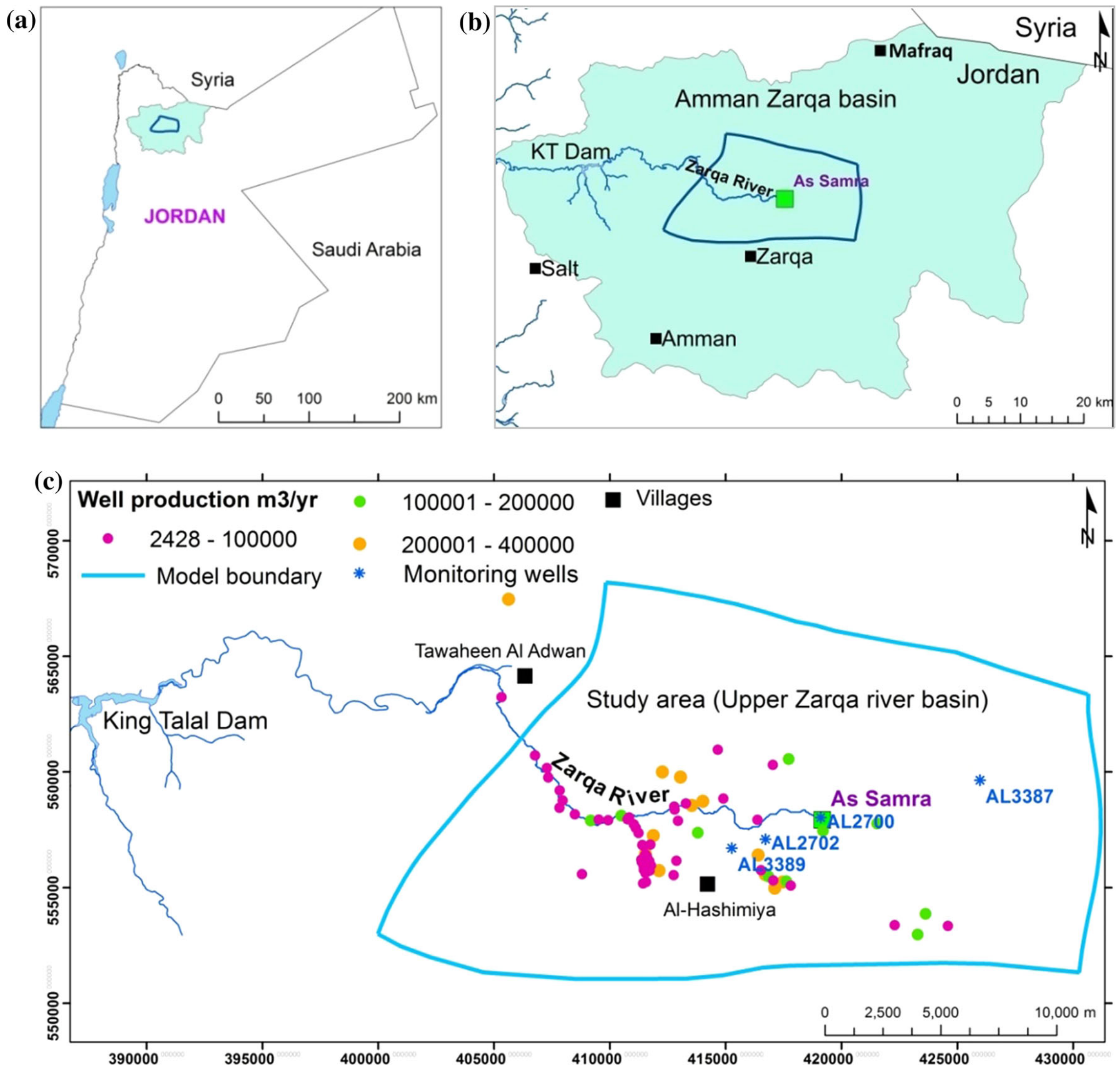

Fig. 1 Study area map of the Zarqa River: **a** general location, **b** the Amman-Zarqa Basin, **c** area under investigation with irrigation and monitoring wells (well production rates obtained from MWI 2014)

The As Samra plant located near Khirbet improves the flow conditions along the Zarqa River and enhances the storage of King Talal Dam, which is utilized for irrigation in the Jordan Valley. The availability of more than 110 million m^3/year of permanent flow within the river system augmented the groundwater levels through recharge and shifted the dependency for irrigation water from the groundwater to TWW in the river for more than 20 % of farms. Downstream, the water is channeled to the Jordan Valley, where it mixes with water from King Abdullah Canal and is used for irrigation, especially in the Deir Alla area (Central Jordan Valley). In a sense, agricultural usage of TWW in Jordan is more common than in the neighboring Gulf countries (compared with, for example, Al-Sharhan et al. 2001).

The current pumping is mainly utilized for direct and conjunctive use in agriculture with a total of 6.9 million m^3/year extracted from 72 wells (Fig. 1c) penetrating the upper limestone aquifer known as Hummar Aquifer which extends to a depth of 200 m below the ground surface with an average tested well production (capacity) of 40 m^3/h (MWI data bank 2015).

The groundwater system in the study area is monitored by four observation wells managed by MWI on a monthly basis (Fig. 1c). The small number of available observation wells represents one of the limitations of this study. However, in such arid underdeveloped areas an initiative (such as this study) must be taken to draw information that may assist in installing additional observation wells and lay out the ground for future developments. Observation wells at and downstream of the As Samra plant area indicated a dramatic water level recovery due to a continuous recharge from the river while the upstream well recorded a declining water level as a response to over-pumping as will be discussed below.

Climate

Amman-Zarqa Basin is bordered by the Northern highlands of Jordan in the west and the foothills of the Jabal Al Arab in the northeast that represent the water divide of the basin (Al Mahamid 2005). Thus, the basin is located in a rain shadow area, where moist air masses can only enter through two different locations, one through Zarqa River Valley from the west and the other near Mafraq 20 km north of the study area.

The average annual rainfall varies from less than 200 mm northeast to more than 500 mm northwest, close to the Bal'ama station (Fig. 2a) and in the west close of the Salt station over the basin, respectively. The average of maximum daily rainfall is 61.8 mm in January and 23.2 mm during the dry season (from May to October). The average daily temperature in the basin is 12.4 °C during the wet season (from November to April) with average daily minimum and maximum temperature of about 4.1 and 33.1 °C, respectively.

The prevailing wind direction in the study area is west–southwestern in winter and shifting to the west–northwestern in summer. The average daily wind speed is 2.1 m/s, ranging between 1.9 and 2.3 m/s in winter and 1.6 and 2.4 m/s in summer. The average daily relative humidity varies from 65.2 to 82.6 % in winter and from 59.2 to 71 % in summer (Al Mahamid 2005).

Due to the high temperatures, low topographic elevation and presence of green cover, the estimated evapotranspiration within the study area is high. Climate data are available on a daily basis at the Khirbit station (at the As Samra plant) in the study area and three other stations in a radius of 15 km from the As Samra plant. Potential evapotranspiration in the Amman-Zarqa Basin, including the study area, was calculated by Al Mahamid (2005) using the Penman equation (Jensen et al. 1990) and long-term climatic data series (1984–2002). These datasets were extended to the records of 2014 at station AL0066 located at the As Samra plant. In this work, the potential evapotranspiration was recalculated for the time period

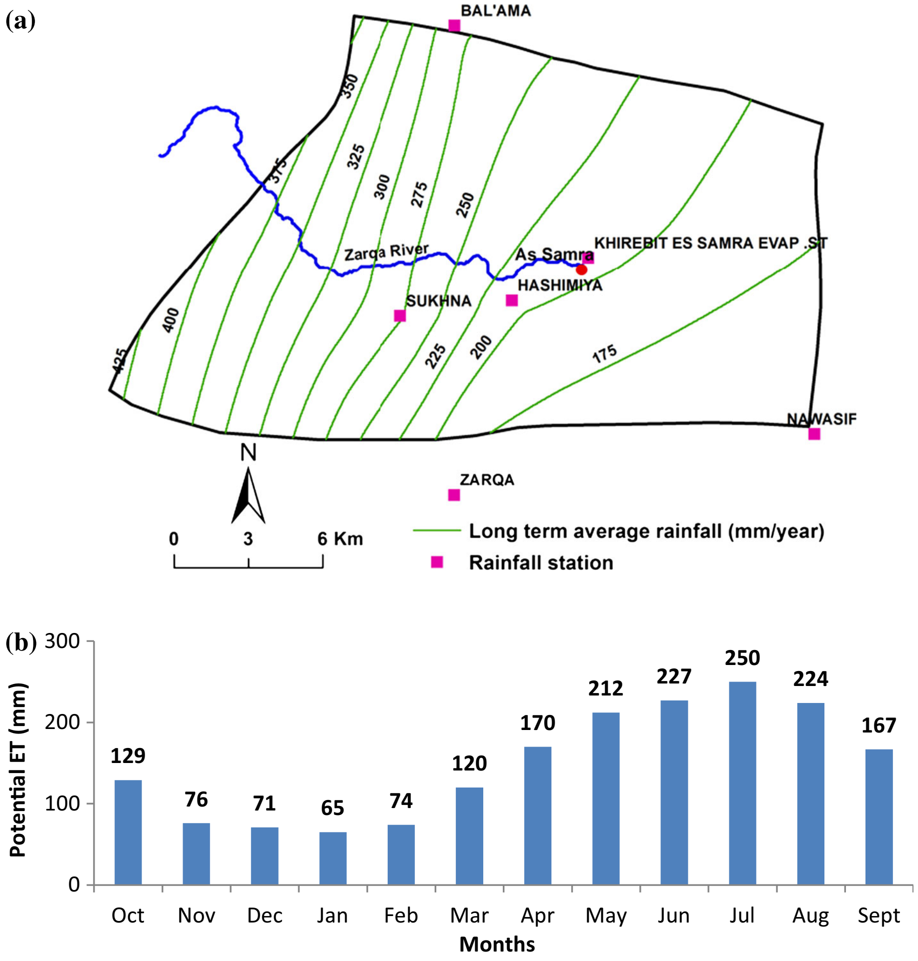

Fig. 2 Climate data for the area: **a** precipitation (mm/year, averaged rainfall rates over 40 years), **b** long-term monthly averages of potential evapotranspiration (mm, calculated by Al Mahamid 2005)

1984–2014 using the method and characteristics presented by Al Mahamid (2005). Long-term monthly averages of potential evapotranspiration over the study area are shown in Fig. 2b. The potential evapotranspiration ranges between 65 and 170 mm/month in winter season (November–April) and between 129 and 250 mm/month in summer (May–October). The annual potential evapotranspiration rate is 1785 mm (Al Mahamid 2005).

Conceptual aquifer model

Geology

The outcropping formations in the Amman-Zarqa Basin range from Triassic sandstone to recent alluvium (Fig. 3a). The Kurnub Sandstone (Lower Cretaceous—Neocamian-Albian), which crops out in the western parts of the study area, represents the oldest formation in the subsurface of the Zarqa Basin (Fig. 3b). The surface geology of the Zarqa River Basin is dominated by Late Cretaceous carbonates known as the Hummar Formation that represents the main water-bearing formation. The Na'ur Formation that is predominantly composed of clay and silt layers forms an aquitard that hydrologicaly separates the two formations: the Kurnub and the Hummar (Al Mahamid 2005). The hydrostratigraphic unit considered in this paper is the Hummar limestone forming the upper aquifer in the area and is exposed along the river and east of As Samra plant. It is covered by thin soil (<70 cm) north of the plant (MOA 1993). The aquifer (Hummar unit) is composed of poorly karstified limestone and is a part of the Late Cretaceous (Cenomanian-Turonian) sequence known in Jordan as the lower Ajloun Group (A1/A6) dominated by limestone, dolomitic limestone and marly limestone. The poor nature of karstification in the Hummar Formation may

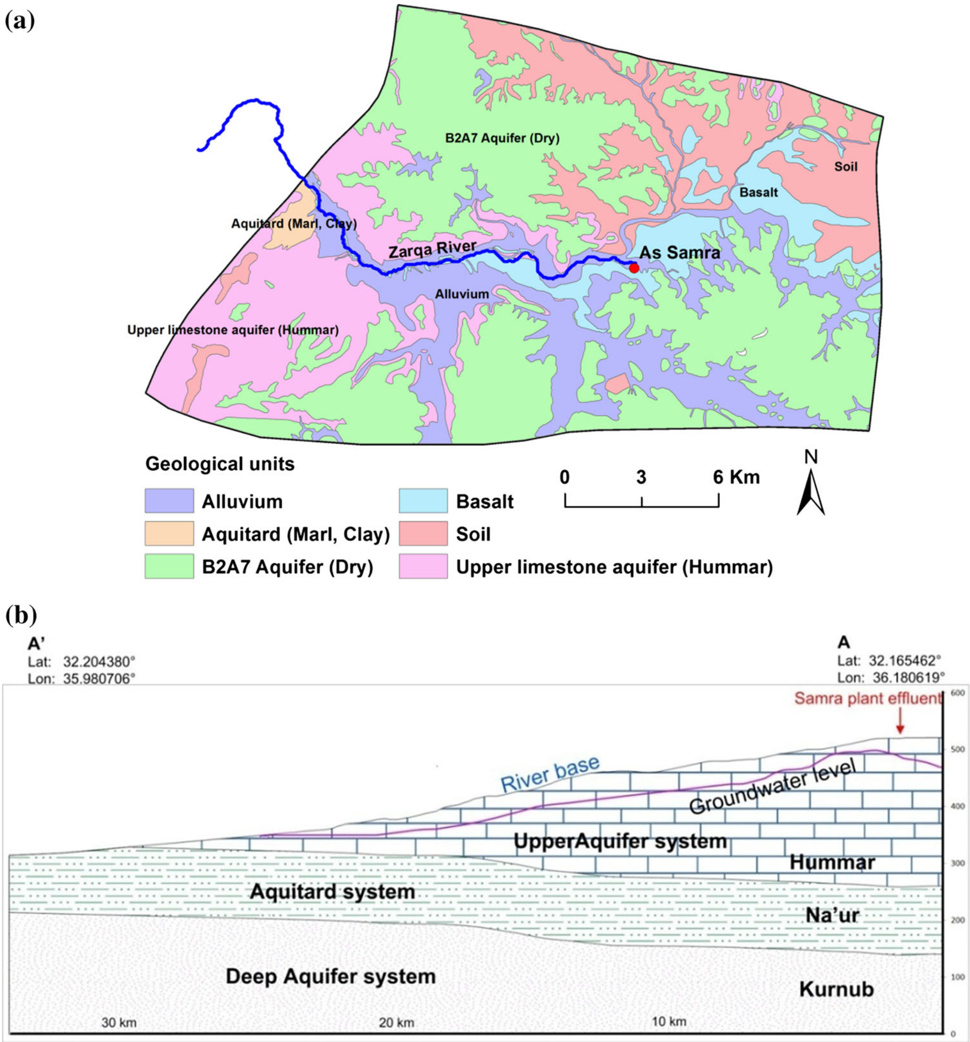

Fig. 3 Hydrostratigraphy of the area: **a** geological map of *upper* Zarqa River area; **b** hydrogeological cross section along the river (modified after NRA 1993, 1998)

justify its consideration as porous medium in the current modeling exercise.

Based on the hydraulic parameters, the Hummar limestone is a water-bearing formation with an average thickness of 150 m and an average saturated thickness of 120 m as shown in the hydrogeological cross section along the river (Fig. 3b). The regional aquifer saturated thickness was estimated by Wagner (2011, p. 91) as 40–45 m.

Hydrogeology

The Hummar Aquifer is separated from the deep sandstone aquifer by the clay and silt layer of Na'ur marlstone with an average thickness of 100 m (NRA 1985; Bender 1968; Al Mahamid 2005). The deep sandstone aquifer system (known locally as Kurnub Sandstone Aquifer) received less attention in water resources studies as its salinity exceeds 2500 mg/l (MWI 2014), which deems this aquifer use economically infeasible. Direct interaction between the upper and the deeper aquifer is neglected due to the very low hydraulic conductivity of the aquitard, which ranges from 8.6×10^{-7} to 6.0×10^{-4} m/day (Al Mahamid 2005).

The Hummar Aquifer is part of the Amman-Zarqa synclinal structure, which controlled the groundwater flow pattern until the establishment of As Samra treatment plant, which changes the groundwater regime within the river basin (USAID and MWI 2001). The synclinal structure is trending NE–SW with an axis located 10 km west of As Samra plant making Hummar Aquifer base at the lowest level with 300 m (asl) compared to 350 m in the eastern parts of the area as shown in Fig. 4a.

According to the heads data from wells drilled and tested prior to the operation of the plant, the groundwater flow was controlled by a relatively high natural recharge in the northern and southern highlands forcing groundwater to flow prevalently toward the western parts of the basin. The continued over-pumping resulted in a decline of the water level at average rate of 1 m/year. This stress was amplified due to climate change impact, which was reported by Al-Qaisi (2011) with 11 % reduction in rainfall in less than 60 years in the Amman-Zarqa Basin. Starting from mid-1990s, the water levels notably recovered within the As Samra plant and the downstream areas, indicating the development of recharge mound in the Hummar Aquifer. The recent initial groundwater level map (Fig. 4b) clearly depicts the recharge mound extending 5 km downstream the treatment plant and 2 km upstream with an average horizontal extension of 7 km. In the upstream reaches, due to groundwater mound the river changes its hydrological regime from losing to gaining. The modeling exercise will investigate this transition.

Time series record (MWI data bank 2015) from the monitoring well east of the As Samra plant (AL3387) shows water level declines due to over-pumping (Fig. 5a). Monitoring wells (AL2700, AL2027, and others) located close to the plant and downstream clearly indicate the effects of the recharge from the plant that led to the water table recovery by more than 8 m (Fig. 5a). The groundwater depth in the study area for year 2014 ranges from 2.25 m at the recharge mound on the Zarqa River to 533 m in the mountainous area north and south the river (see Fig. 5b).

Groundwater recharge

Few studies published recharge calculations in the area (Margane et al. 2002; Al Mahamid 2005; Wagner 2011). All studies calculated the recharge rates for the B2A7

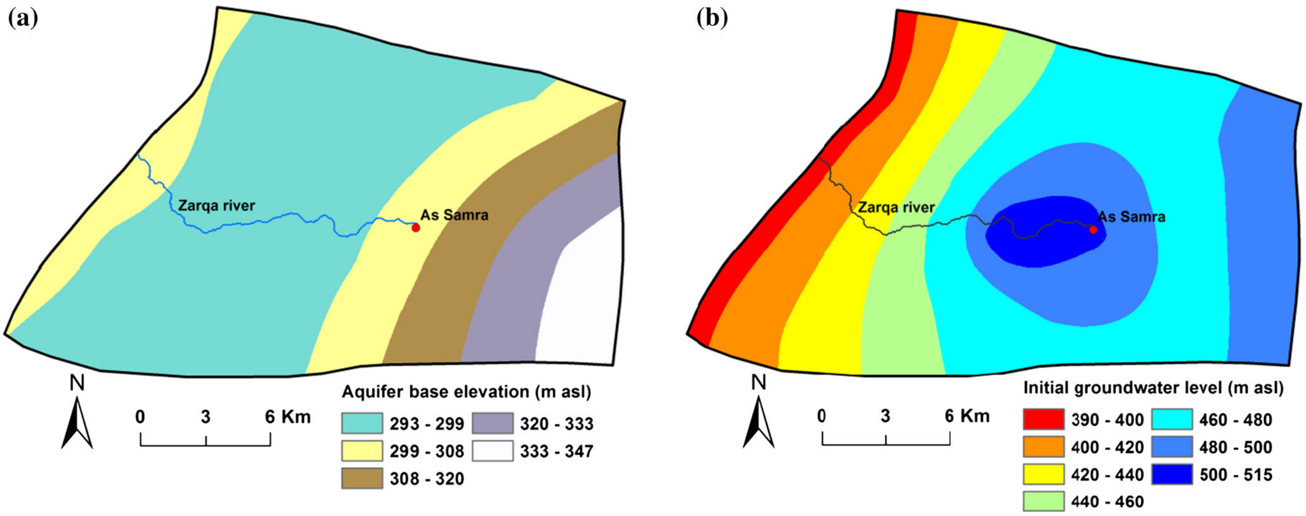

Fig. 4 Aquifer base and water level data: **a** elevation of the aquifer base (m asl); **b** initial groundwater level map for Hummar limestone aquifer in the *upper* Zarqa River area (m asl)

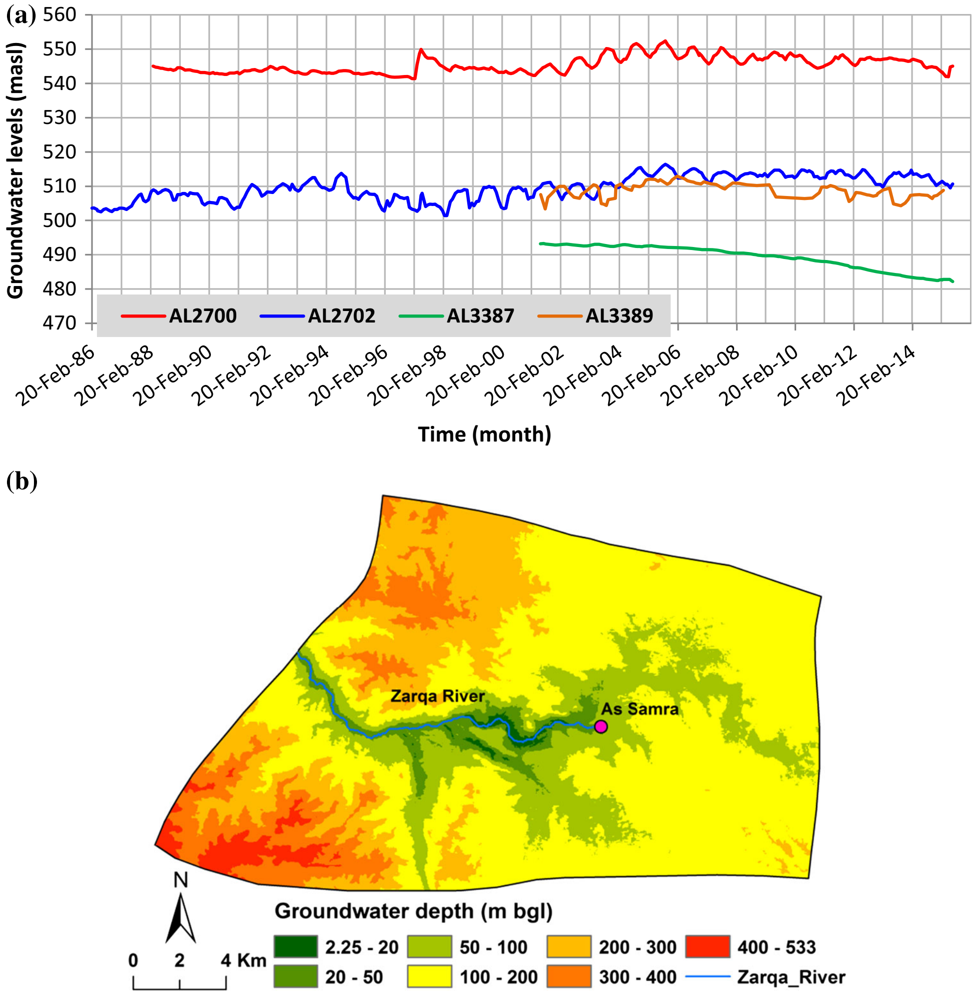

Fig. 5 **a** Groundwater levels in monitoring wells AL2700, AL 2702, AL3387 and AL3389 (for well locations, see Fig. 1); **b** depth to groundwater table below ground level (m bgl) in the study area for year 2014

aquifer, located in the highland, but without focus on the river basin dominated by the Hummar aquifer. Seiler and Gat (2007, p. 176) pointed out that in arid zones, especially in large basins, measurements of evaporation, lysimeter studies or simplified water balances do not contribute much to assessments of recharge to the aquifer. In our case, these conditions are exacerbated by poor logistics and absence of site-specific field studies. Therefore, the water budget approach (Healy 2010, p. 16) was used for estimating the recharge rate D (mm/year) distribution over the study area:

$$D = P - \mathrm{ET} - \Delta S - R_{\mathrm{off}} \qquad (1)$$

where P is precipitation (mm/year), ET is actual evapotranspiration (mm/year), ΔS is the change in soil water storage in the soil column (mm/year), and R_{off} is runoff (mm/year).

Precipitation includes mainly rain over the study area; major snowfalls are absent as the area is located in the rain shadow of the mountains in western Jordan. Rainfall isohyets were plotted using the weighted average and Thiessen polygons (Chow et al. 1988). To achieve acceptable statistical certainty, data for the time period 1984–2014 were collected from MWI climate and rain stations with daily measurements. Daily records were averaged on monthly and yearly basis. The long-term precipitation data from various stations were interpolated using the inverse distance weighing method (IDW) with elevation correction to produce isohyetal map giving an average rainfall of 250 mm/year in the central parts of the study area (Fig. 2a). In Eq. 1, we used the actual evapotranspiration which is derived from the potential evapotranspiration.

The change in soil water storage was calculated using J2000 hydrological model, which is a software associated with GIS system to estimate the water budget (Kralisch et al. 2007). Soil properties play an important role in recharge processes. Hydraulic parameters needed for the J2000 model are presented in Table 1.

Soil data were limited within the Zarqa River Basin, and we collected soil samples from 20 referenced sites four times at each site during the rainy season 2013–2014. Sampling

Table 1 Soil data for soil module in J2000, after Nepal (2012)

Parameter	Description
SID	Soil type ID
Depth (m)	Soil depth
kf_min (m/day)	Minimum coefficient of hydraulic conductivity
Depth_min (m)	Depth of the horizon above the horizon with the lowest hydraulic conductivity (m)
kf_max (m/day)	Maximum coefficient of hydraulic conductivity (m/day)

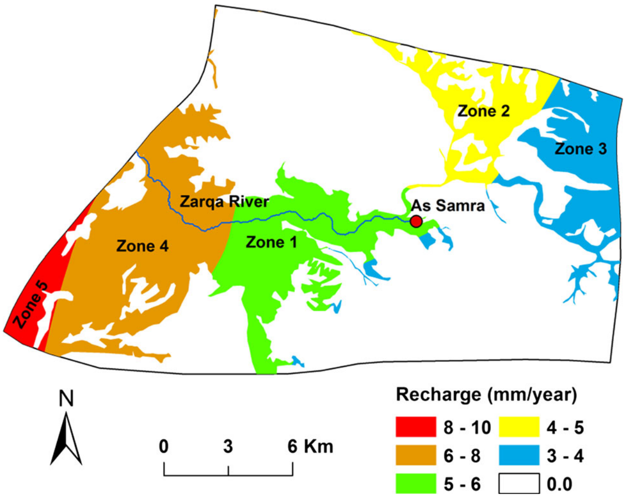

Fig. 6 Estimated spatial distribution of groundwater recharge

was conducted the next day of the rain events. In total, eighty 10-cm-radius and 30-cm-height cores were tested to measure kf_min (m/day), depth_min (m) and kf_max (m/day). Soil type ID parameter was assigned using the categorization of all soils within the study area, based on infiltration capacity and soil group type. With these parameters, the soil module of the J2000 software resulted in the calculated water storage in the soil of 27 mm/year for 2014.

Runoff was calculated based on the runoff curve number method (Hjelmfelt 1991; SCS 2004) using data from the Wadi Zarqa gauging station AL0060 for more than 110 runoff records. Records of the rainfall station at the As Samra plant for the period 1982–2014 were plotted versus generated runoff recorded at the Wadi Zarqa gauging station, yielding a runoff coefficient of 4.7 % of the total rain. Based on the daily rainfall records for 6 rainfall stations in the area and considering the calculated runoff coefficient, the generated floods were modeled for the main wadis with an average of 11.8 mm/year.

Finally, GIS maps of budget components in Eq. 1 were updated for estimating the recharge in the GIS raster calculator. The zonation of recharge in the study area is shown in Fig. 6. The maximum recharge zone is located in the western parts of the study area with a value of about 10 mm/year, while the lowest value 0.0 mm/year was assigned in the blank (white) areas on the map due to the clay and marl formations. It should be noted that Wagner (2011, p. 100) estimated the average recharge for entire basin as 19 mm/year.

Return flow to aquifer in the entire Amman-Zarqa Basin was estimated by Courcier et al. (2005) to be 35 % of the total pumping, due to irrigation and leakage from pipes. Within the study area, data about agricultural practices, irrigation patters and return flow are unavailable. To identify irrigation return flow to the aquifer in the river basin, infiltration tests were performed to calculate soil water-holding capacity in different soil types at the sites, sampled for the water storage calculations. Infiltration rates measured to be 12 mm/h in the loamy soil close to the As Samra plant. In more sandy soils to the west, infiltration rates increased to 22 mm/h. Considering the infiltration rate, soil thickness, water-holding capacity and irrigation amounts, the return flow was estimated to be 17 % of the total irrigation water and was added to the groundwater recharge in the corresponding irrigated parts of the study area (zone 1, see Fig. 6).

Numerical groundwater modeling

Conceptual model and implementation

We use model of a single unconfined aquifer considering low-permeability material of an underlying aquitard and lack of data for deeper hydrostratigraphic units. The slope of the aquifer bed ranges from 0 to 2 % with an average of 0.24 % (see Fig. 4a).

The northern and southern boundaries were assigned as no-flow boundaries as deduced from geology (impermeable marly limestone outcrops in the north and south) and the regional groundwater flow pattern (equipotential lines run north–south). Based on the initial distribution of groundwater level map (Fig. 4b), values of constant head were assigned to the east (483 m) and west boundary (390 m) (Fig. 7a). Though assigning constant head boundaries can affect water budget sometimes, close attention was paid to ensure that model's sinks and sources do not affect boundaries. The aquifer base was assigned as a no-flow boundary. Total area of the model is 387 km^2.

A steady-state 2D numerical simulation was developed using the USGS modular three-dimensional finite-difference package MODFLOW-2005 (Harbaugh 2005) with ModelMuse (Winston 2009) as a graphical interface. The horizontal grid block dimensions are 30 m × 30 m with 572 rows and 960 columns, while the vertical discretization has one layer of variable thickness (ranges from 111 to 560 m). The modeled aquifer is considered to be isotropic.

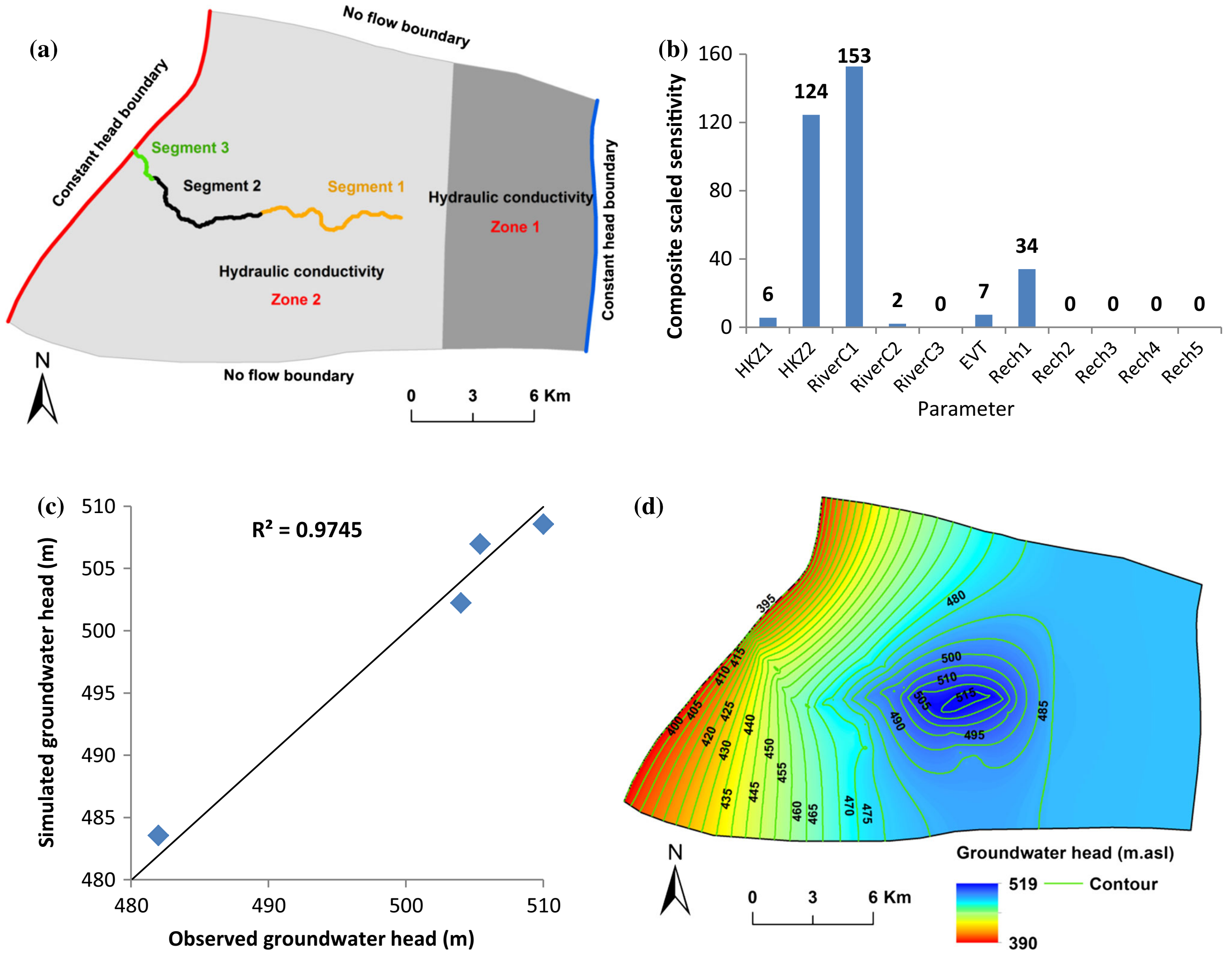

Fig. 7 Model calibration and sensitivity analysis: **a** parameter zonation, **b** composite scaled sensitivities calculated for hydraulic conductivity, river conductance, evapotranspiration and recharge; **c** *scatter plot* for simulated versus observed heads of steady state using four observation wells; **d** simulated groundwater head using calibrated parameters

In arid areas, actual evapotranspiration (ET) from shallow water tables can lead to losses of a significant quantity of water from the aquifer. Most commonly, ET is calculated using a "linear" model including potential ET and extinction depth (Baird and Maddock 2005). The land surface boundary was obtained from ASTER 30 m × 30 m DEM. Initially, we assigned 1785 mm/year as annual potential evapotranspiration rate. This value has been estimated by Al Mahamid (2005), but for the whole Zarqa River Basin. From model calibration process, the calibrated potential evapotranspiration rate was found to be 2190 mm/year (6 mm/day) which is within the acceptable ranges of the potential evapotranspiration rate (Al Mahamid 2005) with an extinction depth of 11 m.

In this study area, data for 72 irrigation pumping wells (Fig. 1) with a total abstraction rate of 18,895 m^3/day were obtained from the database of the MWI and incorporated into the model. According to the pumping test data (MWI 2014), the eastern part of the model is more conductive (5–12 m/day), while the western part is characterized by lower hydraulic conductivity values (0.3–1.0 m/day).

The Zarqa River is simulated with a river package (RIV) using the parameters presented in Table 2, measured from November 2014 to February 2015. As the river characteristics vary with distance, the river over the study area is divided into three different segments (1, 2 and 3).

The river conductance, c (m^2/day), was calculated as follows (McDonald and Harbaugh 1988):

$$c = k_s \frac{wl}{m_s} \qquad (2)$$

where k_s is the hydraulic conductivity of the streambed sediments (m/day), w is the width of the river reach (m), l is the length of the river reach (m), and m_s is the thickness of the streambed sediments (m). Usually, this parameter has substantial uncertainty due to poor hydrogeological

Table 2 Parameter values of the river used in river package (RIV) of the groundwater model

Parameter	Segment 1	Segment 2	Segment 3
River water depth (m)	0.7	0.7	0.5
River bed (m)	DEM – 0.7	DEM – 0.7	DEM – 0.5
River width, w (m)	7	7	7
Thickness of river bed, m (m)	0.2	0.2	0.2
Hydraulic conductivity of the bottom sediments, k_s (m/day)	0.15	0.2	0.1

Table 3 Calibrated parameters for steady-state aquifer model

Parameter	Value	Unit	Description
HKZ1	11	m/day	Hydraulic conductivity of zone 1
HKZ2	0.8		Hydraulic conductivity of zone 2
RiverC1	133	m^2/day	River conductance of Segment 1
RiverC2	150		River conductance of Segment 2
RiverC3	100		River conductance of Segment 3
Rech1	2.0E−4	m/day	Recharge from precipitation and irrigation return flow zone 1
Rech2	2.8E−07		Recharge from precipitation zone 2
Rech3	8.2E−07		Recharge from precipitation zone 3
Rech4	1.9E−06		Recharge from precipitation zone 4
Rech5	2.5E−5		Recharge from precipitation zone 5
Extinction depth	11	m	Evapotranspiration extinction depth

definition of "streambed," compared to fluvial sedimentology (Bridge and Demicco 2008). At the site, small thickness and low hydraulic conductivity indicate moderate connection between surface and groundwater. In this work, the steady-state model is developed based on datasets of 2014.

Sensitivity analysis and calibration

The sensitivity analysis was carried out using UCODE-2005 (Poeter et al. 2005) with the help of ModelMate (Banta 2011). The sensitivity parameters were the hydraulic conductivity, river conductance and evapotranspiration and recharge parameters. Results of the composite scaled sensitivities for the modeled area are presented in Fig. 7b. From this figure, we infer that the modeling results are most sensitive to the river conductance of segment1 (RiverC1), the hydraulic conductivity of zone 2 (HKZ1) and recharge zone 1 (Rech1).

The steady-state model was calibrated using hydraulic head data of year 2014 from 4 monitoring wells (Fig. 1). These wells are located in the vicinity of the As Samra plant (Fig. 1). Calibrated results show a good agreement between simulated and observed groundwater heads with $R^2 = 0.97$. The mean error is -0.03 m, and the root mean square error is 1.6 m. In addition, observed and simulated heads are scattered almost around the mean of observed heads (Fig. 7c), which indicates reasonable model performance (especially in the vicinity of the As Samra plant) regardless the limitation of data availability. The simulated head distribution is presented in Fig. 7d, with a mound head value of 518.7 m around the As Samra plant. The calibrated model parameters are presented in Table 3.

Water balance

The water balance of the calibrated model is presented in Table 4. The total amount of inflow from the river to the aquifer is 59,684 m^3/day, which represents 86 % of the total inflow. Direct recharge from precipitation contributes to the remaining 14 % (9648 m^3/day). This budget illustrates the great importance of the Zarqa River as a source of recharge augmenting the depleted aquifer. The total abstracted volume by pumping wells is 18,895 m^3/day, which is 27 % of the total outflow rates, while ET accounts for 15 % (10,257 m^3/day) of the total outflow. An amount of 30,275 m^3/day (or 44 %) flows out of the aquifer through the western boundary and 4424 m^3/day (6 % only) through the eastern boundary. This may suggest that the infiltrated TWW from the river is mainly flowing in the westward direction, as evidenced from the equipotential lines in Fig. 7c.

Analysis of management scenarios

Scenario selections

Summary of the simulated management scenarios is presented in Table 5. Prior to the construction of the As Samra

Table 4 Water balance of the simulated steady-state model

	In		Out		In − out
	m^3/day	%	m^3/day	%	m^3/day
Eastern boundary	0	0	3.969	6	−3.969
Western boundary	0	0	30,730	44	−30,730
Pumping wells	0	0	18,895	27	−18,895
River	59,684	86	5481	8	54,203
ET	0	0	10,257	15	−10,257
Recharge	9648	14	0	0	9648
Total	69,332	100	69,332	100	0

plant, the channel of the Zarqa River in the study area was dry. This background scenario, indicated as BG in Table 5, is important for illustrating the significance of the restoration of the Zarqa River reach using TWW discharge and assisting the farming community.

The base case (BC) scenario considers the current status of the hydrological system, assuming the steady state after start of operation at the As Samra plant that resulted in discharging of 110 million m^3/year of TWW. This scenario was used in the calibration of the steady-state model. For plant operations, future scenarios of conjunctive use were selected with an aim to address the aquifer responses to the following management scenarios to ensure sustainability of farming:

(A) Increase in the TWW discharge to the Zarqa River, which is justified by the expansion plans of the STP. These scenarios assume no change in abstraction of water for irrigation.

(B) Increase in groundwater abstraction due to the irrigation expansion. Such scenarios are developed to address the conditions, when standards of irrigation water quality are enforced by the government, which prohibits direct use of TWW from the river. In this case, farmers are expected to restart some abandoned groundwater wells and/or increase pumping from the existing well. In addition, expansion of the irrigated areas is expected by 30 %, reaching 15.55 km^2 compared to the current area of 11.96 km^2, which was estimated using satellite images (http://modis.gsfc.nasa.gov/) and Google Earth data and validated on the ground. Due to the availability of suitable lands for agriculture in the study area, accompanied by the enforcement of the regulations and irrigation water quality standards, a 30 % increase in the abstraction volume is expected.

(C) Potential reduction in the abstracted volume in case of deterioration of groundwater quality.

These scenarios, labeled by A, B and C are described in more detail in Table 5. Among them, the main scenarios were the background scenario (BG), BC, A1, B1 and C, respectively. Other scenarios (A2, A3 and B2) complemented and refined analyses to assess effects of variations in the discharged TWW volumes and abstraction rates.

Table 5 also indicates the impact of increasing the discharge volume of the TWW on the river–aquifer interactions as well as the effects of groundwater withdrawals on stream depths. Such tasks can be addressed using various hydrologic tools (e.g., Dingman 2015). The simplest ones are rating curves, indicating a power relationship between the river discharge (Q) and the depth at the gauging station (H). However, such curves and their parameters are unavailable for the area. Considering a relatively narrow range of the river discharge changes among the various scenarios (Q_{TWW}), compared to the base scenario (BC), a simple linear model, relating Q with H was adopted as a surrogate for rating curve. If TWW-based discharge (Q_{TWW}) from the plant is a relatively stable fraction of the

Table 5 Simulated water management scenarios

Scenario	Descriptions of investigated factors	Q_{TWW} (million m^3/year)	Average stream depth (m)	Abstraction rate (m^3/day)
BG	Aquifer state prior to the As Samra plant construction. The channel of the Zarqa River in the study area is dry	0	0 (dry channel)	18,895
BC	Base case (calibrated steady state, see Table 3)	110	0.63	18,895
A1, A2, A3	Effect of increase in the TWW discharge from As Samra plant to the Zarqa River during the coming 5 years. Scenarios A1, A2 and A3 explore different TWW discharge rates from As Samra plant to the Zarqa River	A1: 120 A2: 130 A3: 135	0.69 0.74 0.77	18,895
B1	Increasing the water abstraction (by 30 %) to meet expected expansion in agricultural areas and enforcement of water quality regulations	110 Same as BC	0.63 Same as BC	24,564
B2	The same as B1	135 Same as A3	0.77 Same as A3	24,564 Same as B1
C	Decreasing abstraction rates due to possible elevated salinity and more depending on river water by 30 %	110 Same as BC	0.63 Same as BC	13,227

stream discharge, it is safe to assume that a linear relationship between the total stream discharge (Q) and TWW discharge from As Samra plant (Q_{TWW}) also holds. Therefore, average stream depth for a given scenario (H_S) is linearly related to the average river water depth for base scenario (H_{BC}) is as follows:

$$H_S = \frac{(Q_{\mathrm{TWW}})_S}{(Q_{\mathrm{TWW}})_{\mathrm{BC}}} H_{\mathrm{BC}} \tag{3}$$

Table 5 presents H_S for scenarios (A1, A2 and A3). H_{BC} is about 0.63 m with average river width of 7 m. $(Q_{TWW})_S$is the TWW discharge for a given scenario (A1 = 120 million m^3/year, A2 = 130 million m^3/year, and A3 = 135 million m^3/year, while $(Q_{\mathrm{TWW}})_{\mathrm{BC}}$ is the TWW discharge for the base case (110 million m^3/year). Equation (3) results in the average stream depth of 0.69, 0.74 and 0.77 m for scenarios A1, A2 and A3, respectively. It means that each 10 million m^3 of TWW rate discharge to the river will raise the river water depth about 6.0 cm.

Results and discussion

Effects of increasing discharge of TWW into the Zarqa River

Water balance components for the simulated scenarios are summarized in Table 6. Gain from the aquifer to the Zarqa River, recharge from the Zarqa River to the aquifer, evapotranspiration, discharge from the aquifer to the east and west boundaries, and changes in groundwater levels are presented as indicators of the management effects on the conjunctive use of the aquifer-Zarqa River water resources. All changes and comparison are made with respect to the base case (BC scenario).

In the BG scenario (absence of the river), the results show that the inflow from the east boundary was 15,125 m^3/day and the outflow to the west boundary was 5875 m^3/day (Table 6). The river helped to raise the water table by 29.39 m on average. The deep water table in case of BG scenario resulted in zero evapotranspiration. MAR via the river using TWW greatly contributes to augmentation of the aquifer storage providing more water resources for irrigation activity, when compared to the BC.

In scenario A1, the rise of the flowing water level in the Zarqa River by 6 cm on average has no flooding risks to the riparian land, but increases the recharge to the aquifer by 2968 m^3/day with respect to BC. Thus, the outflows through both western and eastern boundaries and ET increase by 770, 155 and 932 m^3/day, respectively, with respect to BC. The average groundwater level rises by 0.12 m.

In scenario A2, with increasing the discharge of TWW to the river from 110 million m^3/year (BC) to 130 million m^3/year (A2), the average depth of flowing water in the river was increased 11 cm. Consequently, the recharge rate from the Zarqa River to the aquifer increases by 5260 m^3/day. The average groundwater level rises by 0.4 m with respect to BC (Table 6).

In scenario A3, at the maximum capacity of As Samra plant, which is 135 million m^3/year, the average water river depth increases to 0.77 m instead of 0.63 m (for BC). The recharge rate from the Zarqa River to the aquifer increases by 6557 m^3/day, resulting in an average water table rise by 0.55 m and increases in the amount of outflow through the eastern and western boundaries and ET increase.

All scenarios indicate that the planned extension of the As Samra plant will augment the aquifer storage without significant flood risk to farms located near the river. The maximum rise in the depth of the flowing water is 11 cm, while the infiltration of stream water into the aquifer increased by 11 % (adding 2.4 million m^3/year in the studied part only). This amount represents nearly 30 % of the abstracted volume for irrigation. Hence, expansion of irrigation withdrawals by 30 % will be sustainable, allowing more farming activities and crop production.

Table 6 Water balance components (in m^3/day) and changes in average groundwater level with respect to base case (in m)

Scenario	Outflow through eastern boundary	Outflow through western boundary	Pumping wells	Aquifer Recharge (from river) (m^3/day)	Discharge from aquifer to river	Evapotranspiration	Aquifer recharge (from precipitation)	Average change in groundwater level (m)
BG	−15,125[a]	5875	18,895	0	0	0	9648	−29.38
BC	3969	30,730	18,895	59,684	5481	10,257	9648	0
A1	4579	31,207	18,895	62,652	6592	11,027	9648	0.12
A2	5048	31,557	18,895	64,944	7489	11,603	9648	0.40
A3	5308	31,755	18,895	66,241	8006	11,925	9648	0.55
B1	2656	30,257	24,563	61,382	4373	9181	9648	−1.31
B2	4125	31,363	24,563	68,352	6843	11,106	9648	−0.36
C	5214	31,159	13,226	57,786	6639	11,196	9648	0.69

[a] Negative (−) sign indicates inflow

Effects of increased irrigation abstractions

When abstraction of water for irrigation increased by 30 % (Scenario B1) to 24.564 m^3/day, while keeping all other parameters as that for the BC scenario, the water table elevation drops by 1.31 m (Table 6) on average. This results in increase in recharge to the aquifer from the river by 1698 m^3/day, while the base flow drops by 1108 m^3/day.

The water table decline reduced, when the 30 % increase in groundwater abstraction for irrigation is done when the As Samra plant operates at its maximum capacity (135 million m^3/year) as presented in scenario B2. The results of this scenario show a decline of only 0.36 m (Table 6). Under this scenario, more river water infiltrates to the aquifer (increase by 8668 m^3/day) because of a combined effect of the rise in depth of flowing water in the river (as in scenario A3) and lowering of the water table due to abstraction as illustrated in B1 scenario.

Effect of reduction in abstraction of irrigation water

When the abstraction from the aquifer decreased by 30 % (compared to that of BC) as suggested by scenario C to become 13,227 m^3/day, the water levels in the aquifer rise by 0.69 m on average, causing reduction in infiltration to the aquifer from the river by 1898 m^3/day (3 % only). The results indicate that reduction in abstraction just increases the aquifer storage and with time spreads across the entire aquifer within the basin. The reduction in infiltration means more water will flow in the river channel downstream the basin with less opportunity for further cleaning of the TWW compared to the situation when the TWW percolates into the aquifer.

Effect of management on the groundwater levels

Contour lines of the simulated groundwater levels of the selected scenarios (BG, A3, B1 and C) with the base case (BC) are shown in Fig. 8. The results clearly illustrated the effects of the suggested scenarios on the groundwater levels. The results of scenario BG (prior to the construction of the As Samra plant) show that there was a depression in groundwater table over the aquifer area, especially in the vicinity of the farming area, and the existing now water mound did not exist prior to the As Samra plant construction. The results of other scenarios show that the highest groundwater level values are located around the As Samra plant compared to other locations. The simulated groundwater heads at the most closest two observation wells (AL2700 and AL2702) to the Zarqa River also show the effects of the suggested scenarios on the groundwater system (Fig. 9). The results of groundwater levels show the capability of MRA using TWW on recovering the aquifer system of the Zarqa Basin.

Identifying the gaining and losing sections of the Zarqa River

With the help of the cell-to-cell flux terms in the model output files, exchange fluxes between the river and the aquifer for the base case (BC) and selected scenarios (A3, B1 and C) were analyzed and presented in Fig. 10 (plates a, b, c and d, respectively). The color on the diagram indicates the direction and magnitude of fluxes between the river and the aquifer. The Zarqa River becomes a losing stream at locations with yellow-red color, while it is a gaining stream at locations of green-blue color. In scenario A3 (Fig. 10b), the total length of the losing sections of the Zarqa River was longer than the length of gaining sections of the base case (BC) and scenarios B1 and C (Fig. 10). This relationship is consistent with Table 6, where the total flux from the Zarqa River to the aquifer from scenario A3 (66,241 m^3/day) is greater than those obtained from scenarios B1 and C and the base case (BC). Identifying gaining and losing sections helps in distributing new irrigation wells.

In our simulations, the effect of water losses from the river on stream stage was neglected in each simulation. With known, relatively steady TWW discharge volume from As Samra plant, consideration of stream hydraulics and feedback between the stream and the aquifer could improve accuracy of calculation, but would not alter general conclusions and budget substantially for purposes of our study

Model uncertainty

The developed conceptual model provides only first insights into the surface water–groundwater interactions in the currently unmanaged conjunctive use of scarce water resources. Although data are limited, quantitative analyses of various items in the developed water budget establish role and importance of aquifer recharge by TWW. Main model uncertainties are due to a limited number of observation wells, although the measured groundwater levels in the existing wells match the computed ones. In particular, it is important to expand monitoring network to the Kurnub Aquifer that may be a sources of saline water of low quality. Further, collection of temporal record of TWW discharge into the river, historical and future measurements of the river stage, temporal climatic variations and refinements of groundwater recharge will assist in transient extension of the model and reduction in uncertainty of the model. The current conceptual model sets stage for further model improvements and uncertainty reduction after expansion of network for groundwater level monitoring and data accumulation.

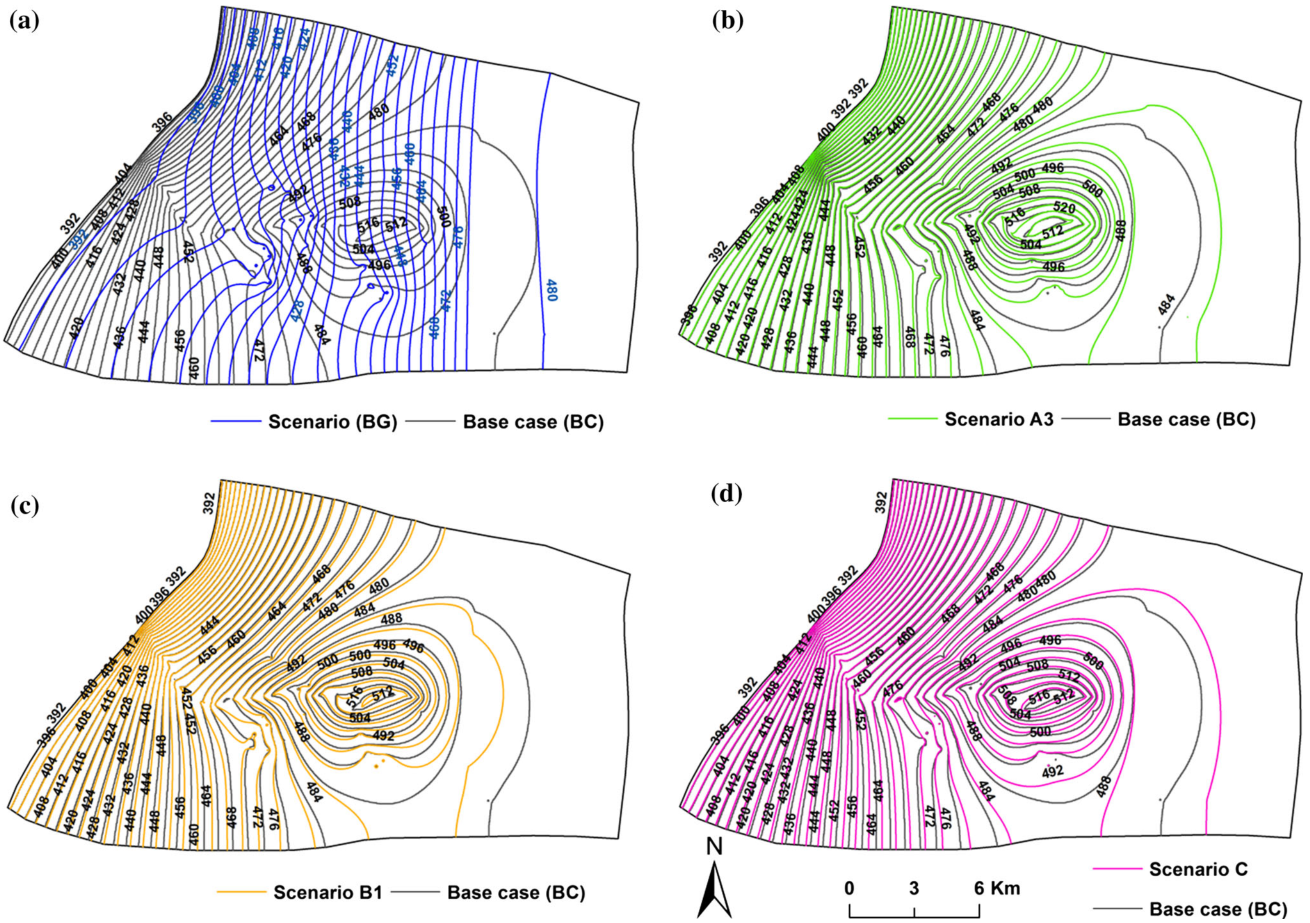

Fig. 8 Contour lines of water table levels (m asl) for selected scenarios compared with the base case (BC): **a** scenario BG; **b** scenario A3; **c** scenario B1; and **d** scenario C

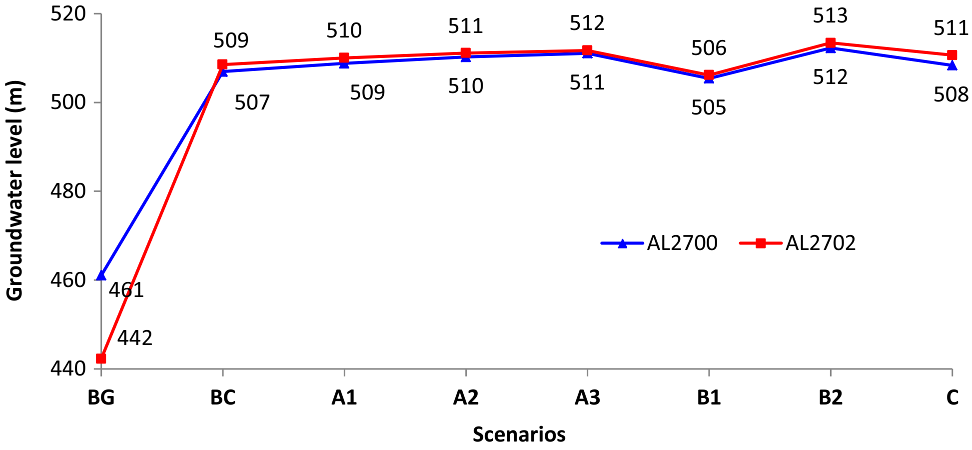

Fig. 9 Simulated groundwater heads (m asl) at the nearest wells (Al 2700 and AL 2702) to the Zarqa River

Conclusions

Our study addresses the effects of different management scenarios of the conjunctive groundwater and surface water use at the Zarqa River watershed that utilizes significant amounts of treated wastewater (TWW) from As Samra sewage treatment plant. The groundwater flow model for the Zarqa River Basin was developed and used to predict changes in the aquifer and stream under a set of different increments in discharge rates from the plant and different groundwater pumping rates. Scenarios were selected with the aim to understand the aquifer response to three factors:

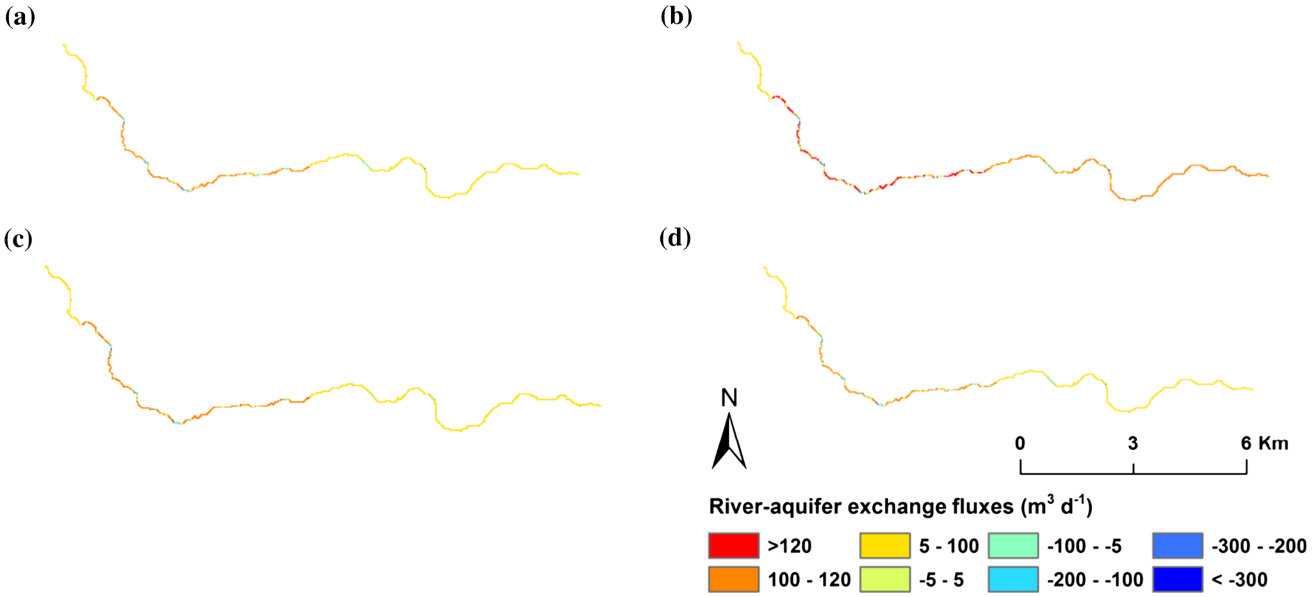

Fig. 10 Zarqa River–aquifer exchange fluxes for different scenarios: **a** base case (BC); **b** scenario A3; **c** scenario B1; and **d** scenario C. *Positive values* indicate losing sections of the Zarqa River, while *negative values* indicate gaining sections

(a) Increase in the TWW discharge to the Zarqa River from As Samra plant; (b) increase in groundwater extraction from irrigation wells; and (c) potential reduction in the water extraction in case of deterioration of groundwater quality.

The groundwater flow model was used to estimate the water budgets of the subjacent unconfined aquifer and the Zarqa River itself. The results of the situation prior to the As Samra plant construction (BG) show that the water table in the study area was deteriorated with an average water table decline of 29.36 m comparing with the current situation (BC). The results of increasing the TWW rate to 120 million m^3/year, 130 million m^3/year and 135 million m^3/year (maximum capacity of As Samra TWW plant) show that the average groundwater level rises by 0.12, 0.40 and 0.55 m, respectively, compared to the base case, 110 million m^3/year.

The increase in abstraction rate by 30 % with the current TWW discharge from As Samra plant (110 million m^3/year) results in the further average groundwater level decline by 1.31 m with respect to the base case. Even in the case of the As Samra plant reaching the maximum capacity (135 million m^3/year), the groundwater level declines by 0.36 m with respect to the base case after the 30 % increase in the abstraction rate.

It is not feasible to meet the growing water demand for irrigation from the aquifer without groundwater depletion and possible water quality deterioration. Therefore, 30 % reduction in the abstraction rates from the base case conditions was studied; the results show that the average groundwater level rises by 0.69 m with respect to the base case. Consequently, the best management results could be achieved when integrated management of groundwater abstraction with MAR using TWW is used.

Considering the strong hydraulic connection between surface and groundwater in the area, the use of water directly from the Zarqa River becomes advisable as an alternative to groundwater abstraction, assuming that water quality constraints are met. The simulated scenarios highlight the significant role of releasing TWW in recharging the aquifer and increasing the availability of water in the Zarqa River Valley that allows expanding the farming activities. However, calculation of the optimal abstraction rates of irrigation water that would induce minimum damage to the aquifer and the river basin in general is important, but not addressed in this work. The optimization–simulation study should be the future work, complemented with socioeconomic analysis for better understanding the trade-off between MAR using TWW and the agriculture production in the Zarqa River Valley.

For the effective water management of the watershed, future research priorities should include:

- Establishment of a broader hydrological groundwater-monitoring network;
- Improving the model calibration using measured water levels along the river which can be used in the groundwater model calibration (Seyoum and Eckstein 2014);
- Refinement of methodology for estimating groundwater recharge and data collection;
- Regular recording and documentation of the river hydrological regime.

- Development of rating curves at several stream reaches;
- Transient groundwater flow modeling with calibration on a greater number of wells and stream budget;
- Comprehensive study of agroecological indicators of water quality (groundwater, surface water and irrigation water) over entire basin.

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Appendix 1

See Table 7.

Table 7 Wastewater treatment plants in Jordan (Jordan water sector facts and figure 2013, MWI)

WWTP name	Technology	Service governorate	Design capacity (m^3/day)
Aqaba—Natural	Waste stab ponds	Aqaba	9000
Aqaba—Mechanical	Extended aeration	Aqaba	12,000
Baqa	Trickling filter (TF)	Amman, Balqa	14,900
Fuheis	Activated sludge	Amman, Balqa	2400
Irbid—Central	TF and active sludge	Irbid	11,023
Jerash—East	Oxidation ditch	Jerash	9000
Karak	Trickling filter (TF)	Karak	5500
Kufranja	Trickling filter (TF)	Ajloun	9000
Madaba	Activated sludge	Madaba	7600
Mafraq	Waste stab ponds	Mafraq	6050
Ma’an	Extended aeration	Ma’an	5772
Abu Nuseir	Active sludge R, B, C	Amman	4000
Ramtha	Activated sludge	Irbid	7400
Sult	Extended aeration	Balqa	7700
Tafila	Trickling filter (TF)	Tafila	7500
Wai Al Arab	Extended aeration	Irbid	21,000
Wadi Hassan	Oxidation ditch	Irbid	1600
Wadi Mousa	Extended aeration	Ma’an	3400
Wadisseer	Aeration lagoon	Amman	4000
Alekeder-Tankers	Waste stab ponds	Mafraq	4000
Lajjon-Tankers	Waste stab ponds	Karak	1200
Tal AlMantah-Tankers	TF and active sludge	Balqa	400
Al Jiza	Activated sludge	Amman	4500
As Samra	Activated sludge	Amman, Zarqa	364,000
Al Merad	Activated sludge	Jerash	9000
Shobak—Tankers	Waste stab ponds	Ma’an	350
Mansorah—Tankers	Waste stab ponds	Ma’an	50
South Amman		Amman	52,000
Mu’tah and Adnaniyyah		Karak	7060
Shallaleh		Irbid	13,700
ShounaShamaliyyah		Irbid	1200

Appendix 2

See Fig. 11.

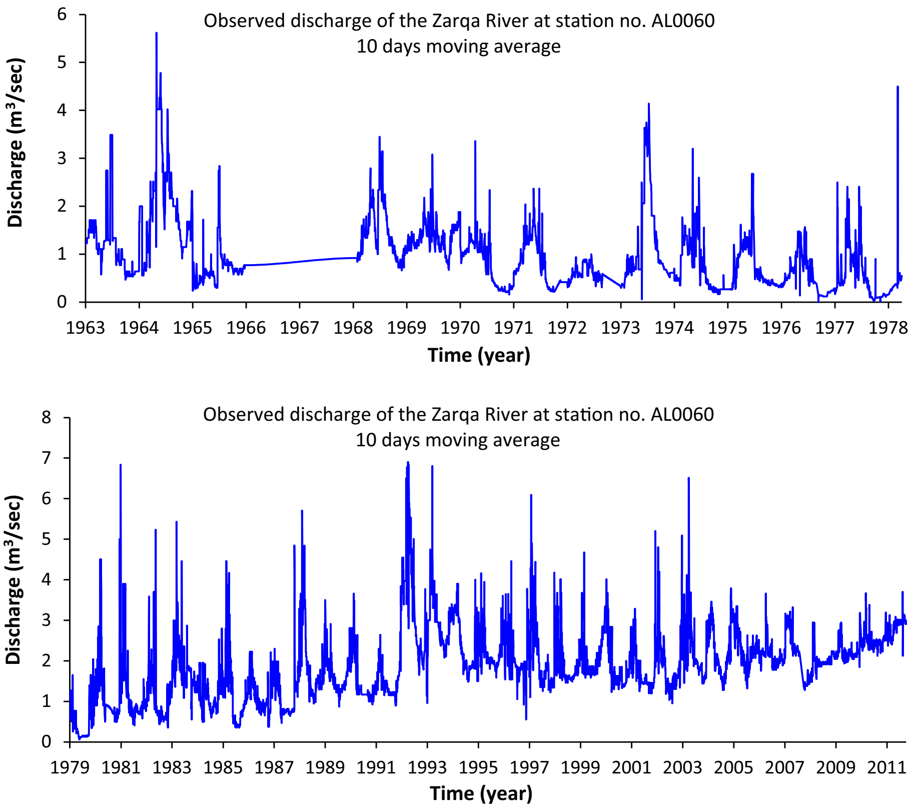

Fig. 11 Discharge of the Zarqa River (MWI data bank 2015)

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