# Hydrodynamic modeling for groundwater assessment in Sana'a Basin, Yemen

**Yahia Alwathaf · Bouabid El Mansouri**

**Abstract** Yemen is a semi-arid country with very limited water resources. Sana'a Basin is located in the central part of Yemen and is the major source of water for drinking and irrigation. High abstraction rates in Sana'a Basin rising from 21.1 million (M) m$^3$ in 1972 to 227.7Mm$^3$ in 2006, have led to a major decline in water levels and deterioration in groundwater quality. Effective management of groundwater resources in Sana'a Basin can be aided by modelling. FEFLOW was used to build a groundwater flow model for the basin and the model was calibrated under transient conditions for the period 1972–2006. The water balance for transient conditions of the Sana'a Basin in 2006 indicated that the total annual inflow was 116.9Mm$^3$, and the total annual outflow was 245.8Mm$^3$. Three scenarios for potential groundwater extraction for the period 2006–2020 are presented. The first represents the present status based on the 2006 extraction rates without introducing any management measures. The second is based on maximum domestic, agricultural and industrial consumption of water resources. The third simulates the effect of water-resource augmentation, i.e. the increase of groundwater recharge, and maximizes sustainability by reducing water consumption. Identified areas of the basin require prompt management action.

**Keywords** Yemen · Modelling · FEFLOW · Management · Sustainability

## Introduction

The Republic Of Yemen is located at the south–southeast part of the Arabian Peninsula. The topography of the country varies widely between sea level in the western and southern coastal plains to elevations of more than 3700 meters above sea level (m.a.s.l.) in the northwest mountains of the country.

Sana'a Basin is an inter-mountain plain located in the central Yemen highlands. The plain has an elevation of about 2200 m.a.s.l., but is surrounded to the west, south and east by mountains rising to more than 3000 m.a.s.l. The basin has an area of some 3200 km$^2$ and forms the upper part of the catchment of wadi al Kharid, a subcatchment of the wadi al Jawf (Fig. 1). The climate is semi-arid with an average annual rainfall of 235 mm at Sana'a. The population of the Sana'a Basin was estimated to be about one million in 1995 and 2.0 million in 2004, of which 1.75 million lived in the city of Sana'a (5.5 % annual growth rate) and 0.25 million lived in the rural areas (3.2 % annual growth rate; CSO 2005a).

Groundwater in the Sana'a Basin is the major source of drinking water. With the increasing needs for groundwater resources and as a result of human activities affecting the aquifers, problems such as decreasing groundwater heads and deterioration of the groundwater quality have been lately observed in many places. The Sana'a Basin has been an important center for the development of agricultural, industrial and domestic activities for the last few decades and groundwater has also been the main water supply for these activities. Groundwater demands have thus been steadily increasing. In 1972, the annual exploitation of groundwater was an estimated 20.10$^6$ million (M) m$^3$ which increased to approximately 227.10$^6$ Mm$^3$ in 2008. Due to over abstraction of groundwater, the local springs dried up and water levels became significantly low. The quality of groundwater was also impacted. This increasing demand for groundwater necessitates its effective management, and since groundwater flow modeling is essential for such effective management, the model may in future help decision makers and planners in selecting optimum management schemes suitable for arid and semiarid regions (Abdulla and Al-Assa'd 2006; Wen et al. 2007). FEFLOW was used to build a regional groundwater flow model for the basin. This model will be used as a tool to predict the groundwater level in the basin over the next 10 years.

## Geology

The stratigraphic sequence outcropping or present in the subsurface in Sana'a Basin ranges from Jurassic to

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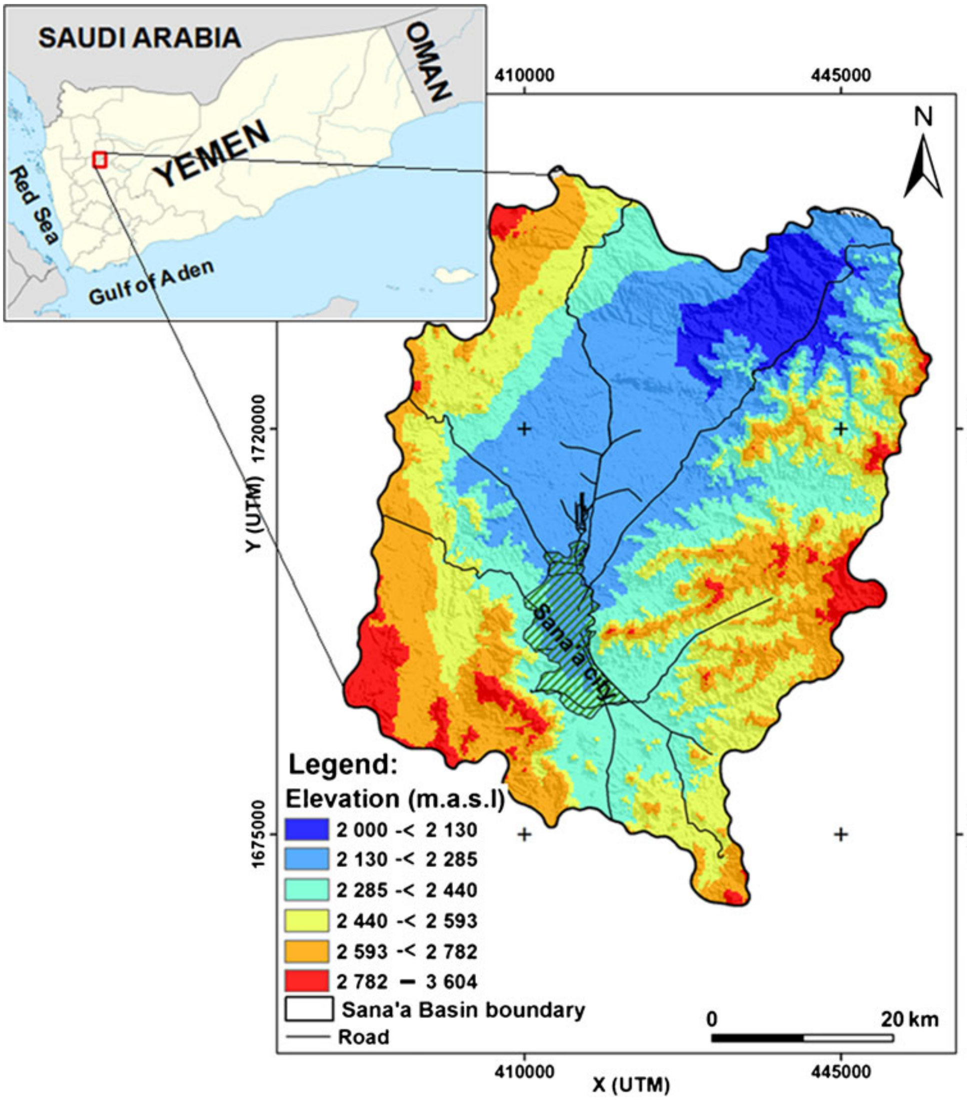

**Fig. 1** Location and topographic map of the Sana’a Basin (digital elevation map from a satellite dataset)

Quaternary (Italconsult 1973). It can be divided into three major groups: Mesozoic and Paleocene sedimentary formations, Tertiary trap volcanic series and Quaternary sedimentary. A short description of each of these formations is summarized (Italconsult 1973; Foppen 1996) in the following sections.

### Kohlan Group (Triassic to Middle Jurassic)

This is the oldest sedimentary formation overlying the Basement in the major part of Sana’a Basin although not found on the surface. It consists of green shale with sandstone and conglomeratic bands in the lower parts and sandstone and conglomerates in the upper part; the thickness is over 300 m (Italconsult 1973).

### Amran Group (Middle to Upper Jurassic)

The Amran Group comprises limestone, marls and shaly limestone. It covers 15 % of the outcrops in the north of the basin where its thickness ranges from 350 to 1,000 m based on surface sections and the two wells which were drilled though it, namely DS-1 and DS-2 wells which are located about 10 and 30 km northeast of Sana’a city (Fig. 2; Kruseman and Vasak 1996). As is illustrated by a north–south cross-section (Fig. 3), the Amran Group deepens progressively southward below the surface at the southernmost part of the basin. The Amran Group is overlain by a sequence of lagoonal shales, marls and fine grained sandstones interbedded with lignite probably of Upper Jurassic or Lower Cretaceous age which crops out in a narrow band in the north-eastern part of the basin.

### Tawilah Group (Cretaceous to Tertiary)

This group comprises a series of continental cross-bedded sandstones generally medium-to-coarse-grained with interbedded mudstones, siltstones and occasional silty sandstones. The overlying MedjZir Formation consists of fine-grained sandstone with a higher proportion of

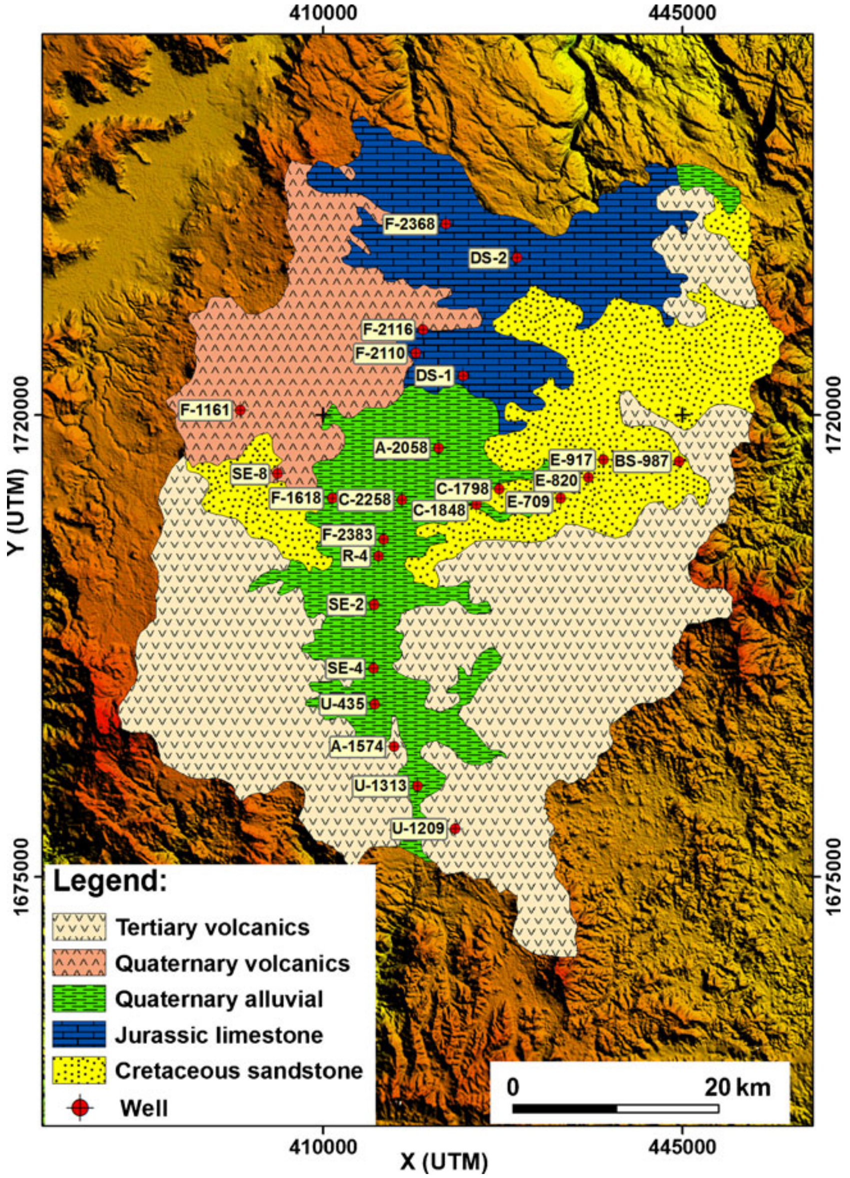

**Fig. 2** Geological map of the Sana'a Basin (Sources for Sana'a Water Supply 1996)

siltstones and clays. It also contains decomposed volcanic tuffs and "soapy clay beds" associated with the start of regional volcanic activity. It has proven difficult to distinguish the Tawilah and MedjZir both in aerial photographs and drill cuttings. They are therefore mapped as one formation and referred to as the Tawilah Sandstones or "Cretaceous Sandstones". The Tawilah Sandstones crop out over about 15 % of the basin area in the northern part of the basin. They are thought to reach a thickness of 400–850 m where it has been protected from erosion by the overlying Tertiary volcanics (Fig. 3).

### Tertiary volcanics

Formerly called the Trap Series, these rocks crop out over some 35 % the Sana'a Basin area. They form high plateaus to the south, west and east of the Sana'a plain and underlie the Quaternary deposits in the south of the basin. The sequence is divided into two groups. The lowest group is the "Stratoid volcanics" which include the basalt (a dense homogenous basalt flow with columnar jointing), basalts, tuffs and pyroclastics interbedded with fluvio-lacustrine deposits. The upper "Chaotic volcanics" comprise mixed basalt flows and rhyolite lavas. The total thickness is variable; reaching an estimated maximum of 600–800 m. Basic intrusive rocks of Tertiary age are present throughout the area in the form of volcanic plugs and dykes.

### Quaternary volcanics

Volcanic activity continued into the Quaternary forming a plateau of extensive basalt cones in the northwest of the basin interlayered with tuffs and alluvial sediments. The Quaternary basalts have a total thickness of about 100–300 m and cover about 20 % of the area of the basin. They

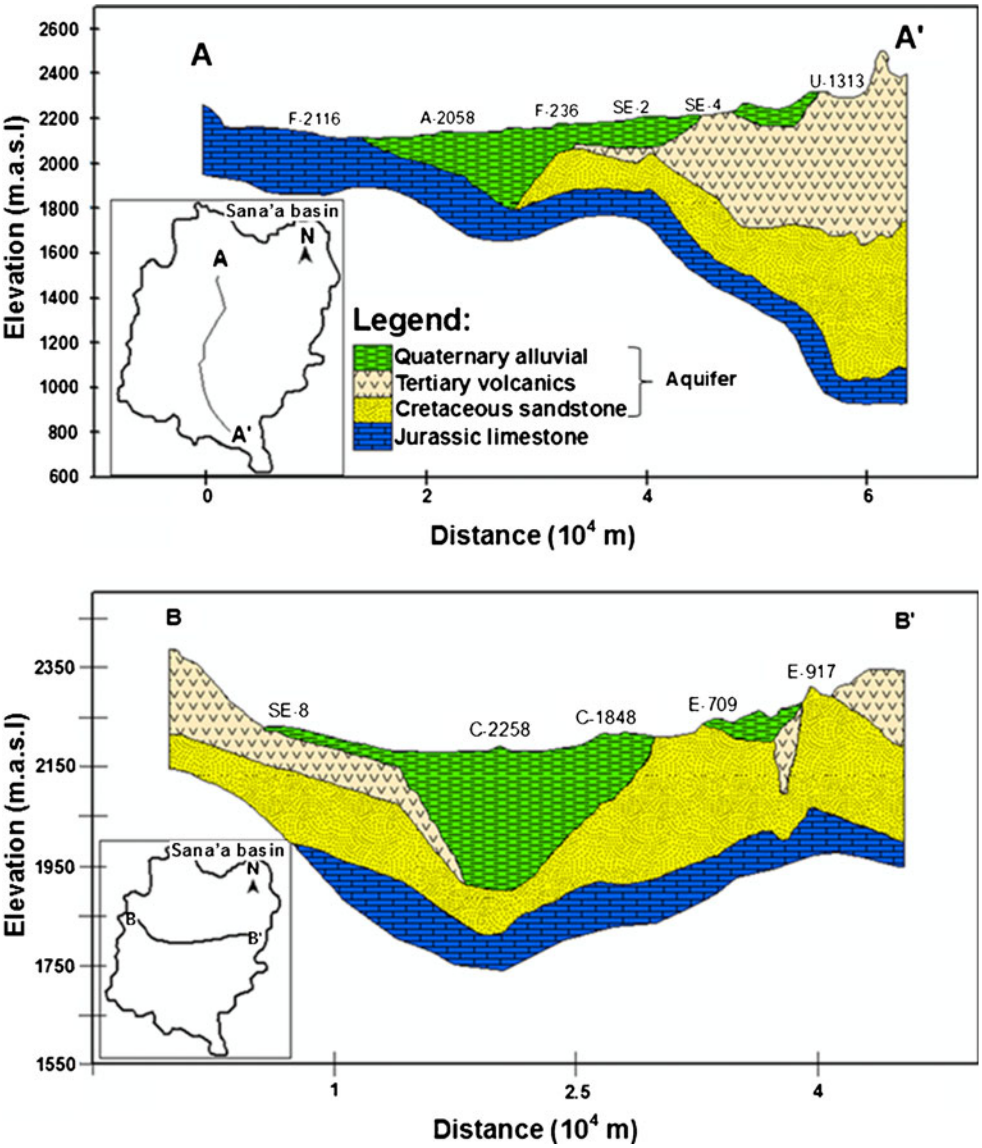

Fig. 3 Geological cross-sections of the Sana'a Basin

overlie the Amran limestone, Tawilah sandstone and Tertiary volcanics.

### Quaternary alluvium

Unconsolidated sediments (mainly alluvial) cover about 15 % of the basin area. They are confined to wadi beds and low areas that form the Sana'a plain. Deposition appears to have been of fluvio-lacustrine nature, which led to the accumulation of clays and silts in basins 100–300 m deep. Coarse-grained colluvium and alluvium occurs in the wadi beds at the foot of hills.

## Hydrogeological overview

The Amran limestone is generally considered to be a poor aquifer although water supplies can be obtained from zones of secondary permeability. Karst features however are poorly developed. The water table is over 100 m deep

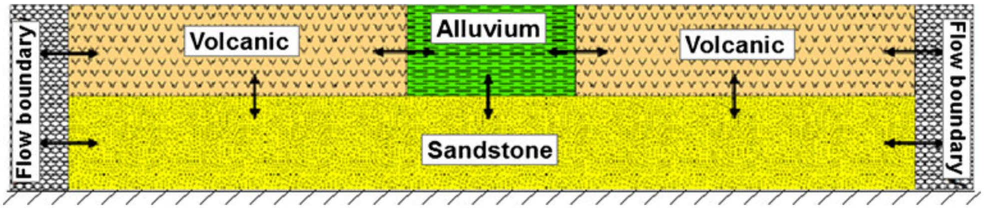

Fig. 4 Schematic conceptual model

in the plateau area in the northwest of the basin. In the northeast, in valleys leading to the wadi al Kharid the depth to water is less than 35 m and groundwater is abstracted mainly by means of dug wells (Foppen 1996; Kruseman and Vasak 1996). The Tawilah sandstone forms the main aquifer in the region. It has low regional permeability but locally higher permeabilities are found in weathered and fractured zones. It is heavily exploited to the northeast and northwest of Sana'a where it either outcrops or occurs beneath up to 50 m of unconsolidated cover. Depths to water in the main area of abstraction were about 30–40 m in the early 1970 but have declined by 2–4 m/y since. The sandstone is confined under several hundred meters of Tertiary volcanics in the south of the basin. The basalt flows and stratoid sequences of the Tertiary volcanics act as aquitards, except where fractured or where primary permeability occurs in sediments between flows. The mixed basalt and rhyolite flows at the top of the sequence are more highly fractured and contain perched aquifers which supply dug wells and feed high level springs. The upper layers of the volcanics are highly weathered and relatively permeable where they underlie the unconsolidated Quaternary deposits in the south of the basin. Here they are exploited together with the unconsolidated aquifer by dug and drilled wells. The Quaternary basalts are highly permeable due to fracturing and to the presence of clastic deposits between flows. Where the formation is saturated it provides an unconfined aquifer. Water levels are deep ranging from 60 to 130 m depending on the elevation. Wells are generally limited to the southern edges of the outcrops where water levels are less than 100 m deep. In the rest of the area, surface water is stored in cisterns to provide water for

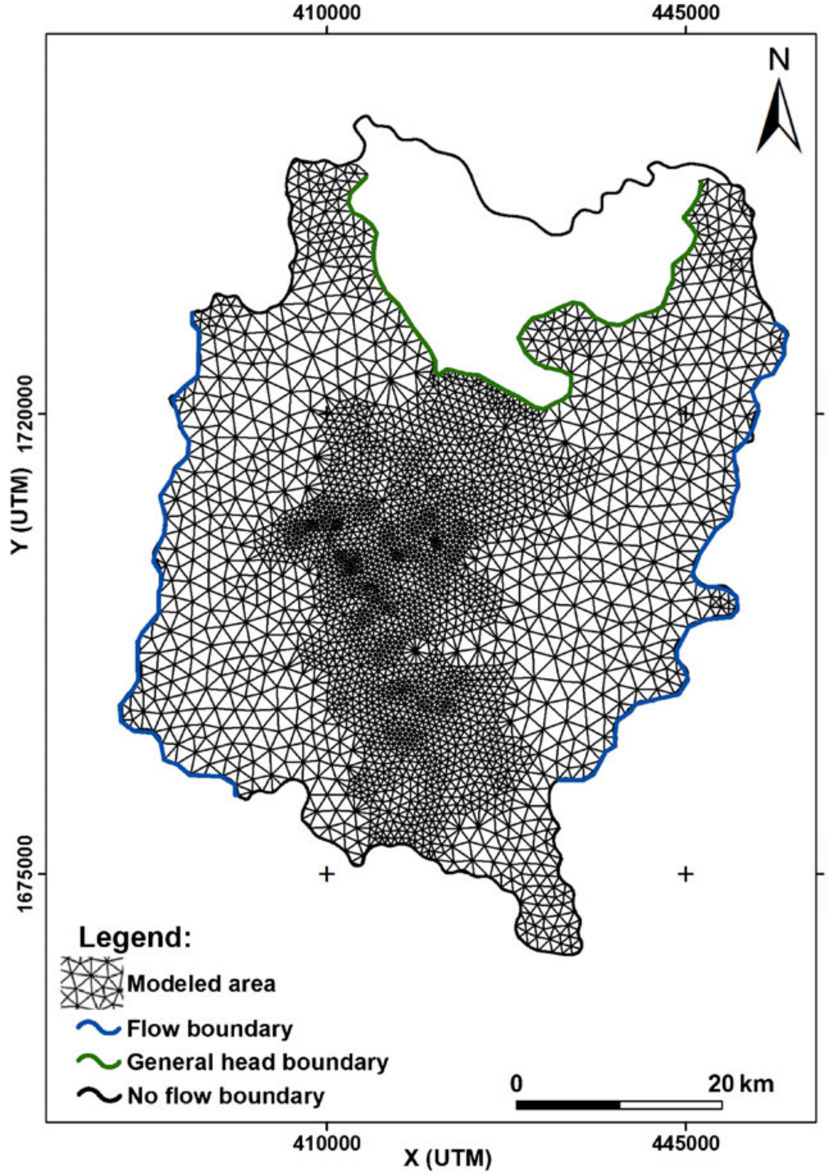

**Fig. 5** Two-dimensional (2D) mesh network and boundary conditions of the model

domestic purposes. The unconsolidated Quaternary deposits provide a poorly permeable aquifer, which has been heavily exploited in the Sana’a Basin due to its proximity to the urban area. The aquifer is regionally unconfined but locally semi-confined. Due to the fine-grained nature of the deposits in the plain recharge is expected to be mainly indirect, into coarse-grained material along wadis and at the base of the hills (Foppen 1996).

## Conceptual model

The conceptual model of the hydrogeological system is based on the geological information from boreholes and water-level fluctuation in observation wells. The groundwater flow is modelled using FEFLOW software (Dierch 1998a, b), and the aquifer is classified into two hydrogeological layers: the upper layer, which represents the (Quaternary alluvium, Quaternary and Tertiary volcanics, with a thickness of alluvium varying from 100 to 300 m and thickness of volcanics varying from 300 to 800 m), and the lower layer (consisting of sandstone with a thickness varying from 400 to 700 m).

The conceptual model was designed according to the actual groundwater flow in the basin. The model is simulated by two layered aquifers, where the horizontal flow and the vertical flow among the simulated layers were considered (Fig. 4). Such conceptualization captures the main features of the hydrologic conditions of the basin, including the inflow boundary and the general head boundary. The groundwater flow system was determined for the upper layer and lower layer. This information is represented in Fig. 4, where the flow system constitutes one hydraulically connected system. The conceptual model was defined, and the hydraulic boundary conditions

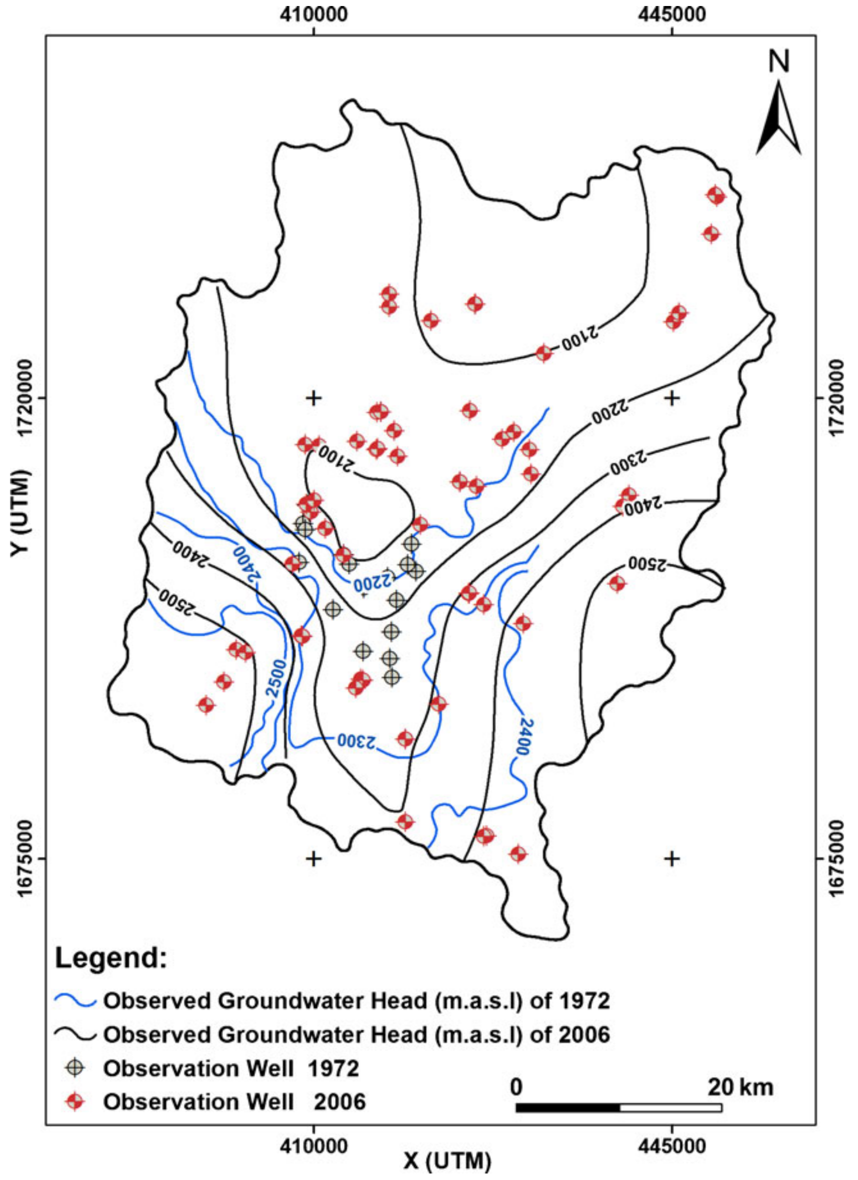

**Fig. 6** Groundwater level in the Sana’a Basin in 1972 and 2006 (Italconsult 1973, NWRA 2006)

were identified according to the hydro-geological conditions. The conceptual model is described below and illustrated in Fig. 4.

## The zone of the study area

The Sana'a Basin has an area of about 3,200 km$^2$. The model will overlook the composition of the Amran limestone because of the lack of information about its geometry dimensions. Since this limestone covers some 478 km$^2$ in the north of the basin, the model covers the rest (2,722 km$^2$) of the basin and is composed of alluvial, volcanics and sandstone formations.

## Boundary conditions

The aquifer limits can be described by natural or hydrological boundaries, as shown in Fig. 5. An inflow boundary (Neumann type) was defined along the western and eastern boundaries for all layers, the flow rates imposed on the east and west boundaries are 21.2 and 29 Mm$^3$/y in 2006 respectively. The mountains in west and east of basin are constantly fed by high rainfall that occurs in these higher altitudes, and because evapotranspiration is also much smaller than in the plain, the mountains form an upstream supply of groundwater for the Sana'a plain. Also, outcropping of sandstone in some areas in west and east in addition to the presence of cracks in the volcanic rocks promotes a steady feed from the groundwater reserves in these mountains to the Sana'a Basin (Fig. 3), since the elevations (about 2,500–3,200 m.a.s.l.) and extension of these mountains allow for collection of large amounts of rainfall that subsequently percolates under the influence of gravity through the volcanics and sandstone rocks to the Sana'a Basin. The general head boundary (drain) was defined along the northern boundary of the basin for all layers. Eventually part of the groundwater discharges into the wadi al Kharid springs through the Amran limestone (Foppen 1996).

## Initial conditions

The 1972–2006 period was chosen as the calibration period. Figure 6 shows groundwater level in the Sana'a Basin in 1972 and in 2006. There are two types of groundwater head observations: the first corresponds to a set of measurements from 1972, but only in nineteen observation wells located in the central and northern part of the basin (Italconsult 1973). These observations were used to obtain the evolution of the average groundwater level shown in Fig. 6. The second set of groundwater head measurements is from 57 observation wells that are well spread over the Sana'a Basin, but only for the years from 2003–2008. These data were obtained from the National Water Resource Authority (NWRA 2006) in Sana'a. An average value was calculated for each observation well and used for interpolating these values to obtain an estimated map of the groundwater heads.

## Groundwater recharge

The groundwater recharge (Mm$^3$/y) in each of these 22 sub-basins that constitute the Sana'a Basin was determined; recharge is calculated as two components: direct

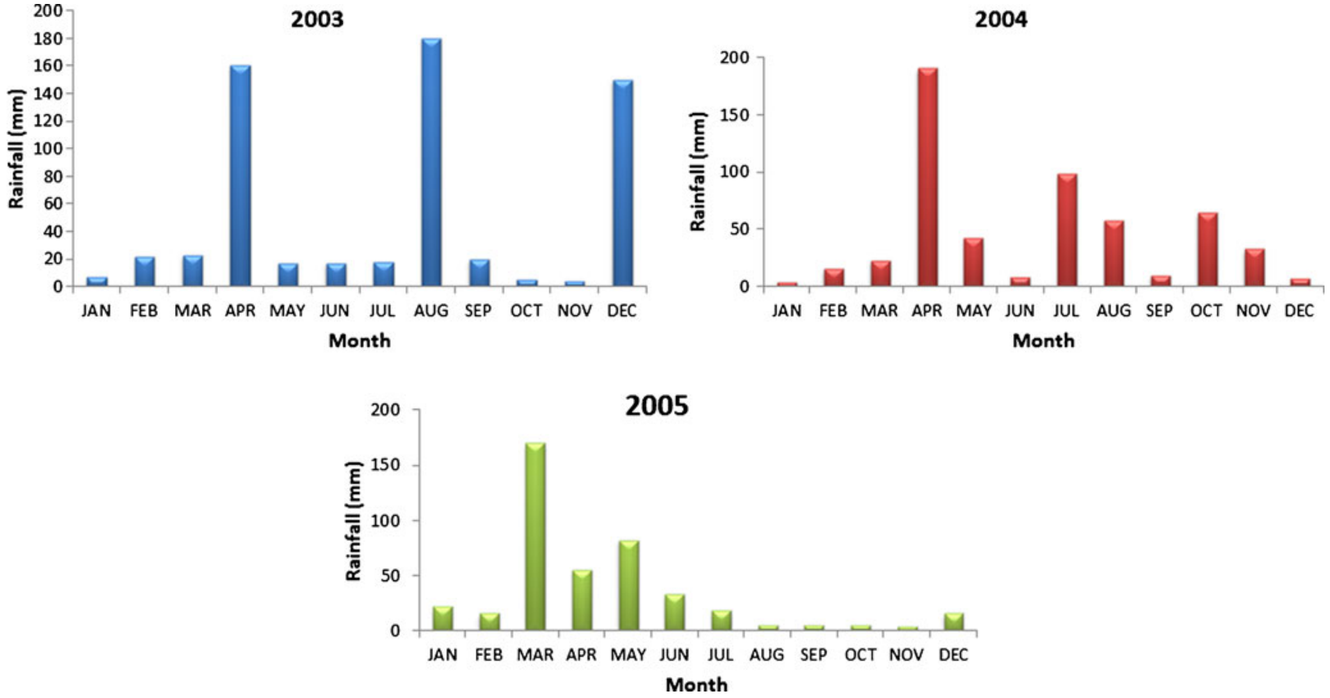

**Fig. 7** Average monthly rainfall in Sana'a Basin for the period from 2003 to 2005 (NWRA 2006)

recharge from rainfall calculated by soil-moisture water-balance method as described in the following and wadi bed recharge. In Sana'a Basin there are two rainy seasons separated by a distinct dry interval (May to mid-July). The annual rainfall generally varies from 150 to 250 mm, with some years having higher rainfall amounts above 350 mm. the first rainy period starts mid-March to beginning of April. The second rainy period starts from mid-July to beginning of August and stops abruptly at the end of August. The months of September through February are generally dry (Fig. 7), although occasional thunderstorms may bring some rain, groundwater recharge is only 8 % of rainfall while evapotranspiration consumes 92 % of annual rainfall (Water and Environment Center, unpublished data, 2002).

The soil moisture balance method was applied to estimate groundwater recharge from direct rainfall. The main hydrological variables used were precipitation (daily rainfall), evapotranspiration and runoff. These were used to estimate a component of water balance, usually groundwater recharge, as the residual of all other fluxes that can be measured or estimated more easily (Lerner et al. 1990). The general relation between fluxes—i.e. precipitation ($P$), surface runoff ($Q$), evapotranspiration (ET), groundwater recharge ($R$), and change in water storage in the saturated and unsaturated zones ($\partial S$)—is:

$$P = Q + \mathrm{ET} + R \pm \partial S$$

Recharge in the 22 sub-basins was calculated at 67.7 Mm$^3$ derived from two components: direct recharge from rainfall calculated by soil-moisture water-balance method as described in the preceding and Wadi bed recharge. Results shown in Fig. 8 indicate that recharge from direct rainfall is a rare phenomenon, occurring only during intense rainfalls where the soil field capacity is

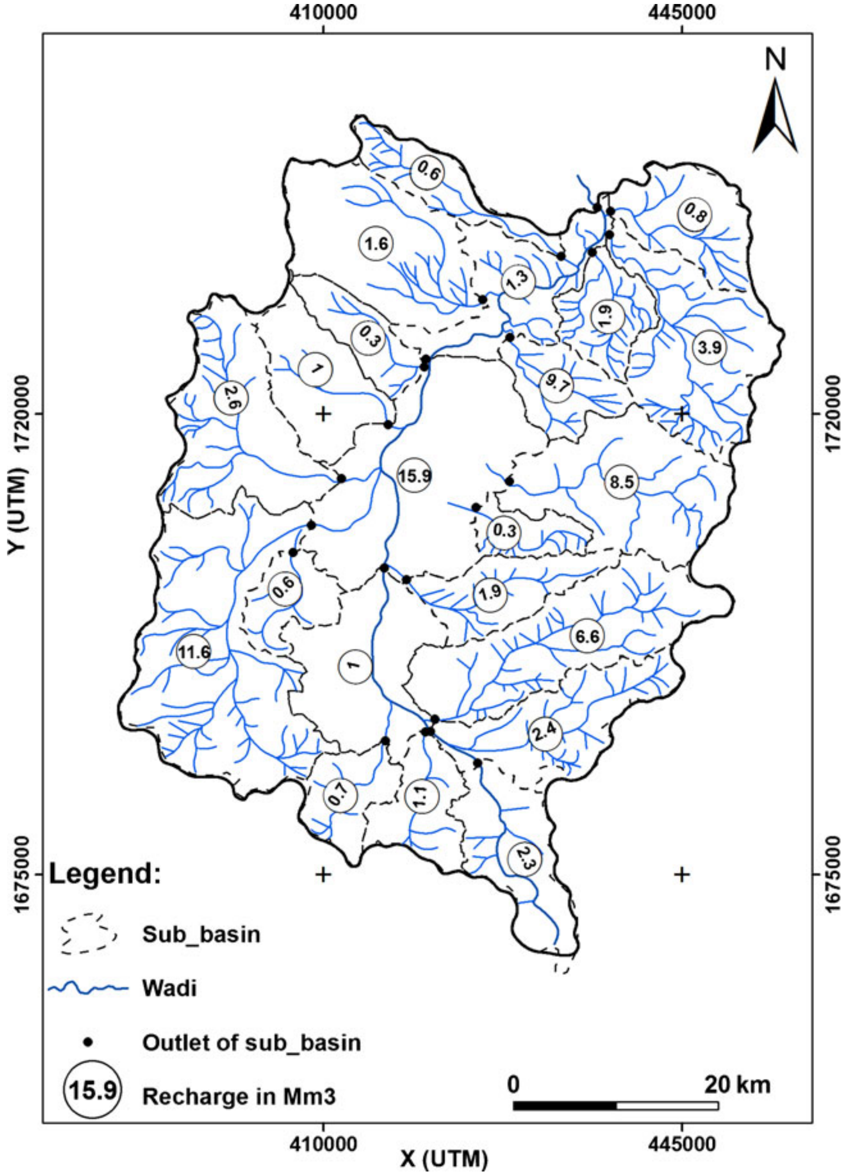

**Fig. 8** Annual groundwater recharge (Mm$^3$/y) for sub-basins in Sana'a Basin (Water and Environment Center, unpublished data, 2002)

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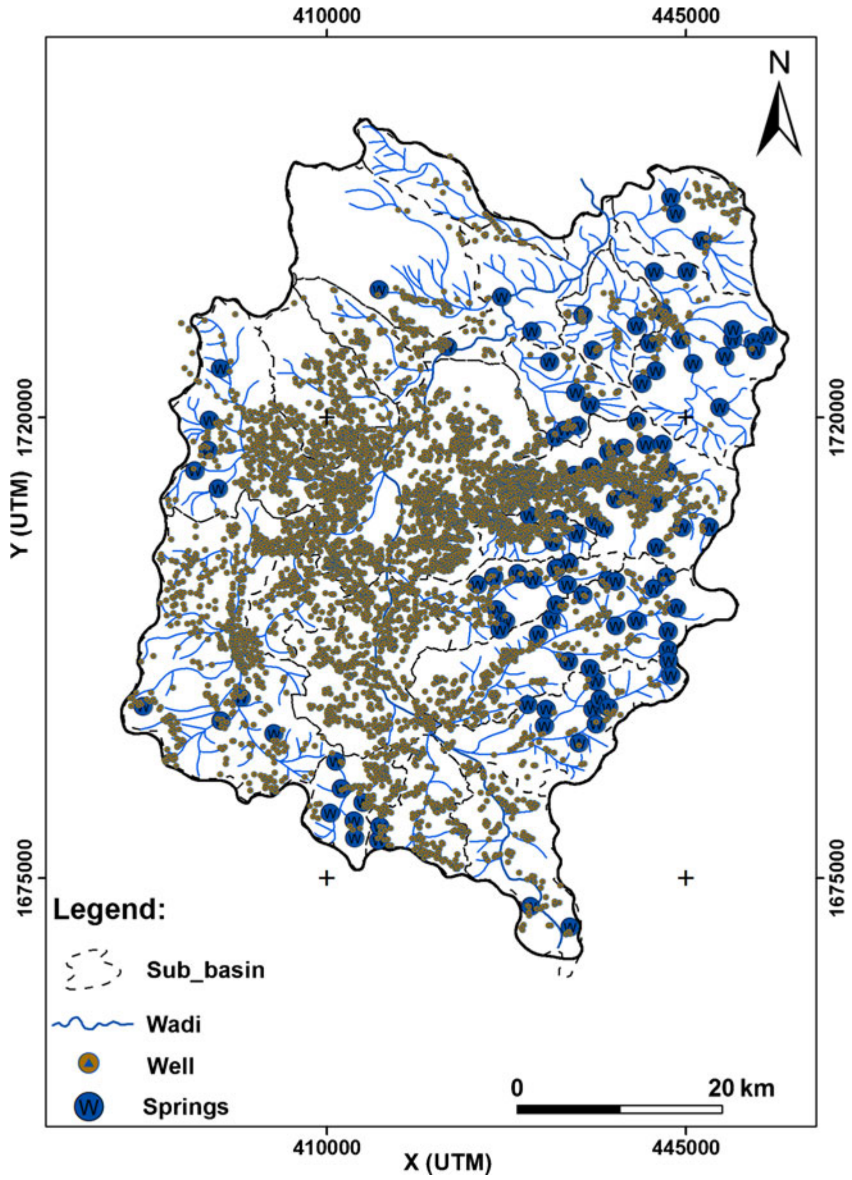

**Fig. 9** Springs and Wells in Sana'a Basin (Water and Environment Center, unpublished data, 2002)

exceeded by the amount of water percolating. The mean annual value of direct recharge for sub-basins is only 4.9 $\mathrm{Mm}^3$. The major recharge in Yemen is assumed to occur from surface runoff and infiltration through the wadi beds, which is estimated herein at 62.7 $\mathrm{Mm}^3$/y (Ministry of Oil and Mineral Resources/TNO 1995). Accordingly, in most of the sub-basins in Sana'a Basin, wadi runoff is diverted for spate irrigation; hence, it is reasonable to

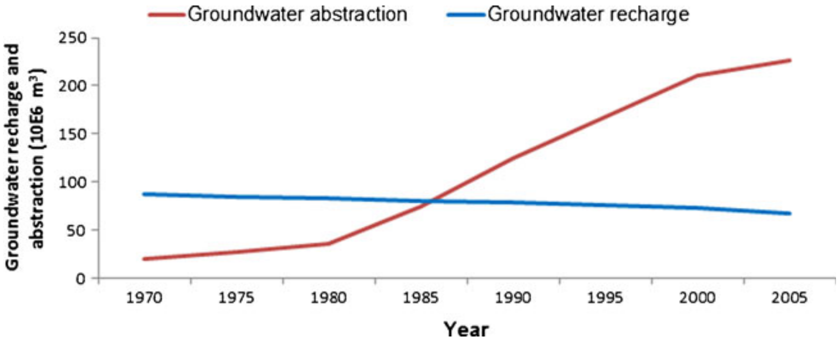

**Fig. 10** Comparison of groundwater recharge and abstraction in the Sana'a Basin from 1970 to 2005 (Water and Environment Center, unpublished data, 2002)

assume that 70 % of the runoff ends up as groundwater recharge and this will be the major form of recharge in the basin.

### Groundwater discharge

Groundwater discharge from Sana'a Basin occurs in two types of zones: natural discharge zones and abstraction zones. Evidence for the occurrence of natural groundwater discharge occurs as springs, especially in wadi al Kharid in north of the basin (Fig. 9).

Discharge through well abstraction, however, is more easily detectable. The Water and Environment Center (Water and Environment Center, unpublished data, 2001) carried out a complete hydrogeological survey for all the wells in Sana'a Basin. This survey included an inventory of the hydrogeological data for 13,426 water points (Fig. 9). It estimated the total abstraction to approx. 227 Mm$^3$ in 2002 (Water and Environment Center, unpublished data, 2002).

The Sana'a Basin relies to a large extent on groundwater for both irrigation and the urban water supplies. Figure 10 compares quantities of groundwater recharge and abstraction. It is evident that the groundwater recharge has been less than groundwater abstraction since 1985. Increased groundwater abstraction is due to greater population growth in Sana'a city as well as increased agricultural activities. There is a decrease in groundwater recharge, possibly partly due to climate change in the last few years leading to a decrease in the quantity of rainfall.

## Numerical modelling

### Software

The groundwater numerical flow model was developed using FEFLOW version 5.3 (finite element subsurface flow system) working under both steady-state and transient conditions. For theoretical and practical information concerning software use and the solution of equations, the reader can refer to the respective manuals (Dierch 1998a, b). The finite element method was adopted for its flexibility and capacity to simulate complex geometric forms and to refine the nodal grid around points and/or single lines (observation points, boundary line, etc.). Lithological, hydrogeological data processing was carried out in a geographic information system (GIS) environment (ArcView) that can be totally interfaced with FEFLOW; this is very useful in the development of the conceptual model, in the creation of the numerical model and in the analysis of simulation results.

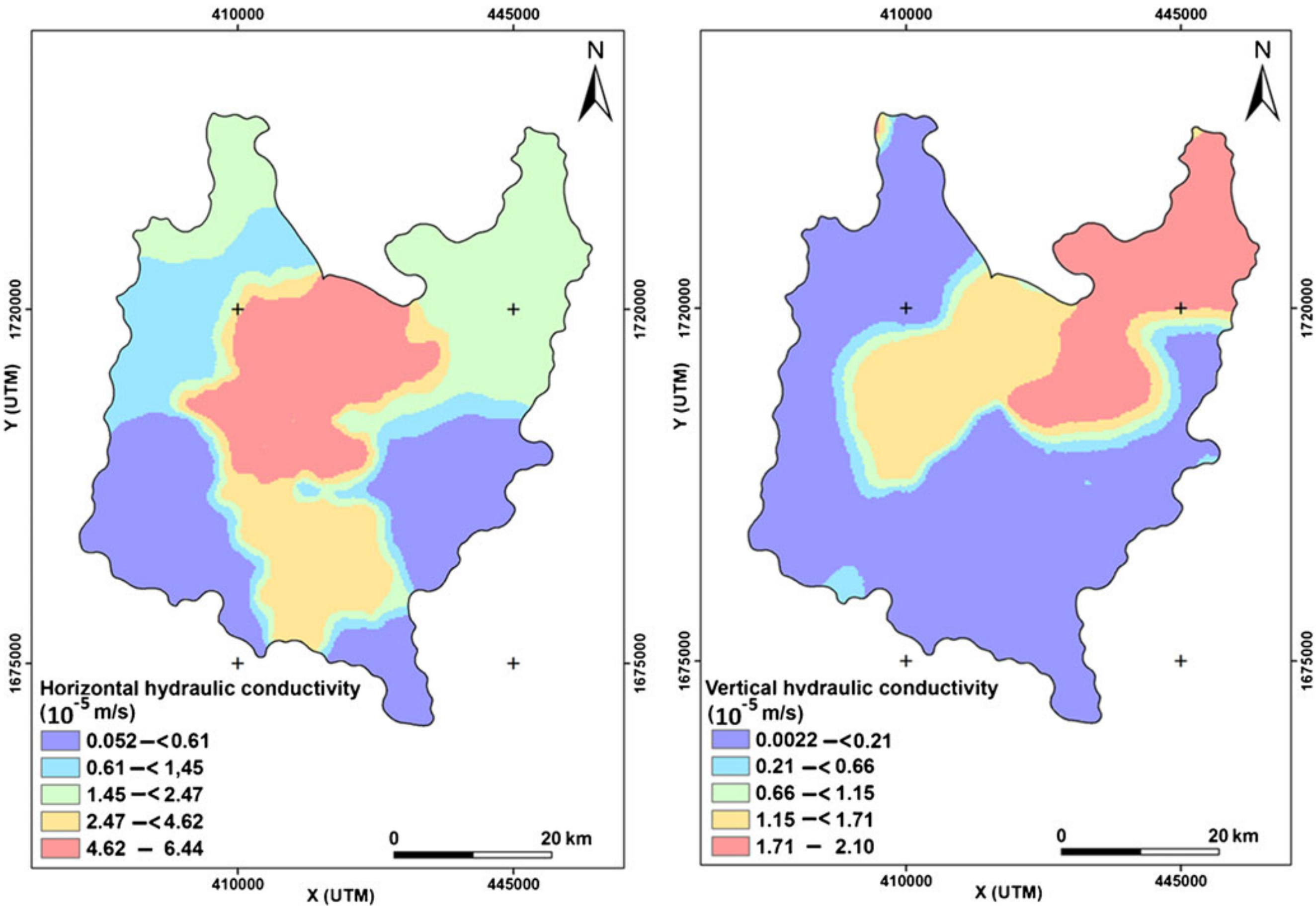

**Fig. 11** Distribution of hydraulic conductivity for the upper-layer aquifer

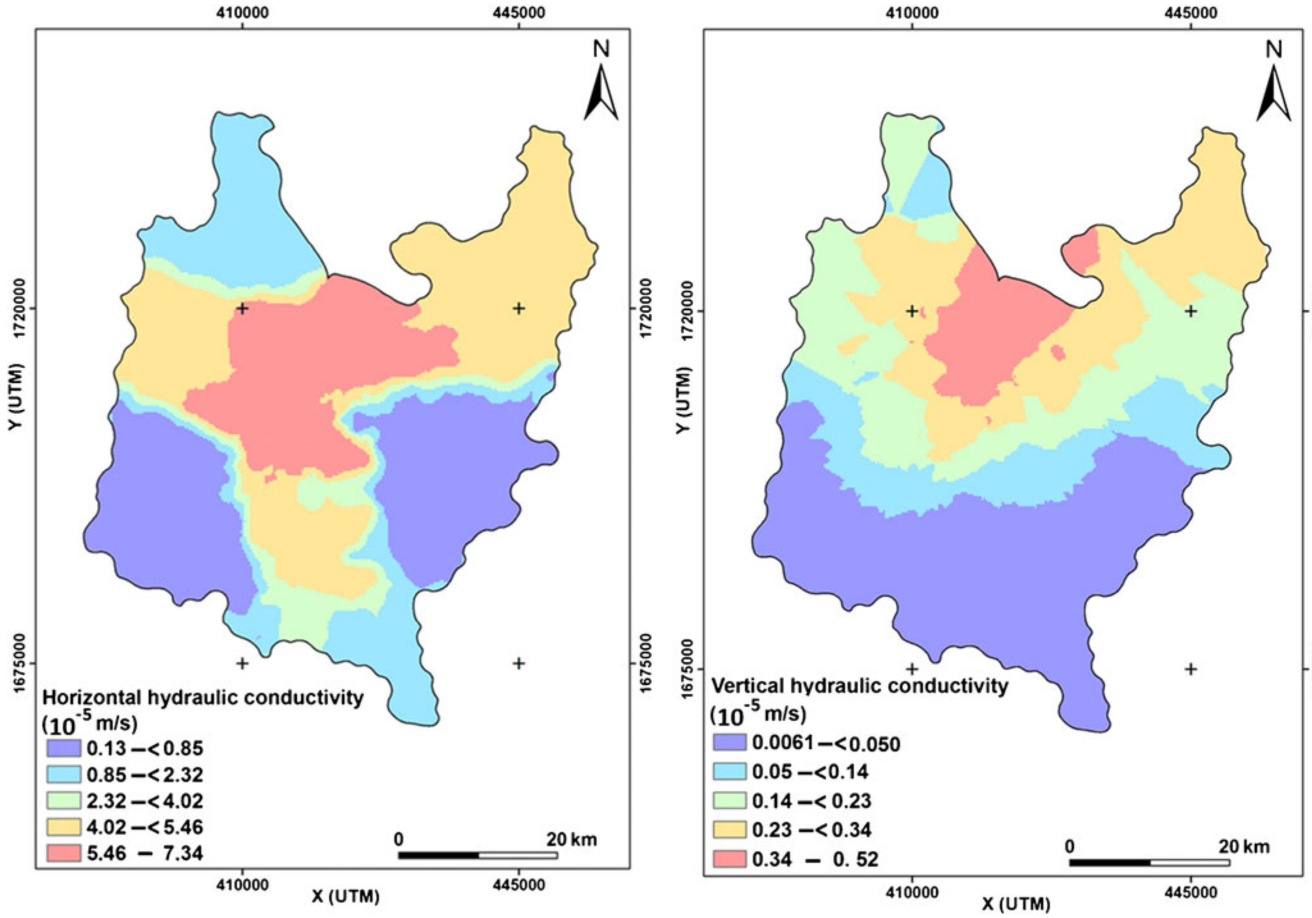

**Fig. 12** Distribution of hydraulic conductivity for the lower-layer aquifer

## Model structure

Spatially, the three-dimensional (3D) model domain covers a surface area of 2,722 km$^2$. The domain was discretized into 11,144 triangular prismatic mesh elements with 8,722 nodes in the horizontal orientation. The aquifer consists of two layers with different thickness. The finite element grid was generated automatically with moderate refinement along the zone of abstraction in middle of the model area.

## Model inputs

The model inputs include the hydrogeological parameters hydraulic conductivity ($K$), transmissivity ($T$) and storage coefficient ($S$). The aquifer properties such as horizontal hydraulic conductivity ($K_h$) and vertical hydraulic conductivity ($K_v$), used in the model were derived from pumping tests. Initial spatial distributions of hydraulic conductivity were obtained from the available data (42 measurements obtained from upper layer and lower layer). Data were spatially interpolated using kriging and the corresponding results were divided into arbitrary zones. The hydraulic conductivity in upper layer was obtained from the available data (28 measurements), ranging from 9E-5 m/s in the north and middle of the basin, and decreasing to less than 0.051E-5 m/s towards the east and west of the aquifer. The hydraulic conductivity of lower layer was obtained from the available data (15 measurements), with $K$ values greater than 4.6E-5 m/s in the middle and north of the basin, and decreasing towards the west and east parts of the aquifer to less than 0.081E-5 m/s. Specific yield ($S_y$) and specific storage ($S_s$) were also

**Table 1** Properties used to determine sensitivity effects of modeled groundwater level in 2006 (M = million)

| | Recharge | | Horizontal hydraulic conductivity ($K_h$=3.26E-5 m/s) | | Vertical hydraulic conductivity ($K_v$=1.17E-5 m/s) | |
|---|---|---|---|---|---|---|
| | Increase 50 % (about 34 Mm$^3$) | Decrease 50 % (about 34 Mm$^3$) | $K_h \times 10$ | $K_h \times 10^{-1}$ | $K_v \times 10$ | $K_v \times 10^{-1}$ |
| Variation of groundwater level | Increase 144 m | Decrease 116 m | Decrease 43 m | Increase 54 m | Increase 79 m | Decrease 67 m |

**Table 2** Calculated water budget of Sana'a Basin from 1972 to 2006 (Mm$^3$/y)

| Year | | In | | | | | Out | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1972 | 1980 | 1990 | 2000 | 2006 | 1972 | 1980 | 1990 | 2000 | 2006 |
| Water-balance components | Boundary conditions | 21.3 | 27.5 | 33.6 | 39.1 | 49.2 | 88.2 | 74.3 | 31.8 | 26.3 | 18.6 |
| | Recharge | 88.3 | 82.7 | 78.8 | 74.3 | 67.7 | 0 | 0 | 0 | 0 | 0 |
| | Abstraction | 0 | 0 | 0 | 0 | 0 | 21.4 | 35.9 | 125.6 | 211 | 227.2 |
| | Total | 109.6 | 110.2 | 112.4 | 113.4 | 116.9 | 109.6 | 110.2 | 157.4 | 237.3 | 245.8 |

assigned to the model. The values of specific yield ranged from 0.05 to 0.28 and were obtained from pumping tests. The value of the storage coefficient for the upper layer was estimated at 3.74E-7, and for the lower layer at 0.908E-4 (Naaman 2004).

## Model calibration

Before the model was used to forecast future groundwater levels, calibration was carried out using historical groundwater-level data. A transient simulation was undertaken for the 35-year period from January 1972 to December 2006 with a monthly time step. The calibrated vertical and horizontal hydraulic conductivity values for the upper and lower layers are shown in Figs. 11 and 12, respectively.

The additional model parameters for transient state calibration are the specific yield ($S_y$) and storage coefficient ($S$) (storage coefficient = specific storage × aquifer thickness). In the upper layer the model was calibrated using specific yield values 0.0002–0.02 for the middle and north modeled area, 0.001–0.019 for the north-west zone, 0.00084–0.067 for the east and west zones, and 0.08–0.1 for the north-east zone use. The lower layer is confined under a thick layer of volcanics in the south of Sana'a Basin and unconfined where it crops out in the northern part. The aquifer was calibrated using a specific yield value of 0.008–0.01 for the unconfined part of the aquifer and a specific storage value of 1.14E-6 to 1.2E-2 for the confined part of the aquifer.

The sensitivity of the model to input parameters was tested by varying only the parameters of interest over a range of values. The purpose of a sensitivity analysis is to quantify the uncertainty in the calibrated model caused by uncertainty in the estimates of aquifer parameters. Uncertainties are quantified by calculating the magnitude of change in heads from the calibrated model, caused by the change of the value of parameter. The results of the sensitivity analysis give better understanding of the performance of the model and indicate where data have to be collected in the field to enhance the performance of the model (Anderson and Woessner 1992).

In the case of this study, it was decided to evaluate model sensitivity to varying recharge and permeability. Table 1 shows the effect of sensitivity of the modeled groundwater level in 2006. The results of sensitivity analysis showed that the model is very sensitive to changes in recharge, horizontal permeability of the Cretaceous Sandstone, and vertical permeability of Tertiary volcanics—for instance, a 50 % increase in recharge (about 34 Mm$^3$) caused an average increase of calculated heads of 114 m, and 50 % decrease in recharge (about 34 Mm$^3$) caused a decrease of calculated heads of 116 m. The same pattern is noted for changes of values of horizontal hydraulic conductivity and vertical hydraulic conductivity—the change in the average of horizontal hydraulic conductivity (about 3.26E-5) multiplied by 10 caused a decrease of calculated heads of 43 m, and

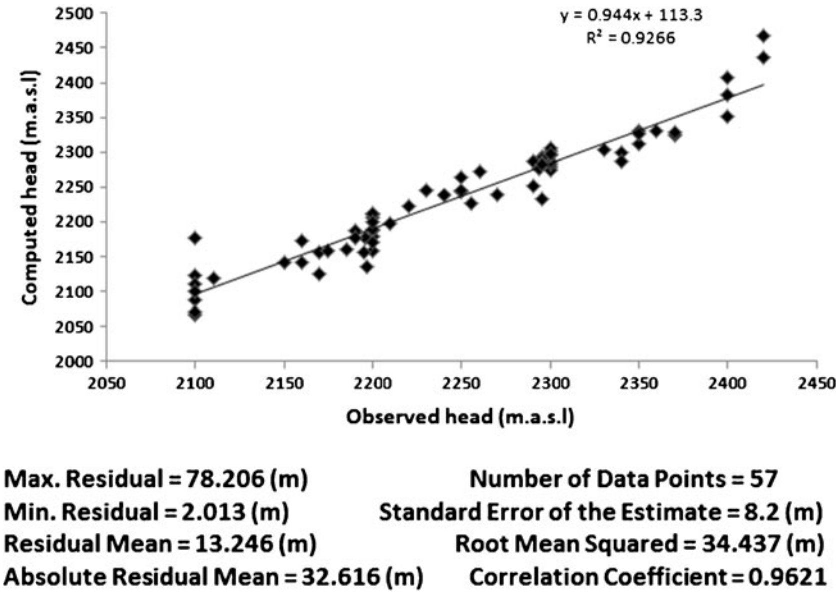

**Fig. 13** Computed versus simulated groundwater head in 2006, under transient-state calibration

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multiplied by $10^{-1}$ caused an average increase of calculated heads of 54 m, while change in the average of vertical hydraulic conductivity (about 1.17E-5) multiplied by 10 caused an increase of calculated heads of 79 m, and multiplied by $10^{-1}$ caused an average decrease of calculated heads of 67 m.

## Water balance

The water budget of the entire aquifer obtained from the groundwater flow model is presented in Table 2. Budget terms are expressed in $Mm^3$/y, and the water-balance components are boundary condition (inflow and drain), recharge and abstraction. The total water budget over the entire aquifer shows a perfect balance between inflows and outflows of water from 1972 to 1985. From 1990 to 2006 the outflow is greater than inflow as a result of the significant increase in abstraction from the basin, and it is due to the increase in both population growth and agricultural activity. The difference in water balance is expressed as depleted water in storage and a drastic water-level decline in all aquifers in Sana'a Basin; there is a threat that the groundwater reservoir in Sana'a Basin will be depleted within the next few decades.

## Simulation results

The transient models were calibrated satisfactorily (Fig. 13) based on the close agreement between computed and observed heads from January 1972 to December 2006

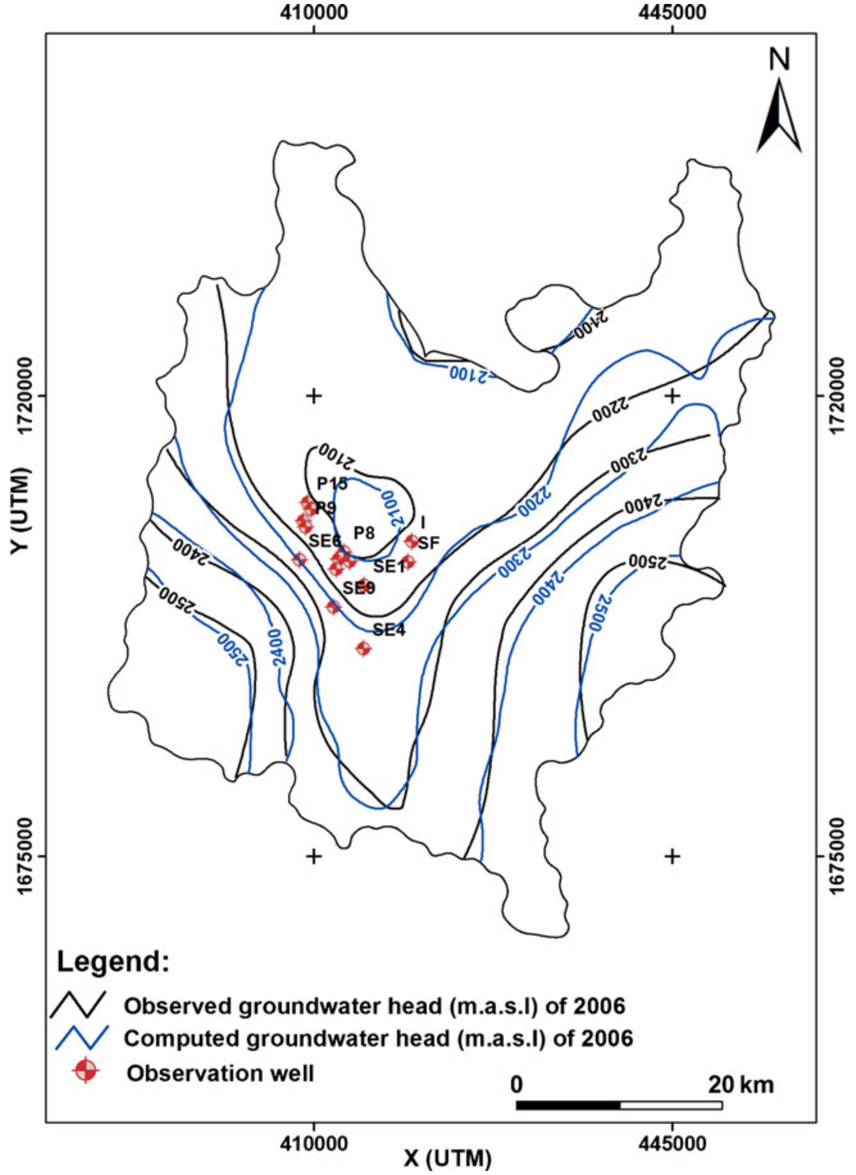

**Fig. 14** Comparison of computed and observed groundwater levels in 2006 for the top model layer. Groundwater heads in the second layer are similar

at 57 observation wells distributed throughout the aquifer (Fig. 6). The results of our model are shown in Figs. 14 and 15. Figure 14 shows a comparison of computed and observed groundwater levels in 2006 for the top model layer. Groundwater heads in the second layer are similar and the contour maps of simulated groundwater levels versus observed groundwater levels indicate fairly good agreement. Figure 15 shows comparison between computed and observed heads in observation wells (P7, SE6, O12, SE1, SE4 and I). Hydrographs of these wells show that calculated heads fit reasonably well with the measured heads; differences are generally less than 10 and 20 m. In the western well field, the modeled drawdown of water level with time seems to be faster than measured drawdown in well O12, while in the eastern well I, the modeled drawdown is slower than the measured drawdown—the reason is the fractures and increase of agricultural activities in this part of the basin.

In wells P7 and SE6, the rate of abstraction of water has increased and the water table has therefore gradually declined. In the south of Sana'a Basin, the SE4 hydrograph showed good agreement between modeled and measured water levels, especially in the beginning of the monitoring period (before 1983) when data were available.

## Assessment and evaluation of planned groundwater development

The calibrated model was used to evaluate three plans for potential exploitation of groundwater in the Sana'a Basin, with the objective of predicting aquifer drawdown. Simulations were made for the period 2006–2020. The first scenario represents the present status based on the 2006 extraction rates without introducing any management measures. A simulation of this situation was made to predict the drawdown in 2020, assuming the present rate of pumping and present rate of groundwater recharge continue. Figure 16 shows the predicted overexploitation areas in 2020 for the first scenario; two main zones are shown with drawdown greater than 50 m, which are located in the north-east and the north-west of the basin, with areas of approximately 177 and 88 km$^2$ respectively. These two zones will become the driest zones of the basin because of a complete dewatering of the aquifer by 2020.

The second scenario is based on a maximum domestic, agricultural and industrial consumption of water resources during the period 2006–2020 and an annual population growth of about 5.5 % during this period (the total population of the Sana'a Basin was 2.25 million in 2006 and, based on this 5.5 % growth rate, it will be 3.88

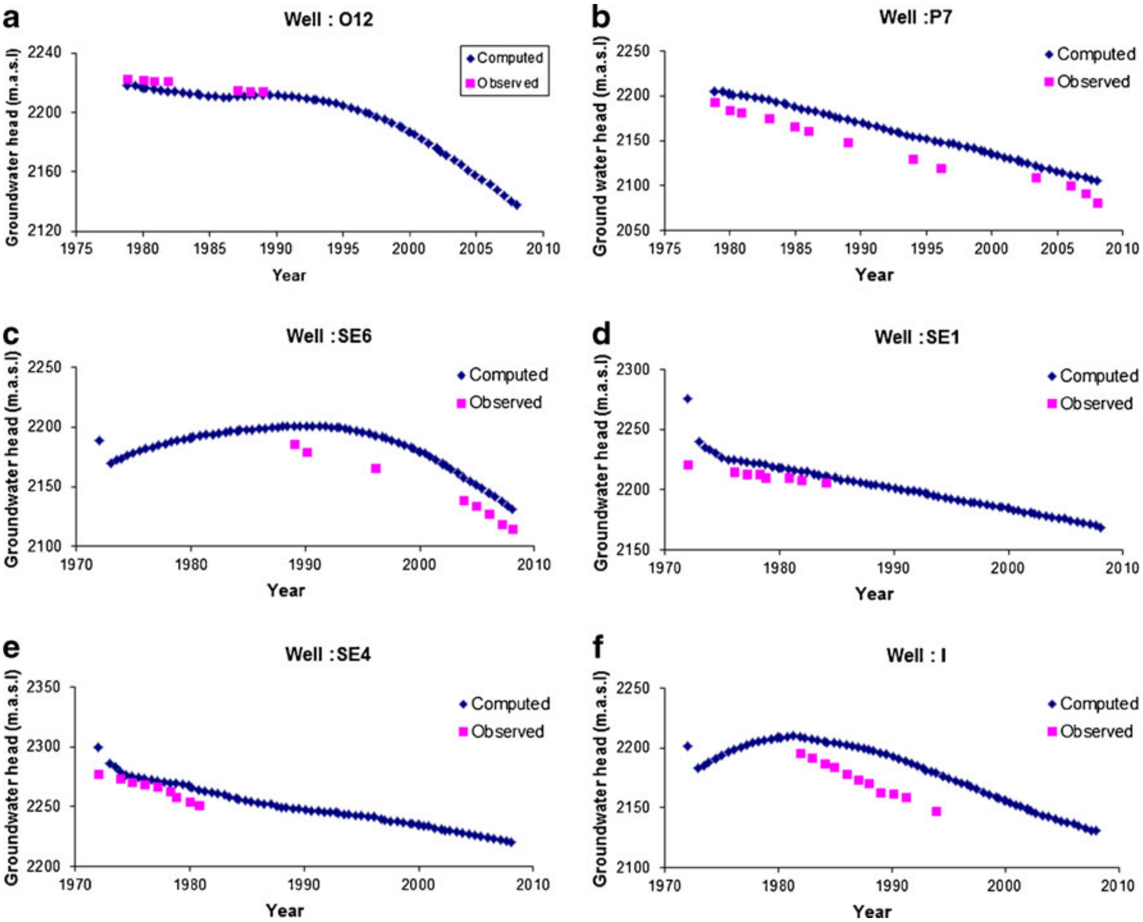

**Fig. 15** Simulated and observed heads at observation wells **a** O12, **b** P7, **c** SE6, **d** SE1, **e** SE4 and **f** I

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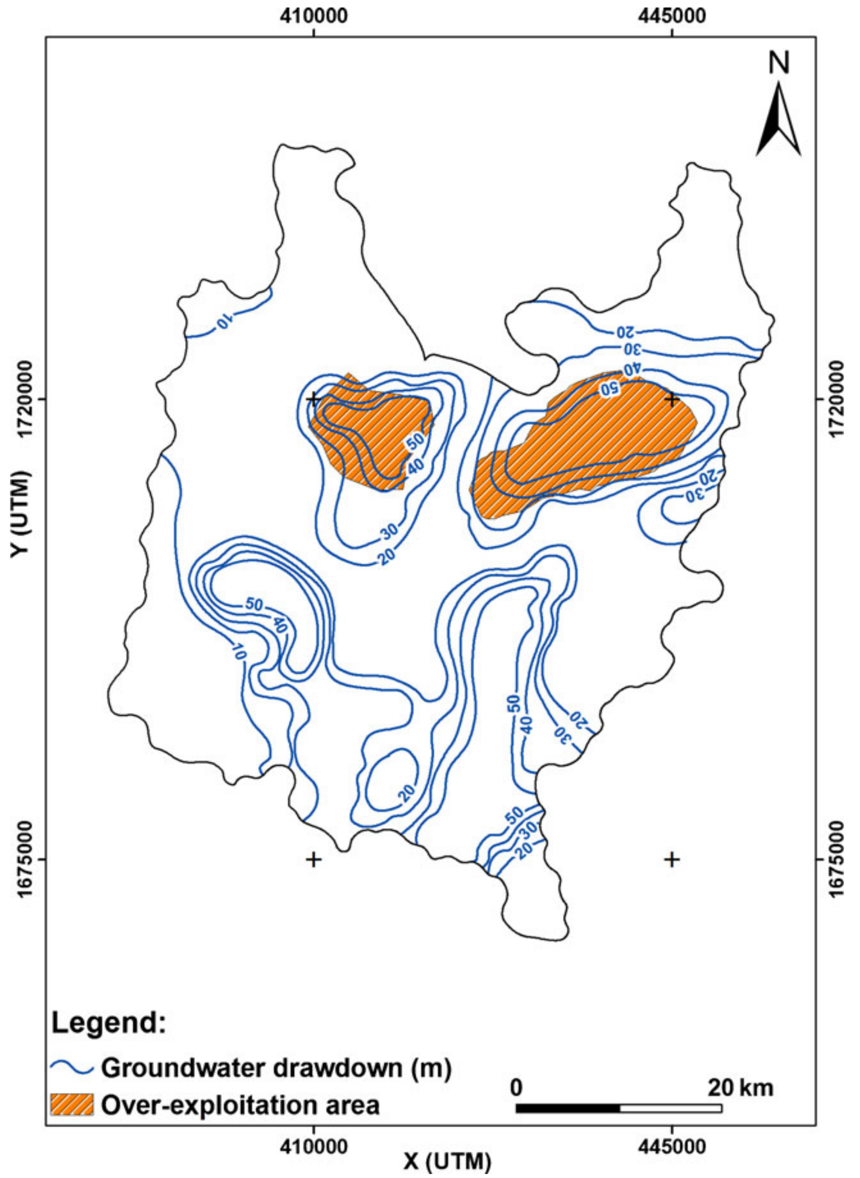

**Fig. 16** Groundwater drawdown, and expected over-exploitation areas for the year 2020 (scenario 1)

million by 2020). For domestic consumption, we used the forecast by the National Water and Sanitation Authority in 2000 (JICA 2007), which is the full service option of 80 L/day. For agricultural consumption, we used forecasts given by the *Agricultural statistics year book 2005* (CSO 2005b), which are based on the annual growth of the irrigation area between 2006 and 2020. For 2006 and 2020, predicted estimations of irrigation area are 18,954 and 21,738 ha, respectively (CSO 2005b). The total forecast for water demand is show in Fig. 17.

The contours of drawdown for the second scenario at 2020 are shown in Fig. 18 with a drawdown of more than 90 m in the north-eastern, the eastern and north-western parts of the basin, 70 m in the central part, and more than 110 m in the western part. The predicted overexploitation areas by 2020 for the second scenario are in one main zone which is located in northern part of the basin, and covers approximately 625 km$^2$ (Fig. 18). This zone will become the driest zones of the basin because of a complete dewatering of the aquifer by this 2020.

The third scenario simulates the effect of water augmentation, i.e. the increase of groundwater recharge based on government strategies to increase recharge in

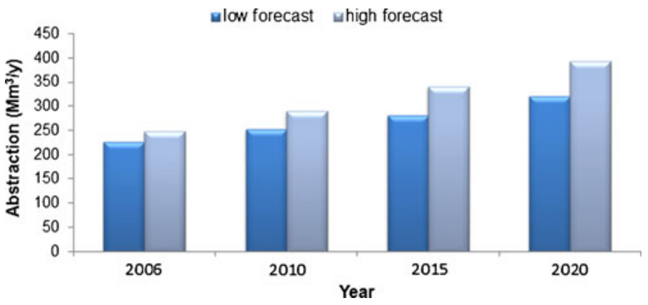

**Fig. 17** Forecast pumping rates during the period 2006–2020 for second and third scenario

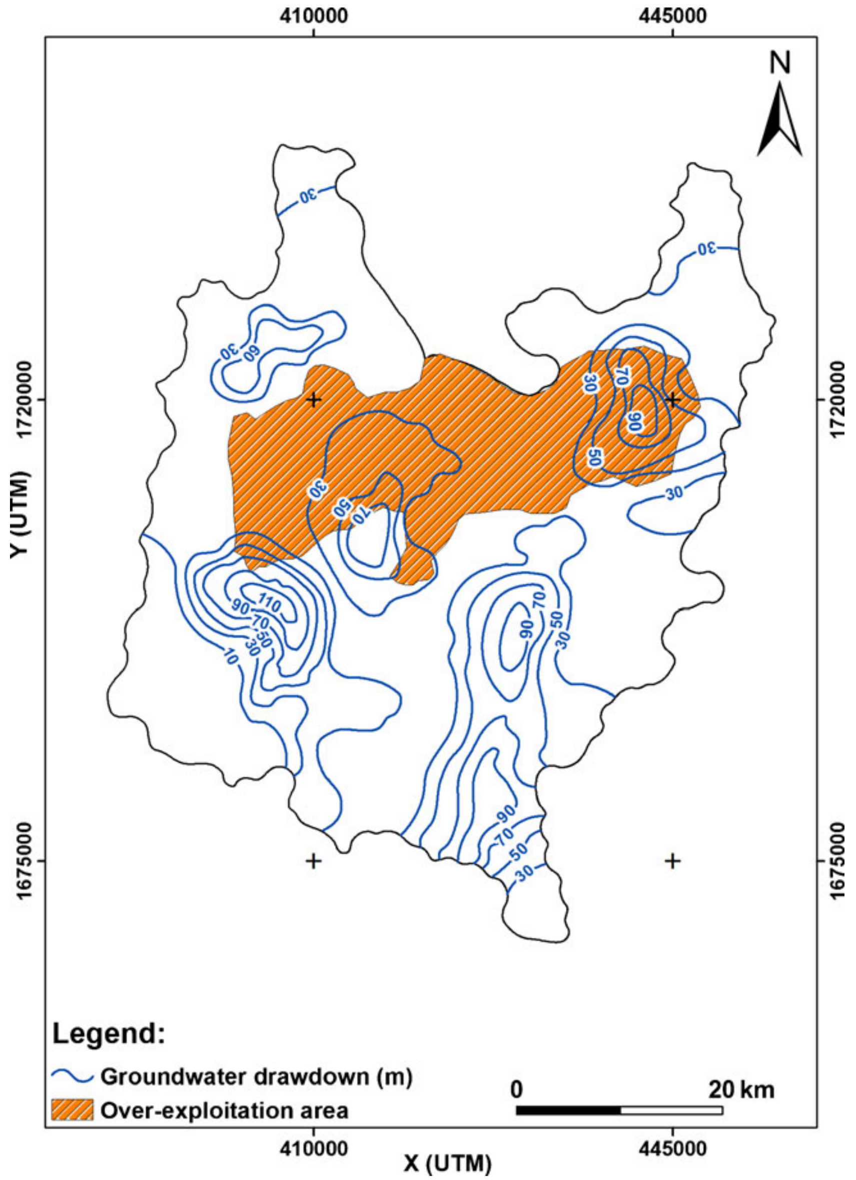

**Fig. 18** Groundwater drawdown and expected over-exploitation areas for the year 2020 (scenario 2)

some selected sub-basins and maximize sustainability by reducing consumption of water resources by using modern methods of irrigation. In this scenario we used low forecast water demand (Fig. 17). The government strategy to increase recharge by artificial recharge can be carried out through the reservoirs of dams in some sub-basins (Fig. 19). Table 3 shows annual average recharge from some dammed reservoirs in Sana'a Basin during the period 2002–2007 (Aderwish 2010).

Our simulations show a reduced rate of drawdown, especially in the middle and north-eastern parts of the basin owing to increased groundwater recharge from the reservoirs. The groundwater head would thus show an increase of 48 and 28 m in the north-eastern and the central parts of basin respectively. In this scenario the predicted overexploitation areas were reduced from about 625 to 92 km$^2$ (Fig. 19) because of the artificial recharge via dammed reservoirs during the period 2006–2020.

## Conclusion

The Sana'a Basin was investigated using FEFLOW to simulate 3D groundwater flow under transient conditions. The results of the model calibration show reasonable agreement between observed and calculated water levels for the observation wells. The calibrated model was used to predict the drawdown for the period from 2006 to 2020 under three different scenarios. In the first scenario, the groundwater abstraction and recharge remains steady until 2020, in the second scenario, the groundwater abstraction increases over the same period, while the third scenario simulates the effect of water-resources management and increased recharge in selected sub-basins.

These investigations in Sana'a Basin have shown that the Basin is now within a high water-stress and water-deficiency situation. The results of the model have shown

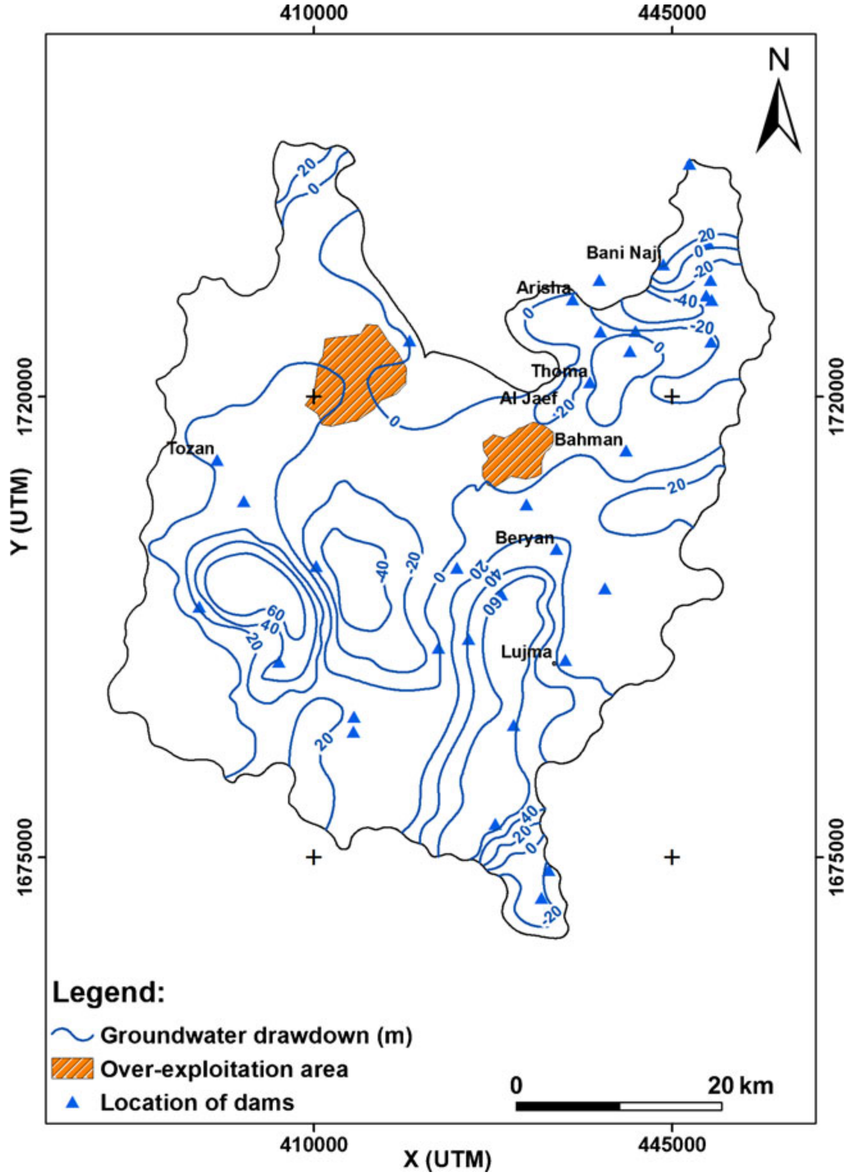

**Fig. 19** Groundwater drawdown and expected over-exploitation areas for the year 2020 (scenario 3)

that the Basin is suffering over-exploitation conditions especially in the north of the basin. The identified areas of the basin that will become the driest by 2020 because of complete dewatering of the aquifer, require prompt action for proper management. These areas must be considered for the implementation of a top-priority pumping-scheme control plan. Meanwhile, measures must be taken to achieve an integrated management plan for the basin.

**Table 3** Annual average recharge from selected reservoirs in Sana'a Basin (Aderwish 2010)

| Dam/ reservoir (see Fig. 19) | Catchment area (km$^2$) | Total runoff (m$^3$) | Evaporation (m$^3$) | Total recharge due to (dam) reservoir (m$^3$) | Natural indirect recharge (without dam) (m$^3$) | Efficiency of recharge due to (dam) reservoir (m$^3$) | Efficiency of indirect recharge (without dam) (m$^3$) |
|---|---|---|---|---|---|---|---|
| Al Jaef | 2.7 | 49,043 | 4,232 | 32,684 | 18,249 | 0.67 | 0.37 |
| Bani Naji | 6.59 | 14,750 | 1,462 | 13,447 | 2,200 | 0.91 | 0.15 |
| Beryan | 10.35 | 106,638 | 30,055 | 60,792 | 38,780 | 0.57 | 0.36 |
| Lujma | 1.30 | 135,875 | 27,831 | 113,502 | 60,511 | 0.84 | 0.45 |
| Mahalli | 13.46 | 209,563 | 44,827 | 171,502 | 79,630 | 0.82 | 0.38 |
| Tozan | 23 | 92,186 | 13.58 | 78,606 | 25,364 | 0.92 | 0.41 |
| Arisha | 6.66 | 115,857 | 17,791 | 71,545 | 53,177 | 0.62 | 0.46 |
| Thoma | 7.25 | 115,857 | 17,791 | 71,545 | 53,177 | 0.62 | 0.46 |
| Bahman | 10.16 | 130,875 | 1,051 | 122,701 | 44,541 | 0.94 | 0.34 |

Development of the groundwater resources involving different methods of water augmentation is recommended.

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