Modelling groundwater flow of the Trifa aquifer, Morocco

Houcyne El Idrysy · Florimond De Smedt

Abstract Trifa is the most productive agricultural plain of north-eastern Morocco. The development of agricultural activities during the last few decades has been mainly based on imported water for irrigation. However, irrigation requirements have become so large that groundwater is used as a secondary source to supply the agricultural and domestic water needs, causing a depletion of the groundwater resources, especially during dry periods. A hydrological and a hydrogeological model for the Trifa plain have been developed, which yield information on relevant parameters such as groundwater recharge, and estimate the amount of pumped groundwater needed to meet the irrigation needs. The models (MODFLOW and WetSpass) provide insight into the status and evolution of the groundwater reserves. The results of the study are useful to predict the sustainability of the groundwater resources in the Trifa plain and to evaluate possible management actions. A reduction in groundwater abstraction by at least 25% may be necessary to achieve sustainable conditions.

Résumé Trifa est la plaine agricole la plus productive du Nord-Est marocain. Le développement de l'activité agricole durant ces dernières décennies a essentiellement reposé sur l'irrigation. Néanmoins les besoins de l'irrigation sont devenus tels que l'eau souterraine est utilisée comme ressource secondaire, pour combler la demande en eau domestique et agricole, induisant un rabattement d'autant plus important durant les périodes sèches. Un modèle hydrologique et hydrogéologique de la plaine de Trifa a été développé sur base des paramètres les plus importants, tels la recharge, et permet d'estimer le pompage nécessaire des eaux souterraines pour combler les besoins de l'irrigation. Les modèles (MODFLOW et WetSpass) apportent une bonne connaissance de l'état et de l'évolution des réserves souterraines. Les résultats de l'étude sont utiles pour prédire la longévité des ressources et pour évaluer différents scénarios de gestion. Une réduction de l'extraction de 25% serait nécessaire pour atteindre un état durable.

Resumen Trifa es la planicie agrícola más productiva del noreste de Marruecos. El desarrollo de las actividades agrícolas durante las últimas décadas se ha basado principalmente en agua importada para riego. Sin embargo, los requerimientos de riego han llegado a ser tan grandes ocasionando que se utilice el agua subterránea como una fuente secundaria para abastecer las necesidades de agua para uso doméstico y agrícola, lo que causa un agotamiento de los recursos de agua subterránea, especialmente durante periodos secos. Se ha desarrollado un modelo hidrogeológico e hidrológico para la planicie Trifa el cual aporta información de parámetros relevantes tal como recarga de agua subterránea y estima la cantidad de agua subterránea que necesita bombearse para satisfacer las necesidades de riego. Los modelos (MODFLOW y WetSpass) aportan una idea acerca del estado actual y la evolución de las reservas de agua subterránea. Los resultados de este estudio son útiles para predecir la sostenibilidad de los recursos de agua subterránea en la planicie Trifa y para evaluar posibles acciones de gestión. Puede ser necesario reducir la explotación de agua subterránea en por lo menos 25% para alcanzar condiciones sostenibles.

Keywords Groundwater modelling · Groundwater/surface-water interaction · Irrigation · Water balance · Water resources sustainability

Introduction

The plain of Trifa, depicted in Fig. 1, is the most productive agricultural area in north-eastern Morocco. It is bounded by the Kiss Wadi in the east which forms the boundary with Algeria, the Beni Znassen Mountains in the south, the Moulouya River in the west, and the Ouled Mansour hills in the north. The major part of the plain of Trifa is located between an altitude of 50 and 150 m. The

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H. El Idrysy (✉) · F. De Smedt
Department of Hydrology and Hydraulic Engineering,
Vrije Universiteit Brussel,
Pleinlaan 2, 1050, Brussels, Belgium
e-mail: hidrysy@yahoo.com

F. De Smedt
e-mail: fdesmedt@vub.ac.be

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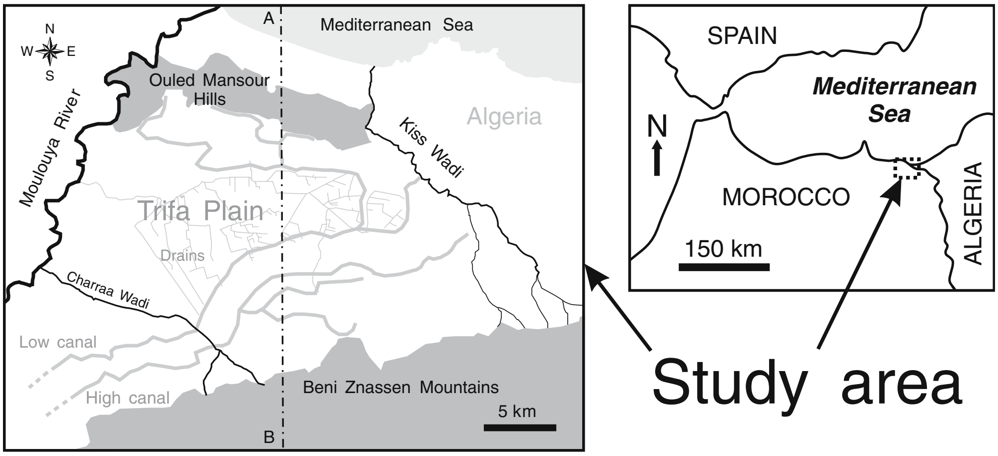

Fig. 1 Location of the plain of Trifa showing geographical and hydrological features (adapted from Anon 1996)

plain drains towards the Mediterranean Sea by its two major rivers: Moulouya and Kiss. In the south of the plain there are several intermittent watercourses. The plain is made up of Quaternary deposits through which rise mountainous secondary deposits in the southern part, as shown in the schematic cross-section given in Fig. 2.

The plain of Trifa has a semi-arid climate with hot and dry summers, and mild and wet winters. This climate is characterized by successive dry and wet periods. Rainfall measurements are available from 13 pluviometers, taken between 1983 and 1995. This is a representative period since it contains equally wet and dry years. The average annual rainfall for this period is about 286 mm. Rainfall mainly occurs in the wet season (October-March) and is generally correlated with altitude. The rainfall is highest in the south limit of the plain near the Beni Znassen Mountains.

Data on the agricultural development, canals, dams and water used for irrigation were obtained from the Office of Agricultural Development in Berkane. Since 1958, due to agricultural development by irrigation, the plain has experienced an important immigration flux from the neighbouring regions. As a consequence, the irrigated area in the plain was extended to about 39,060 ha. These changes influenced qualitatively and quantitatively the water resources on which the agricultural development relies. The plain of Trifa is divided into 12 agricultural zones that are supplied with water imported from two reservoirs: "Mohamed V" and "Machraa Hommadi", located outside of the plain about 60 km to the south-west upstream the Moulouya River. The water is delivered to the Trifa plain by means of a series of canals, shown in Fig. 1. Depending on the topography, the irrigated area is divided into two parts: a lower part irrigated by a canal called 'low' or main canal, and an upper part called 'floors', which is supplied with water by the 'high' canal.

Parts of the Trifa aquifer have been modelled in the past (Khenata and Nakhal 1996; Anon 1996; El Mandour 1998; Jebbari and Lebbe 1999). However, in these models, the hydrogeological setting was very simplified with lumped physical parameters and coarse numerical approximations that did not reflect real-world conditions. In this study, there is an attempt to capture the real conditions in the field by using a multidisciplinary

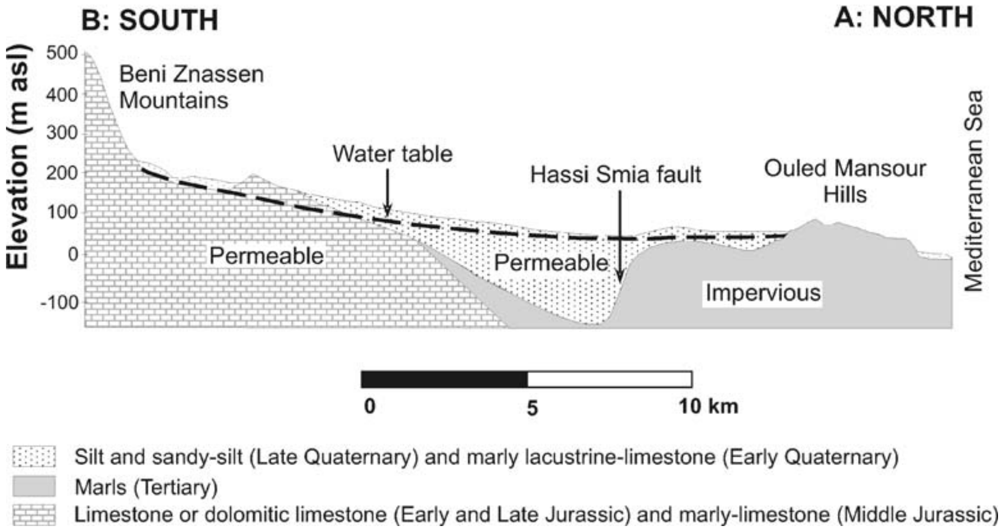

Fig. 2 North-south schematic hydrological cross-section of the Trifa aquifer (adapted from Laouina 1990)

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approach combining geostatistics, and hydrological and hydrogeological modelling. This approach proves to be efficient in analysing the groundwater resources in the area and for predicting water availability and sustainability.

Problem description

General

In the past few decades, agricultural development in the plain has expanded quickly and the need for water has grown continuously. Because the amount of imported water could not keep up with the demand, many wells have been dug and groundwater has been pumped and used as an additional source for irrigation. While the amounts of imported water from the reservoirs are reasonably documented, there is no information about the amounts of pumped and consumed groundwater. There is also little or no control or management of the groundwater reserves and, as a consequence, several problems have occurred in the Trifa aquifer, concerning the quality and quantity of the groundwater. The groundwater quality problem is mainly an increase in salinity that becomes a real threat for the agricultural activities. Concerning the groundwater quantity, two problems occurred in the past: (1) a wetland problem that occurred at the beginning of the agricultural development about 48 years ago because of consecutive wet years and the import of irrigation water from outside the area; a drainage system was progressively installed during the 1960s to deal with this problem (Fig. 1); (2) later on, a marked groundwater depletion occurred caused by prolonged dryness in the 1980s and an increase in groundwater pumping for the expanding agricultural activities. No measures have been taken to deal with the latter problem, because precise information and understanding of the problem is lacking. Hence, in this study, a groundwater flow model is presented and applied, through which an understanding of the aquifer system can be achieved in order to predict future trends and plan management actions.

From 1958 until present, major hydrologic and agricultural changes have taken place in the Trifa plain. Field observations have shown that, since 1958, the evolution of the groundwater levels and salinity became more and more different when compared with the past (Anon 1996). Figure 3 shows the evolution of the hydrological conditions from 1958 to 1998. Shown in the figure are the annual rainfall, the evolution of the average groundwater level in the irrigated areas, and the documented amounts of imported water used for irrigation; data were obtained from the Office Régional de Mise en Valeur Agricole in Berkane, the Direction Générale de l’Hydraulique in Rabat, and Anon (1996). For some years data have been missing or are incomplete. The grey dashed line in Fig. 3 represents the estimated rise in imported water from the reservoirs for irrigation in the initial period when the upper and lower irrigation canals were under construction and no records were made.

From the data shown in Fig. 3, several periods can be distinguished depending upon the agricultural management of the plain, and the evolution in rainfall, groundwater levels, and amount of imported water. From 1958 to 1979, the irrigation canals were constructed and gradually more and more agricultural sectors became irrigated. In 1972, the low canal was completed and the whole area that could be irrigated by this canal was under cultivation. Until that time, records of imported water were incomplete, but from then on amounts of imported water became fairly well documented. The high canal was completed in 1979 and the whole present agricultural area became under cultivation, resulting in a peak amount of imported water of more than 200×10^6 m^3 in 1980. However, this was followed by a very dry period that lasted until 1986. The reservoirs could not keep up with the demand for irrigation water and to compensate for the shortage groundwater pumping intensified, resulting in a marked decline of the groundwater levels. From 1987 onward, rainfall became normal again and the amounts of imported water increased while groundwater pumping decreased, which allowed for a relative recovery of the groundwater levels. Since then, groundwater heads became more or less stationary although never reaching the levels of the past. Obviously, groundwater is still used as a secondary source for irrigation but, unfortunately, there are no records or regulation with respect to groundwater abstraction, so that exact quantities of pumped water remain unknown. As such, it becomes difficult to properly manage water needs and especially the sustainability of the groundwater reserves.

Hydrogeological setting

The groundwater reservoir of Trifa consists of an unconfined aquifer characterized by the presence of two permeable formations and an impervious substratum of different geological ages (Fig. 2). In the north, the aquifer consists essentially of Quaternary deposits underlain by impervious Tertiary marls, while in the south the aquifer is made up of two layers, i.e. Quaternary deposits underlain by pervious secondary formations (de Chevron-Villette 1962; Laouina 1990).

There are two types of groundwater head observations: the first corresponds to a set of measurements from 1972 to 1995, but only in seven observation wells located in the irrigated areas in the central and northern part of the plain. These observations were used to obtain the evolution of the average groundwater level shown in Fig. 3. The second set of groundwater head measurements is available in 59 observation wells that are well spread over the Trifa plain, but only for the years 1995–1996. The locations of the two sets of observation wells are depicted in Fig. 4. These data were obtained from the “Direction Générale de l’Hydraulique”, the central water-management office of Morocco in Rabat.

The values of the second set of observed groundwater levels consist of bi-monthly measurements for the period 1995–1996. An average value was calculated for each

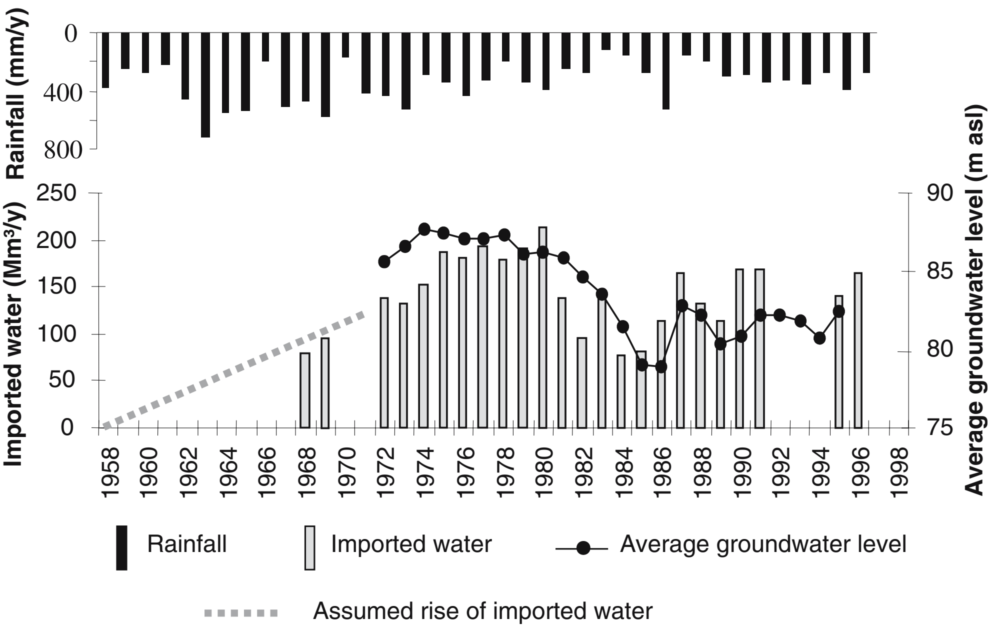

Fig. 3 Evolution of annual rainfall, yearly average hydraulic head, and amount of imported water. Data sources: Office Régional de Mise en Valeur Agricole, Berkane; Direction Générale de l'Hydraulique, Rabat, Maroc; and Anon (1996)

observation well and kriging (Matheron 1965; Delhomme 1978) was used for interpolating these values to obtain an estimated map of the groundwater heads as shown in Fig. 4 (El Idrysy 2003). From this map, one can deduce the direction of the groundwater flow, as shown in the figure. It appears that in the south, groundwater emerges from the Beni Znassen Mountains and flows to the north. Kiss Wadi drains part of that flow, but the majority arrives in the central part of the plain, where the drainage system and most of the pumping wells are situated. Here, the groundwater flow seems to slow down and gradually changes direction to the north-west, where it drains to the Charraa and Moulouya rivers.

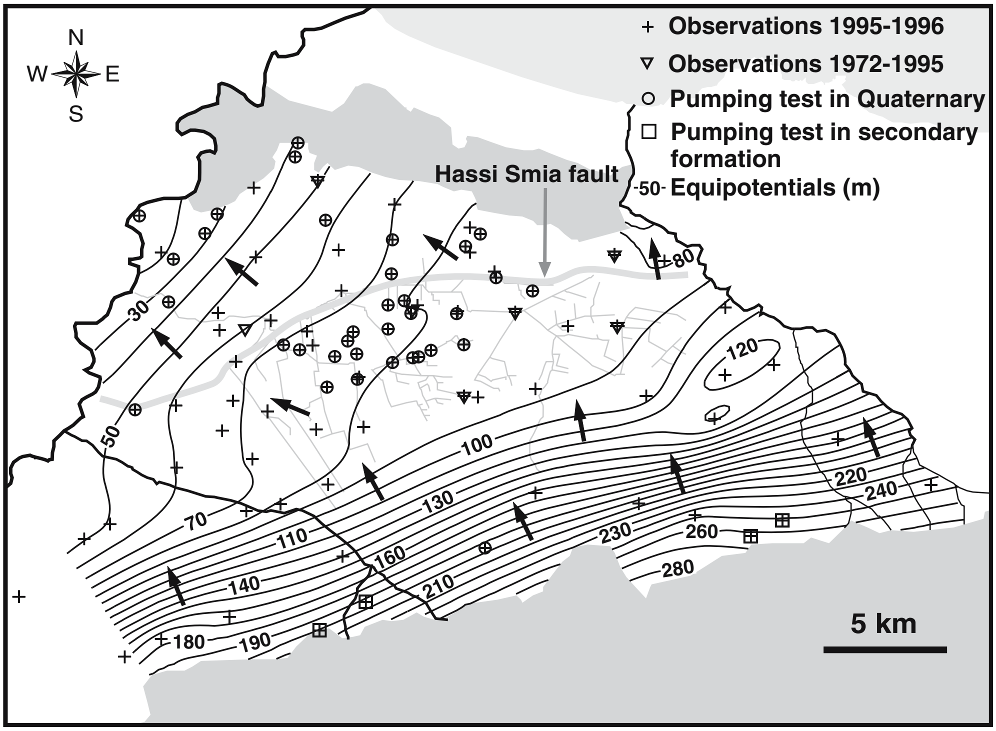

Fig. 4 Average groundwater heads interpolated from bimonthly data of 1995 and 1996, groundwater flow directions, locations of observation wells, and locations of pumping test wells; data source: Direction Générale de l'Hydraulique, Rabat, Morocco

Model development

Model set-up

The groundwater flow is modelled using MODFLOW (McDonald and Harbaugh 1988), in the PMWIN environment (Chiang and Kinzelbach 2001). The aquifer is divided into two layers, i.e. the Quaternary and the permeable secondary formations, and square cells of 200 m. The model is run in steady-state regime to simulate the average behaviour in the period 1993 to 1998.

The two layers of the model are: (1) the upper layer, which represents the Quaternary deposit, with a thickness varying between 30 and about 200 m in the central part of the plain south of the Hassi Smia fault (Fig. 4), and (2) the lower layer, which is distinct from north to south, i.e. in the north the lower layer consists of impervious Tertiary formations and, hence, is inactive, while in the south, the Quaternary is underlain by pervious secondary deposits, which constitute the lower model layer whose base level is not exactly known and therefore, in this study, is set arbitrarily at −150 m below sea level (m bsl). The Quaternary layer is missing in some parts of the plain where underlying layers extend to the surface. This is the case for the Tertiary layer in an area in the west close to the Moulouya River, where, as a consequence, the upper model layer also becomes impervious and inactive; and several zones in the south where the secondary layer punctures through the Quaternary, and where, as a consequence, the first model layer also consists of secondary formations.

A geostatistical methodology was developed to estimate the thickness and base of the Quaternary layer from drilling and geo-electrical sounding data (El Idrysy and De Smedt 2004). Geostatistical methods were also used to estimate the hydraulic conductivities of the Quaternary and secondary formations, based on pumping tests and other observed secondary data as electrical resistivity and groundwater heads, as explained in the literature (Kelly 1977; Kwader 1985; Ahmed et al. 1988). Pumping tests in the Quaternary deposit are available in 34 locations, and in 4 locations for the secondary deposit, as shown in Fig. 4. Several geostatistical techniques were tested and compared such as kriging, cokriging, and kriging with external drift, to determine the spatial variability of the hydraulic conductivity, and the best results were selected for use in the groundwater flow model (El Idrysy 2003. The obtained maps of hydraulic conductivity are shown schematically in Fig. 5. The hydraulic conductivity of the Quaternary, shown in Fig. 5a, was obtained by cokriging data from pumping tests with the slope of the water table as the secondary variable, which proved to be more accurate than kriging or cokriging with electrical resistivity measurements (El Idrysy 2003). The hydraulic conductivity of the Quaternary ranges from more than 90 m/d in the centre of the plain, and decreases towards the outer parts of the aquifer to less than 10 m/d. This variation can be explained by the geological history of the Trifa region that underwent a subsidence in the late Quaternary, as reported by de Chevron-Villette (1962), resulting in more permeable sediments in the central part of the plain south of the Hassi Smia fault. The extent of the Quaternary layer is depicted in Fig. 5a by grey shading; the empty spaces correspond to areas where the Quaternary is missing and underlying formations rise to the surface. The hydraulic conductivity of the secondary formations, shown in Fig. 5b, was estimated by cokriging with pumping tests as the primary variable and more abundant electrical resistivity data as the secondary variable (El Idrysy 2003). The hydraulic conductivity of the secondary deposits is generally less than 2 m/d. The grey shading in Fig. 5b shows the extent of the pervious secondary formations that are in direct contact with the Quaternary in the south part of the study area.

Boundary conditions

The aquifer limits can be described by natural or hydrological boundaries, as shown in Fig. 6. The south boundary of the plain is formed by the Beni Znassen Mountains, made up of permeable limestone deposits. These mountains 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 Trifa plain. Also, the geological build-up of the aquifer in the south promotes a steady feed from the groundwater reserves in the Beni Znassen Mountains to the Trifa plain, since the altitude (about 1,500 m asl) and extension of these mountains allow for collection of large amounts of rainfall that will subsequently percolate under the influence of gravity through the permeable limestone deposits to the Trifa plain. This can also be clearly noticed from the map of observed groundwater heads (Fig. 4), where the groundwater levels keep rising from the centre of the plain towards the Beni Znassen Mountains in the south. The steep hydraulic gradient in the south part of the plain near the mountains reflects the low conductivity of the limestone deposits (Fig. 5). Unfortunately, there are no precise data about the precipitation and evaporation in the Beni Znassen Mountains, and hence, the magnitude of the groundwater inflow from these mountains to the plain cannot be quantified exactly. Because the only source of information are the observed groundwater levels shown in Fig. 4, this boundary was modelled as a constant head condition, with hydraulic head values taken from the observed water levels given in Fig. 4. Assigning variable heads to this boundary would be a more accurate approach but, apart from the 1995 and 1996 data, measurements of the hydraulic head over larger time periods are only available in a very limited number of observation wells, none of which are located near the south boundary. Hence, the constant head boundary is a simplification, as the inflow from the mountains is possibly influenced by dry and wet periods, although the precipitation in the mountains is less affected by climatologic conditions than in the Trifa plain. The constant head boundary condition is applied to both model layers.

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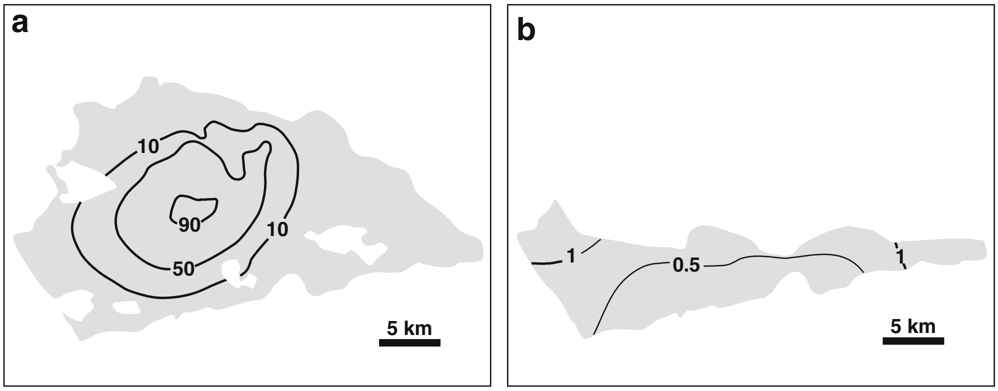

Fig. 5 Hydraulic conductivity (m/d) in: **a** Quaternary, upper model layer, and **b** secondary formations, lower model layer

In the south-west, one assumes a groundwater flow line running from the Beni Znassen Mountains to the Moulouya River, as shown in Fig. 6. This implies that no groundwater can cross this boundary in both model layer and is effectively incorporated in the model as an impervious boundary condition.

The Moulouya River forms the north-west boundary of the study area. Because of its perennial nature, the Moulouya River is considered as a river boundary condition independent of the state of the aquifer, with water levels as derived from the observed water levels adjusted by topographic observations. As there are no data to estimate the river conductance, an arbitrary large value is used to ensure a good contact between the river and the aquifer. The river boundary condition is applied to the upper layer of the model only, while for the lower layer the boundary is considered impervious.

In the north, because they are made up of Tertiary marl deposits, the Ouled Mansour hills are considered as an impervious boundary in both model layers. A small section in the northwest, where the hills flatten, is made up of Quaternary deposits, through which groundwater can flow to the coastal plain and Mediterranean Sea. This section is simulated as a potential boundary condition, with constant groundwater heads obtained from observations in the upper model layer only, as the lower model layer is ineffective here (impervious Tertiary deposits).

The east boundary, consisting of the Kiss Wadi, is simulated as a drain, such that it can fall dry when groundwater becomes depleted and groundwater levels

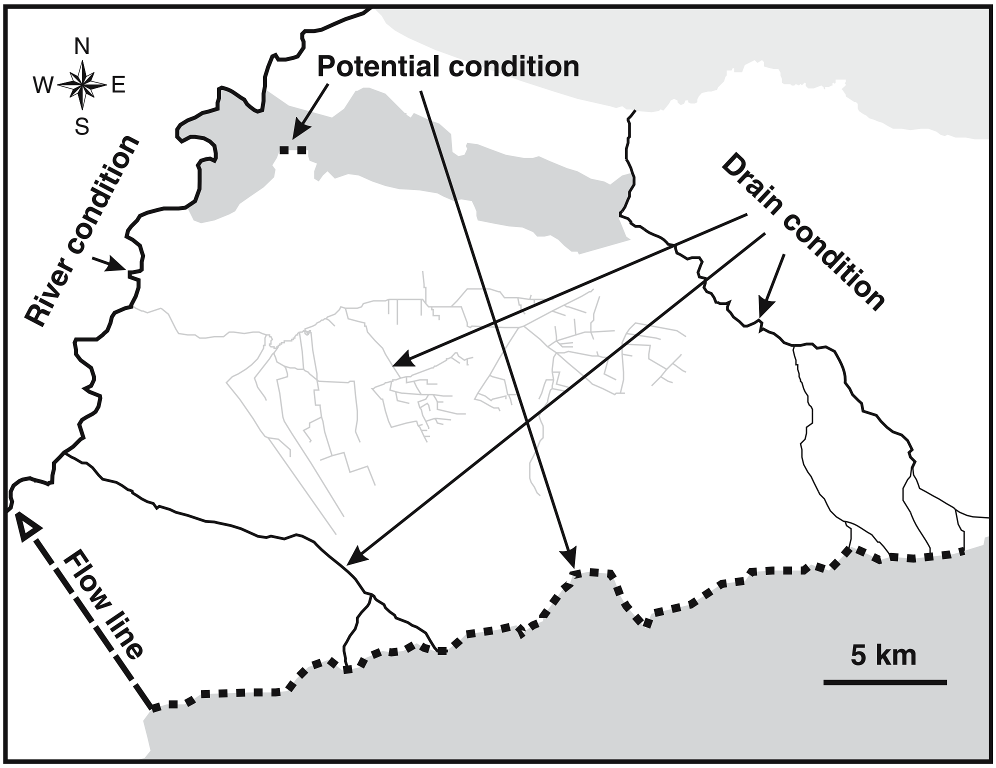

Fig. 6 Boundary conditions for the groundwater flow model

drop below the draining level. The drain conductance is taken as an arbitrary large value to ensure that the wadi becomes active as soon as groundwater levels are higher than the elevation of the wadi. This boundary condition is applied to the upper layer of the model only, while for the lower layer, the boundary is considered impervious. Also, all internal intermittent watercourses and wadis, as well as the drainage systems, are simulated as drains located in the upper layer of the model, with large conductance values.

Estimation of recharge and annual amount of groundwater pumping

The groundwater recharge and the pumped amount of groundwater for irrigation are calculated using the distributed hydrological model WetSpass. This model was developed in the Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, and is explained in detail in several publications, e.g. Wang et al. (1996); Batelaan and De Smedt (2001), and Batelaan et al. (2003). WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State. It is an embedded ArcView raster GIS model, coded in Avenue (Asefa et al. 1999), a programming language integrated into ArcView. The model provides understanding and quantification of the interactions between atmosphere, surface water and groundwater, and yields spatially varying groundwater recharge needed for further use in the groundwater modelling and simulations. In addition, it allows for the estimation of other spatially distributed seasonal hydrological components, as potential and actual evapotranspiration, surface runoff, interception, and infiltration. The input to the model consists of seasonal meteorological data and physical parameters like soil type, topography, land-use, groundwater depth, and rainfall amounts.

For the period 1993–1998, average seasonal rainfalls were calculated: i.e. the sum of rainfall of the months corresponding to dry and wet season, where dry season is assumed from October to March and wet season from April to September. Measured rainfall amounts from different stations were interpolated by kriging to obtain distributed maps of seasonal rainfall. It is clear that rainfall occurs mainly in the wet season (October–March) and is generally correlated with altitude. In the south limit of the plain near the Beni Znassen Mountains, rainfall is highest, whereas precipitation becomes less towards the northern and western parts of the plain with lower topographic elevation. In order to take into account the effect of imported water, the quantities of water used for irrigation in the different agricultural sectors were added to the rainfall.

The WetSpass model calculates different maps of actual evapotranspiration, surface runoff, and groundwater recharge for each season. The resulting average annual groundwater recharge for the period 1993 to 1998 is shown in Fig. 7. This average annual groundwater recharge is calculated as the sum of the seasonal recharges, but it is clear from the WetSpass simulation results that groundwater recharge occurs mainly in the wet season. The recharge is due to rainfall but also partially to irrigation with imported water in the cultivated areas. The highest amount of recharge, about 200 mm/y or somewhat more, occurs in the eastern part of the plain where there is more rainfall due to the higher elevation. In the irrigated areas situated in the central part of the plain the recharge amounts to about 150 mm/y.

From the results of the WetSpass model, it is also possible to estimate the groundwater pumping. The amount of groundwater used for irrigation is considered to be equal to the quantity of water needed to meet the potential evapotranspiration demand, assuming that all excess pumped water returns back to the aquifer as infiltration (irrigation return flow; Alley et al. 1999; Kendy 2003). Hence, the net groundwater pumping is considered to be equal to the evapotranspiration deficit, i.e. the difference between potential and actual evapotranspiration, which can be evaluated from the WetSpass simulation results. The obtained distribution of groundwater abstraction, in mm/y, is shown in Fig. 8. Groundwater pumping is restricted to the agricultural areas and varies between zero and 500 mm/y, corresponding to a maximum pumping rate of about 1,370 m^3/d in an area of 1 km^2. As can be expected, the central part of the plain that receives most water for irrigation from the reservoirs needs less water from groundwater pumping wells. Nevertheless, the groundwater abstraction in the centre of the plain varies between 200 to 400 mm/y, or about 300 mm/y on average, i.e. about 820 m^3/d per km^2. Some agricultural areas in the north-west and in the south need more groundwater pumping to meet the irrigation needs because they receive smaller amounts of water from the reservoirs; here groundwater pumping can amount to more than 400 mm/y or about 1,090 m^3/d per km^2. When quantities of groundwater recharge and pumping are compared, it turns out that the groundwater recharge is less than groundwater abstraction everywhere in the irrigated areas. The information on groundwater recharge and pumping obtained with WetSpass is used in the groundwater flow model as input conditions.

Model results and discussion

General results

The simulated groundwater heads in the top model layer are shown in Fig. 9; groundwater heads in the second layer are similar. The simulated groundwater levels show a distinct pattern, i.e. starting from the highest levels in the south (about 200–280 m asl), decreasing to the centre of the Trifa plain at about 80 m asl, and from there decreasing in different directions to the rivers at elevations of 50–20 m asl. In the south, where the groundwater flow is essentially governed by the less conductive secondary layer, the equipotential lines are spaced very close to each other. Some local abrupt variations occur in areas where the Quaternary deposits are lacking and secondary formations rise to the surface. On the other hand, in the central part of

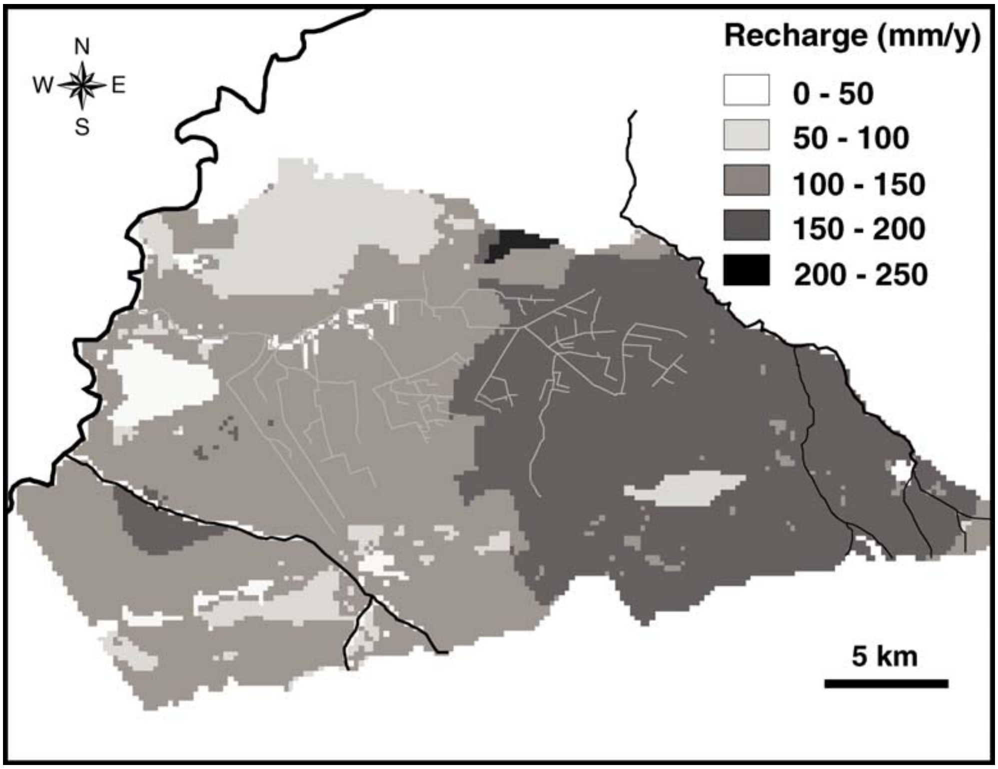

Fig. 7 Annual groundwater recharge (mm/y) estimated with the hydrological WetSpass model (1993–1998)

the plain, the equipotential lines of the groundwater heads are very widely spaced, which is the result of the high hydraulic conductivity in this region and also of the effects of the drainage system and groundwater abstractions in this area, as will be discussed further on.

From the shape and pattern of the groundwater potentials in the southern part of the plain, one can clearly

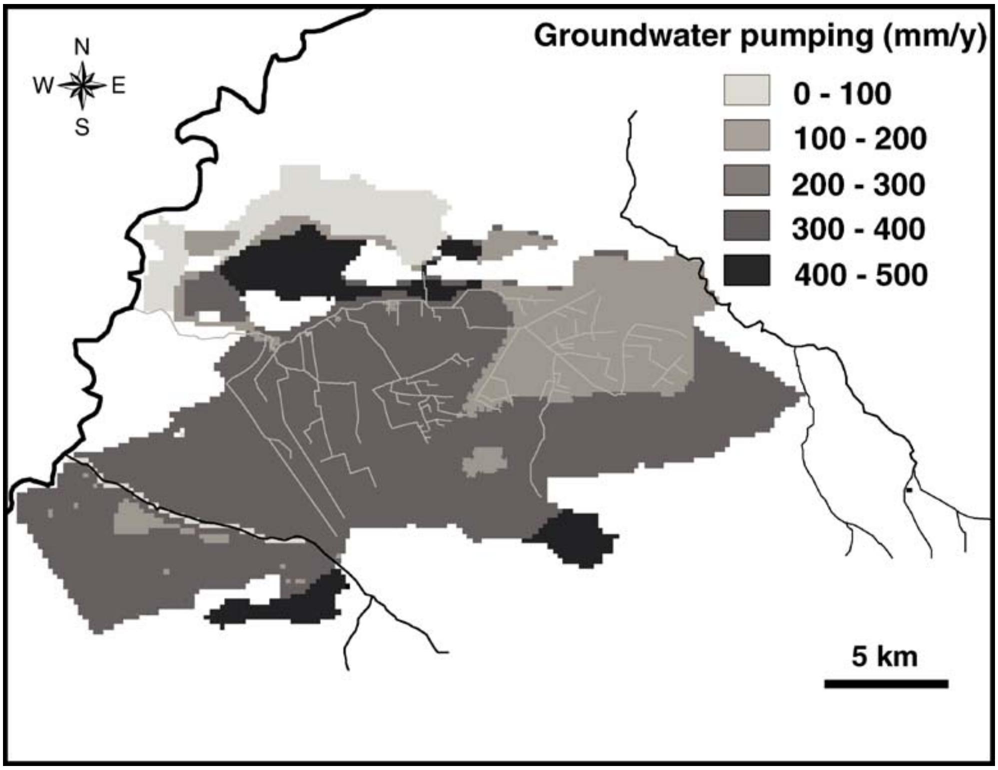

Fig. 8 Annual groundwater pumping (mm/y) estimated with the hydrological WetSpass model, estimated as the deficit between potential and actual evapotranspiration

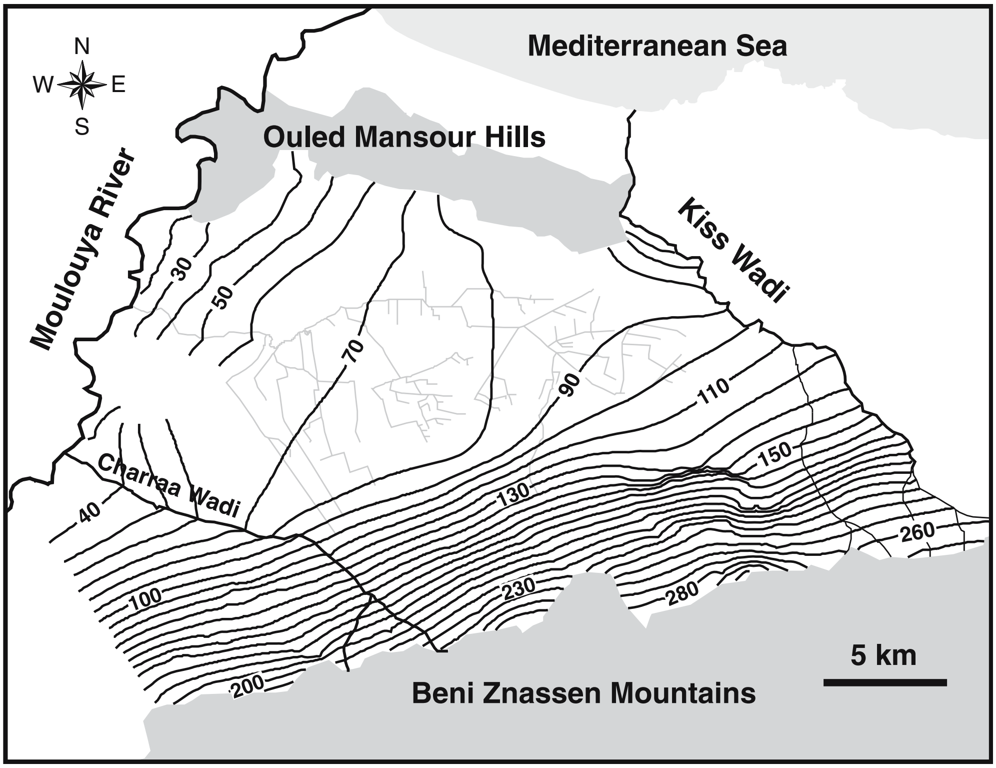

Fig. 9 Simulated groundwater heads in the top model layer. Groundwater heads in the second layer are similar

deduce that the Beni Znassen Mountains are an important source of groundwater input to the Trifa aquifer. Part of that groundwater flow is drained by the Kiss Wadi in the east and by the Charraa Wadi in the west, but the majority arrives in the centre of the Trifa plain. Together with the groundwater recharge, this forms the major source of groundwater that is exploited for irrigation purposes. The convex shape of the 80 m potential line indicates that a substantial amount of groundwater is removed from the aquifer in the centre of the plain. This could be either due to drainage system or to groundwater pumping. Closer inspection of the groundwater heads compared to the level of the drainage system shows that the drainage system is largely ineffective, because groundwater levels are lower than the drainage level. Hence, the larger part of the groundwater is lost by pumping wells. Some of the remaining groundwater flows to the north-west where it drains to the Moulouya River.

Model verification

The average groundwater head observations in the 46 observation wells for the years 1995–1996, are compared to the simulated groundwater heads in Fig. 10, and yield a maximum deviation of 5 m and a correlation coefficient of 0.99. One can notice from this figure that the model performs rather well without any bias or abnormal deviations. This rather good result has been achieved without any model calibration.

In many groundwater models, hydrogeological parameter estimation often remains the most difficult problem that many studies try to overcome by assigning a uniform spatial distribution or by dividing the parameter values into classes corresponding to different parts of the area, which can be adjusted by calibration. In this study, the model parameters are fully physically distributed and have been estimated independently from the model so that calibration is not necessary. When injected in the model,

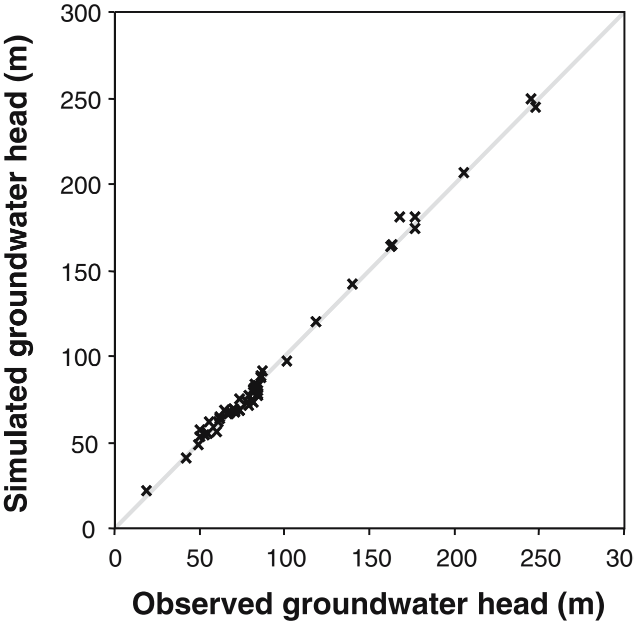

Fig. 10 Comparison of measured and simulated groundwater heads (m asl)

these already estimated parameters satisfactorily reproduce the observations as shown in Fig. 10, and consequently accurately describe the distributed and complex behaviour of the hydrogeological conditions in the Trifa plain. Also, the groundwater recharge, which is often a very uncertain parameter in groundwater modelling, and the groundwater pumping, which is uncontrolled and consequently unknown in the Trifa plain, have been estimated in this study independently using the WetSpass hydrological model which takes into account the spatially distributed variation of soil type, land-use, topography and climatologic conditions.

Hence, the good results obtained with the model without calibration, proves the usefulness and effectiveness of the present multidisciplinary approach based on geostatistical and GIS tools to deal with the spatial distribution of hydrological and hydrogeological parameters, and to accurately describe the interaction of the groundwater system with its environment.

Water balance

The water budget of the entire aquifer obtained from the groundwater flow model is presented in Table 1. Budget terms are expressed in Mm^3/d and are considered positive when entering and negative when leaving the groundwater system. The total water budget over the entire aquifer shows a perfect balance between inflows and outflows of water, which is consistent with the steady state modelling hypothesis. The last column of Table 1 gives the different water-balance terms as percentage of the total input or output. The last row of Table 1 gives the yearly average amount of imported irrigation water in the period 1993 to 1998 for comparison.

Groundwater inflow from the Beni Znassen Mountains supplies the aquifer with most of its water. This amounts to more than 200 Mm^3/d, or about 76% of the total input to the Trifa aquifer. However, one should keep in mind that the south boundary is modelled as a constant potential, based on observations in years 1995 and 1996, which had a normal rainfall. This simplification could lead to erroneous estimates of the inflow in other periods, in particular an overestimation in dry periods. On the other hand, the rainfall in the Beni Znassen Mountains is much larger than in the plain and consequently less affected by drought. In addition, a decline of the groundwater levels in dry periods, caused by increased groundwater pumping for irrigation in the agricultural areas in the centre of the plain, give rise to larger hydraulic gradients that can invoke more groundwater flow from the south. Hence, the error arising from the constant potential boundary assumption at the Beni Znassen Mountains is probably mild. A second important source of water is the recharge, which is due to precipitation but partially also to excess irrigation. However, the total amount of recharge is much less than the groundwater inflow from the Beni Znassen Mountains. The recharge amounts to only 68 Mm^3/d, which only represents 24% of the total inflow of water in the aquifer on average. There are no other inputs of water to the groundwater system.

Table 1 Groundwater budget achieved from the groundwater flow model

Water balance term	Mm^3/y	%
Inflow from the Beni Znassen Mountains	216	76
Outflow to the coastal plain	−2	−1
Groundwater recharge	68	24
Outflow to wadis and drains	−194	−68
Outflow to the Moulouya River	−5	−2
Groundwater abstraction	−83	−29
Total inflow	284	100
Total outflow	−284	−100
Imported water for irrigation	152	54

The main outputs of water from the aquifer are drainage to wadis and to the drainage system in the centre of the plain and groundwater abstraction by pumping wells. The drainage amounts on average to −194 Mm^3/d, which represents about 68% of the total outflow. This drainage is mainly directed to the Kiss Wadi in the east and the Charraa Wadi in the west, while the drainage system in the agricultural area in the centre of the plain is largely ineffective because groundwater levels are too low compared to drain levels, as stated before. Groundwater drainage to the Moulouya River is rather small compared to the other terms in the water balance, i.e. on average only about −5 Mm^3/d, or 2% of the total outflow. Also, the amount of groundwater outflow to the coastal plain in the north is very small and not important in the overall water balance. This boundary was also modelled as a potential condition and might therefore be less accurately estimated.

Groundwater abstraction in agricultural areas, mainly situated in the centre of the plain, constitutes the second most important loss term in the groundwater balance. Groundwater abstraction amounts to −83 Mm^3/d or about 29% of the total outflow. Notice that the amount of groundwater abstraction is larger than the groundwater recharge, which clearly reflects the agricultural activities and need for irrigation water. Also, the amount of imported water for irrigation compared to the total groundwater balance shows that the agricultural need of water for irrigation is far above the capacity of the groundwater reservoir. Hence, the import of water from outside the plain is a necessity for continued agricultural activities and needs to be maintained and secured in the future. Otherwise groundwater abstraction will lead to groundwater mining especially in dry years, and long periods of drought will cause serious decline of groundwater levels and possible unrecoverable exhaustion of the groundwater reserves.

The above considerations make it clear that the Trifa aquifer is under considerable stress. The main natural source of water is the Beni Znassen Mountains, which however is limited in magnitude, i.e. this will not increase to accommodate any depletion of groundwater reserves in the Trifa plain. The second natural source is groundwater recharge, which, however, is very variable and in case of drought almost nil. Hence, as long as groundwater pumping is larger than the average groundwater recharge, the groundwater reserves will become unbalanced and groundwater levels will decline in time. Remediation is only possible by reducing groundwater abstraction or, if the agricultural activities are maintained, by increasing the import of water from outside of the plain by the same amount. A reduction of groundwater pumping by an amount of 30,000 m^3/d, or about 25% of the present use, would at least be necessary to achieve sustainable conditions, and even then the situation will be far from normal and needs to be closely monitored to avoid unrecoverable damage to the groundwater reserves and loss of sustainability especially in case of drought.

Conclusions

The plain of Trifa is the most productive agricultural area in north-eastern Morocco. In the last decades, the agricultural activities in the plain have grown continuously by importing water for irrigation. Gradually this became insufficient and groundwater pumping wells were installed to satisfy the need of irrigation water. While the amounts of imported water for irrigation are reasonably documented, there is no information about the amounts of pumped and consumed groundwater. In this study, the effect of the agricultural development in Trifa on the groundwater resources is investigated by means of a hydrological and hydrogeological model.

More insight into the functioning of the Trifa aquifer system is obtained with the present methodology that combines groundwater and hydrological modelling. The WetSpass hydrological model is used to estimate the groundwater recharge and the effective groundwater use, assuming that the groundwater abstraction is equal to the difference between potential and actual evapotranspiration. The highest amount of recharge occurs in the eastern part of the plain where there is more rainfall due to the higher elevation, while in the irrigated areas in the centre of the plain the recharge is less. These areas receive most of the imported water for irrigation but still need additional groundwater abstraction to meet the agricultural needs. When groundwater recharge and abstraction are compared, it turns out that the groundwater recharge is less than groundwater abstraction everywhere in the irrigated areas.

The groundwater flow is modelled using MODFLOW in the PMWIN environment. The model results correspond closely to what is observed in the field, without model calibration. The groundwater model gives insight about the groundwater reserves and the different processes that govern the groundwater balance. The main inputs to the Trifa aquifer are inflow from the Beni Znassen Mountains and recharge, including irrigation return flow. The main outputs are drainage to wadis and groundwater abstraction by pumping wells. However, the results show that the situation is far from sustainable, because the total amount of groundwater abstraction for irrigation is larger than the groundwater recharge, which in the long term will undermine the capacity and sustainability of the aquifer. It is proposed that groundwater abstraction should be diminished in order to reach a sustainable situation, and even then, in the case of a prolonged drought, severe problems can still occur.

The model and the obtained results can be an important tool for prediction and risk assessment. Future agricultural practice and surface or subsurface water management can be forecasted and appropriate measures foreseen. Mitigating measures can be investigated, as artificial groundwater recharge in wet seasons, when rainfall is abundant and no irrigation is needed. More sustainability could be obtained when carefully analysing which type and quantities of water to use in each agricultural sector of the plain. Thereby, some sectors could receive more imported water to reduce the need of groundwater pumping, while other sectors as those close to the Beni Znassen Mountains could rely more on groundwater.

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