17 Simulation of Flow in Weathered-Fractured Aquifer in a Semi-Arid and Over-Exploited Region

Shakeel Ahmed and P.D. Sreedevi

Indo-French Centre for Groundwater Research
National Geophysical Research Institute, Hyderabad 500 007, India

INTRODUCTION

The granites in and around Hyderabad, India, form part of the largest of all granite bodies recorded in Peninsular India. Alcaline intrusions, aplite, pegmatite, epidote, quartz veins and dolerite dykes traverse the granite. There are three types of fracture patterns (Fig. 1) in the area, viz. (i) mineralised or weathering fractures, (ii) fractures traversed by dykes, and (iii) late-stage fractures represented by joints. The vertical fracture pattern is partly responsible for the development of the weathered zone and the horizontal fractures are the result of the weathering. Hydrogeologically, the aquifer occurs both in the weathered zone and in the underlying weathered-fractured zone. The Maheshwaram watershed of about 53 km^2 in the Ranga Reddy district (Fig. 2) of Andhra Pradesh, India, is underlain by granitic rocks. This watershed is a representative Southern India catchment in terms of over-exploitation of its weathered hard rock aquifer, its cropping pattern, rural socio-economy, agricultural practices and semi-arid climate. The objective of this study is to develop and test well-suited modelling approaches to simulate the flow in the existing aquifer system that consist of two layers with any separating strata.

However, due to deep drilling and heavy groundwater withdrawal, the weathered zone has now become dry. About 150 dug-wells were examined and the nature of the weathering was studied. The weathered-zone profiles range in thickness from 1 to 5 m below ground level (bgl). They are followed by semi-weathered and fractured zones that reach down to 20 m bgl. Joints

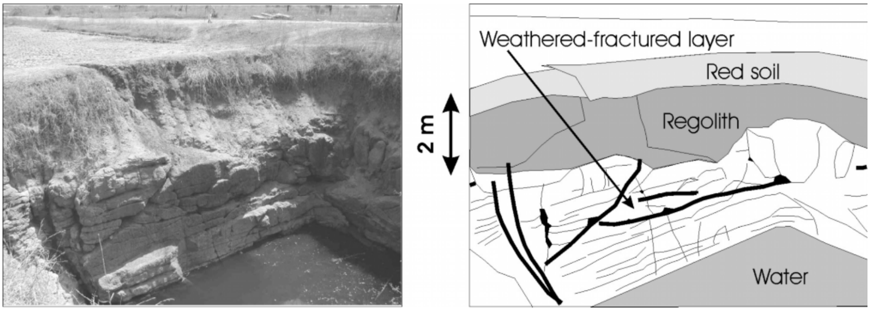

Figure 1. Cross-section of the typical substratum in a dug-well.

are well developed in the main directions: N 0°–15°E, NE-SW, and NW-SE that vary slightly from place to place. The groundwater flow system is local, i.e. with its recharge area at a topographic high and its discharge area at a topographic low adjacent to each other. Intermediate and regional groundwater flow systems also exist since there is significant hydraulic conductivity at depth. Aquifers occur in the permeable saprolite (weathered) layer, as well as in the weathered-fractured zone of the bedrock and the quartz pegmatite intrusive veins when they are jointed and fractured. Thus only the development

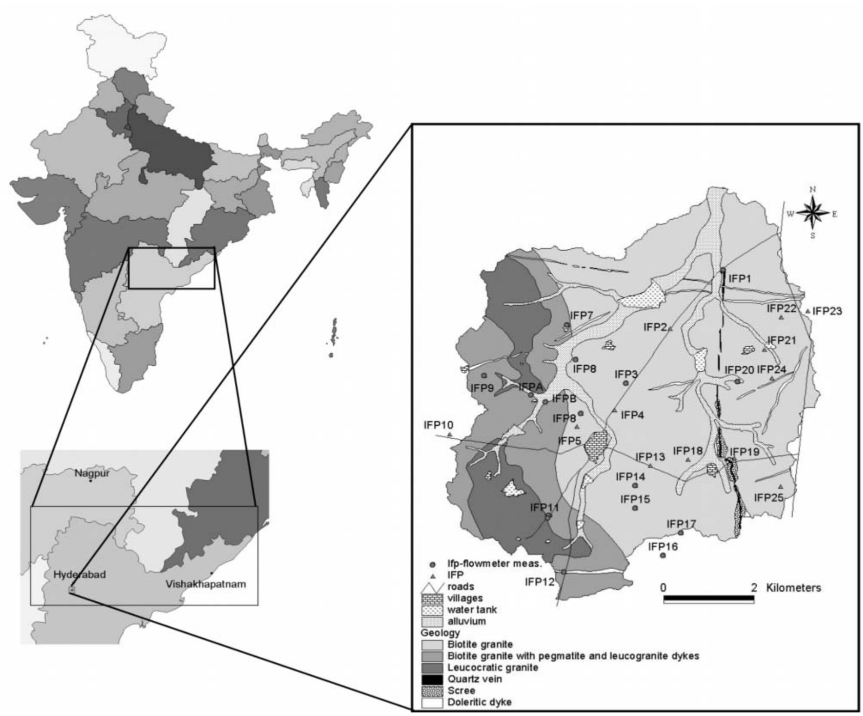

Figure 2. Maheshwaram hard rock watershed in Ranga Reddy Dist., Andhra Pradesh.

of the saprolite zone and the fracturing and interconnectivity between the various fractures allow a potential aquifer.

Mean annual rainfall is about 750 mm, the mean annual temperature is about 26 °C, although in summer, the maximum temperature can reach 45 °C. The resulting potential evaporation transpiration is 1,800 mm/year. The annual rainfall is around 750 mm and the recharge around 10-15 %.

NUMERICAL MODELLING OF AQUIFER FLOW IN MAHESHWARAM WATERSHED

The Maheshwaram watershed was modelled with the MARTHE software developed at the BRGM (French Geological Survey, Thiery, 1993). MARTHE is a transient hydrodynamic modelling code, representing three-dimensional and/or multi-layer flow in aquifers. The solution method uses finite differences with a rectangular grid and offers the possibility of having a free surface in a mesh of any layer.

Model Fabrication

The studied aquifer was represented by a two-layer aquifer flow system. The upper layer for the weathered zone, the lower one in the weathered-fractured granite represented as an equivalent porous medium. Each layer was divided into 5,272 square meshes with a 100-m side (Fig. 3). Layer 1 is unconfined and layer 2 is confined but may become unconfined when layer 1 becomes dry. The MARTHE code is used with its coupled climatic-balance model (GARDENIA: Thiéry and Boisson, 1991). The groundwater flow in the Maheshwaram watershed is simulated in transient regime in order to represent the piezometric variations observed in the wells in the studied area from January 2001 to July 2003.

The thickness of the weathered layer was estimated by kriging from the measurements made in the 25 existing lithologs and the Vertical Electrical Sounding (VES) interpretations (Krishnamurthy et al., 2000). The geometry of the weathered-fractured granite layer was deduced jointly from the total depth of the 900 inventoried wells in the watershed after removing the wells with a total depth of more than 70 m and from the result of the VES. Figure 4 shows the aquifer geometry with bottom of each layer above mean sea level.

Boundary Conditions

The topographical limits of the watershed were taken as the groundwater divides (no-flow boundaries), except at the northern limit where a non-perennial stream at the outlet of the watershed can evacuate the surface water. At this location, the hydraulic heads were prescribed and set the average of the 2000-2002 measured field values.

The streams flow only during heavy rainfall for a few hours in a year due to very rare runoff. That is why, as a first approximation, the role of the hydrographic network in recharging the aquifer is assumed to be negligible. The hydrographic network in the study area includes a few low order ephemeral streams connected to a surface storage tank. The assumption of a negligible recharge is justified in this study as the flow in the streams are rare and fast as well as the vertical hydraulic conductivity of the tank beds are almost zero due to thick silting.

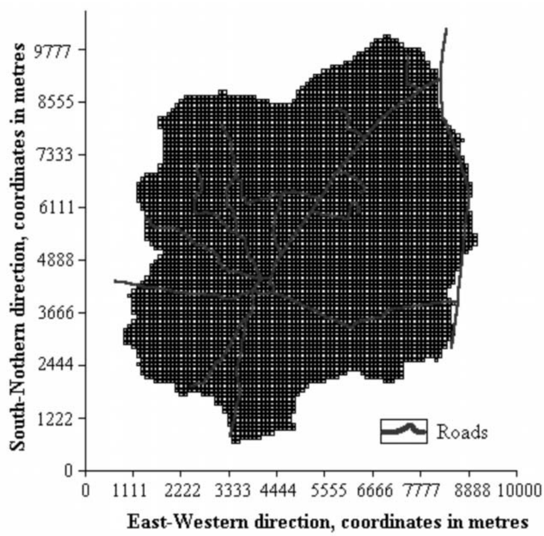

Figure 3. Grid of the watershed, layer 1 is similar to layer 2.

Aquifer Characteristics

No hydraulic tests could be carried out in the first layer because, during the project period (1999 to 2003), the water table was constantly deeper than the bottom of the weathered zone. Thus the hydraulic parameters for that layer were estimated from the literature. The hydraulic conductivities chosen for the weathered layer were selected according to two assumptions:

- The hydraulic conductivity values must be in the range of the ones found in the literature for the same type of geology;
- The variability in hydraulic conductivity is based on the conceptual model of the hydrogeological functioning of weathered-rock/hard rock aquifers in Africa proposed by Chilton and Foster (1995).

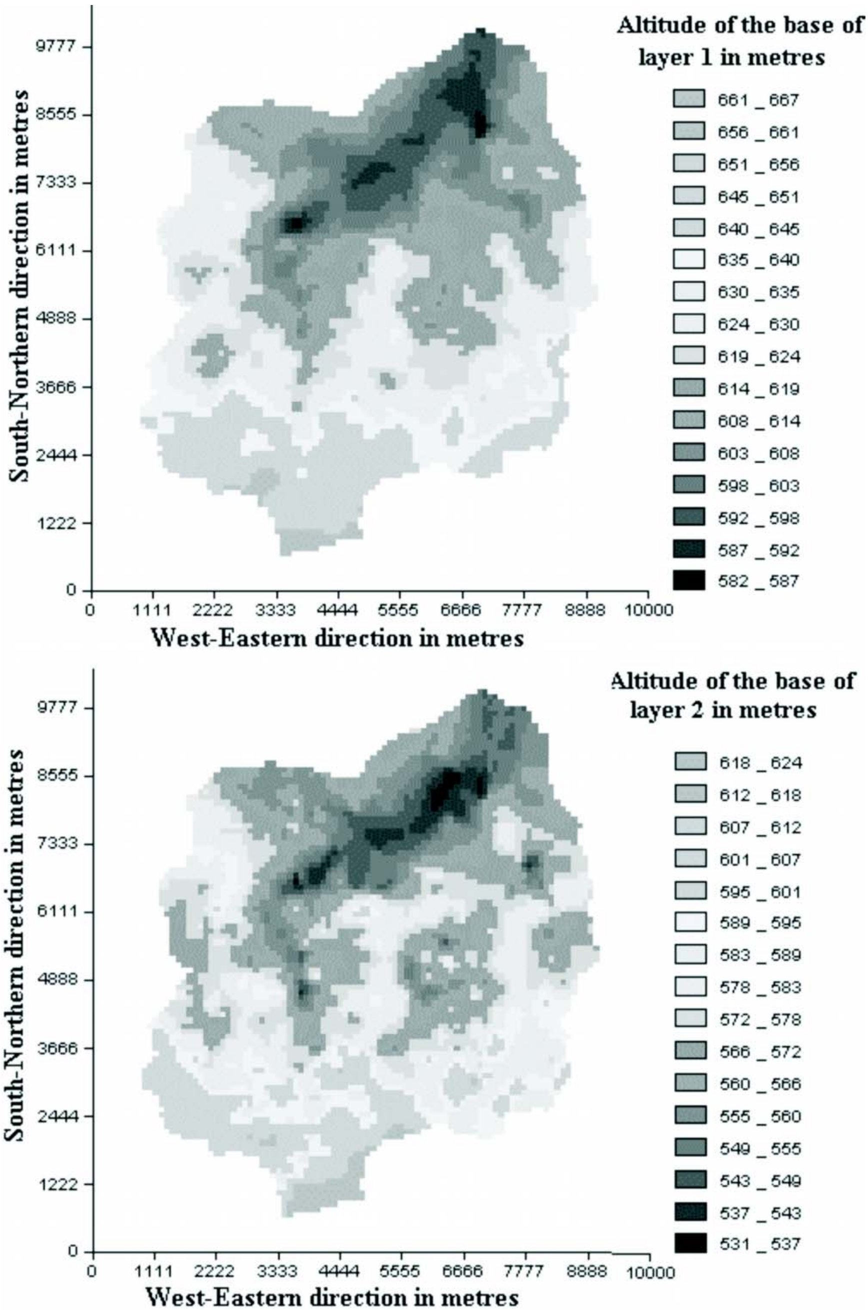

Figure 4. Aquifer bottom of layers 1 and 2 (asl, in m).

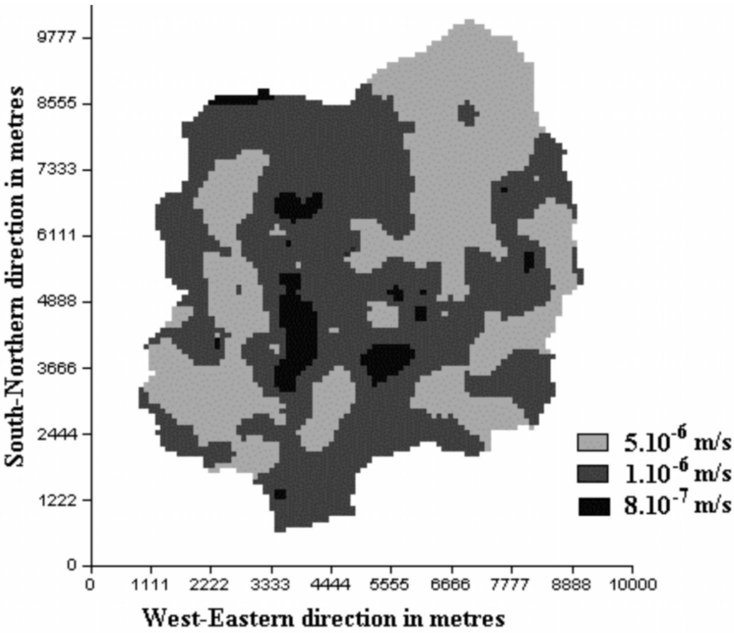

Figure 5. Hydraulic conductivities in the weathered layer, after calibration.

Figure 5 shows the distribution of the calibrated hydraulic conductivities for the weathered layer. They range between 8.10^{-7} $m.s^{-1}$ and 5.10^{-6} $m.s^{-1}$. The transmissivities were calculated from the results of 34 aquifer tests in the weathered-fissured granite layer. But the high variability observed in the field and the difficulties of matching the simulated heads with the measured ones led to additional manual calibration of the hydraulic conductivities in the model.

Average hydraulic conductivity obtained by calibration was compared with the equivalent horizontal hydraulic conductivity calculated by the FRACAS model (Bruel et al., 2002), a "discrete fracture network" model, which was used to interpret 25 slug tests. The hydraulic conductivities in the weathered-fissured granite layer are shown in Figure 6. They exhibit large variability (1.10^{-7} to 3.10^{-5} $m.s^{-1}$) from one place to another because of the heterogeneity of the rocks.

In the weathered-fissured granite layer, linear heterogeneities (impervious vertical barriers) had to be introduced into the model because this was the only way to take into account the observed piezometric data. These heterogeneities were attributed to the dykes that crop out in the studied area, to a South-North quartz reef crossing the watershed and to some assumed extensions of dykes (Fig. 6).

The specific yield was taken to be 2.4% in the weathered rocks. This value is an average of the specific yields observed in the weathered rocks

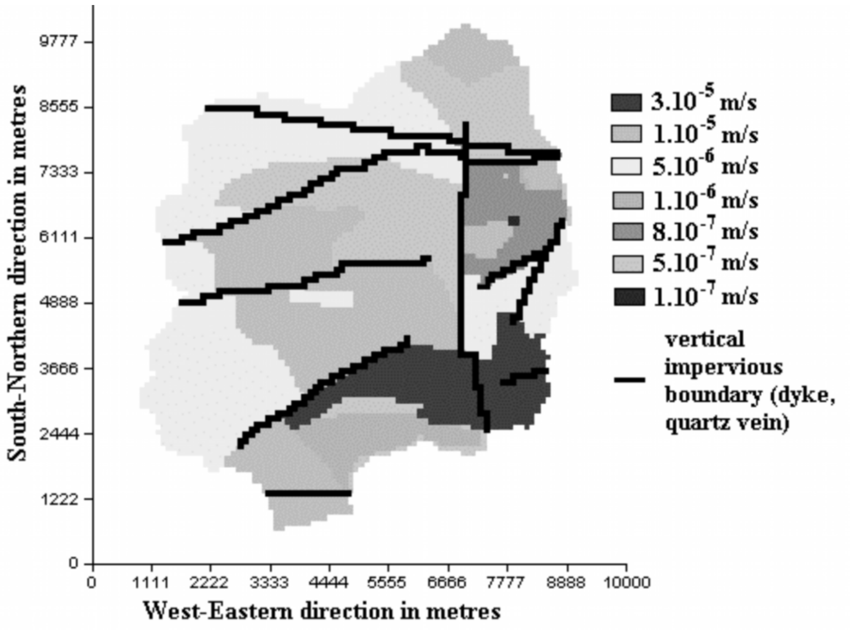

Figure 6. Hydraulic conductivities in the weathered-fissured granite layer, after calibration.

of similar watersheds (Rangarajan and Prasada Rao, 2001). The specific yield of the weathered rocks was also used for the calculation of preferential recharge. This value lies within the orders of magnitude given by the Proton Magnetic Resonance (PMR) measurements carried out in the watershed (Legchenko and Baltassat, 1999). In the fissured granite, this specific yield is assumed constant at a value of 1%, which is close to the value deduced from the discrete-fracture network interpretation (0.8%, Bruel et al., 2002), from pumping test interpretations (0.63%; Maréchal et al., 2004) and water-table fluctuation interpretations (1.4%; Maréchal et al., 2006). Some sensitivity tests were made by decreasing the specific yield in layer 2 by one order of magnitude. This led to a lowering of the simulated water levels due to the effect of pumping.

Storativity of the weathered layer (as a confined aquifer) plays a role in the flow calculations only when this layer becomes saturated (Engerrand, 2002). Its value was taken as 8.10^{-5}. For layer 2, the storativity value was set at 1.10^{-5}.

Aquifer Flows: Recharge, Discharge and Irrigation Return

Total recharge can be divided into three main components (Lerner et al., 1990): direct recharge (by direct vertical percolation through the vadose zone - saprolite), indirect recharge (percolation to the water table through the beds of surface-water courses, almost nil in the study area due to absence of water in surface streams) and local recharge (various scale pathways such as those due to cracks, roots and trenches, dug-wells, brick factories and major landscape features) as preferred path.

The direct recharge was calculated on the basis of tritium injection tests that were carried out in 1999 and 2000. The interpretation by piston flow of the tests indicated that between the end of July 1999 and November 1999, the direct recharge was 22.2 mm (Rangarajan and Prasada Rao, 2001) and that during the 2000 monsoon, the direct recharge was 42 mm. The GARDENIA code was used at a daily time-step to calculate the balance between:

- Rainfall (daily data from a rain gauge located in Maheshwaram village).
- Potential evapotranspiration, calculated from the evaporation in a Pan A and multiplied by a factor of 0.9 (Monteith et al., 1989). The data are daily when collected at Maheshwaram village and weekly, from an average of six years of monitoring at the CRIDA farm (CRIDA, 1991-2000), when they are not available at Maheshwaram.
- Run-off. For the Musi basin, the Central Water Commission calculated a run-off/rainfall ratio of 11.2 % for the period 1989-1994.
- Available water capacity of the soil. The most common soils in the area have an available water capacity ranging from 75 to 110 mm (CRIDA, 1990).

The parameters of the GARDENIA code (run-off and available water capacity) were calibrated for 1999 and 2000 to obtain the measured 22.2 mm and 42 mm of recharge, respectively, for these periods, as obtained by tritium injection. The same parameters were then used in the code to estimate the recharge for the years 2001 and 2002.

Indirect and local recharge was calculated from the groundwater level rise in the weathered rocks during the tritium experiments of 1999. In 2000, most of the dug-wells located near the tritium injection points were dry, preventing us from estimating the preferential recharge. It was thus calculated only for 1999 with the specific yield value of the weathered layer that was known for similar watersheds (Rangarajan and Prasada Rao, 2001) and the groundwater level fluctuations measured in the dug-wells within this layer.

Table 1 shows the calculated direct, indirect and local recharge for the years 1999, 2000 and 2001.

Table 1: Direct, indirect and local recharge for years 1990-2001

Year	*Direct recharge (mm)*	*Indirect and local recharge (mm)*	*Total recharge (mm)*
1999	22.2	13.8	36
2000	42	25	67
2001	83	35	118

The major part of the groundwater withdrawal from the system is due to pumping from the wells. Various means were used to cross-check the estimates; two quite independent methodologies, viz. a direct one based upon the well inventory including the location of the wells, their discharge and pumping duration etc., and an indirect one based upon the demand using data on irrigated areas, cropping pattern and crop water requirements were applied.

Evaluation of the discharge rates due to pumping from the well inventory survey is a direct method of estimation and also provides the grid-wise information as the wells pumping the groundwater can be plotted on the grids. For the years 2000, 2001 and 2002, all the wells drilled up to 2000, 2001 and 2002 respectively were taken into account. The total yearly amount of groundwater withdrawal from the aquifer is given in Table 2. The groundwater pumping is mainly from the 2nd layer due to water level declines but the return flow from the irrigated fields occurs in the 1st layer. It was deduced from the pumping according to:

- Andhra Pradesh Groundwater Department (APGWD) (personal communication, 2000) report on Maheshwaram land use, and
- APGWD (1977) report on hydrologic parameters of groundwater recharge in Andhra Pradesh.

that 86% of the pumped water is used for the rice and 14% for other crops.

In the APGWD report (1977), experiments on the return flow from the rice in a nearby watershed showed that 55 to 88% of the irrigation water returned to the aquifer. After calibration, 60% of return flows from the rice and 20 % from the other crops were assumed. In the model, we do not distinguish between the locations of the rice and the other crops, because they are not known. The average return flow of one crop (rice/other) is then taken as:

$$0.86 \times 60 + 0.14 \times 20 = 54.4 \text{ or } \approx 55\% \text{ of return flow from the withdrawals.}$$

Simulation and Calibration of the Model

The time-steps of the hydrodynamic calculation in transient flow are 14 days during the dry season and one week in the rainy season (they are daily when it rains). The MARTHE code uses GARDENIA to calculate the hydroclimatic balance; this balance is calculated with a weekly time-step during the dry season and a daily one during rainy days throughout the year.

The fitting of the model was carried out by calibrating the following parameters:

- the hydraulic conductivities of the two layers; and
- the return flow from withdrawals.

The fitting criteria were based on:

- probable orders of magnitude of the fitting parameters; and
- the similarity between the hydraulic heads observed in the project wells in the field and the simulated ones.

Groundwater Balance

In 2000, the balance (storage variation) is negative (Table 2). The withdrawals are greater than the recharge and the storage decreases. The pumping wells are in operation at 99.9% of normal capacity. The discharge from the prescribed head-boundaries is 1.3% of the recharge, which is negligible. The overflows are nil.

For 2001, the balance is positive. The recharge is greater than the withdrawals and the stock increases. The pumping wells are in operation at 99.7%. The discharge from the prescribed heads is 1.8% of the recharge, which again is negligible. The overflows are 0.2% of the recharge, which is also negligible. The aquifer overflows are located near the draining meshes, which seems logical.

In 2002, the balance is strongly negative. The recharge is weaker compared to the other years and the withdrawals have increased. The pumping wells are in operation at 97.6%. But the return flow is calculated on the basis of the maximum demand and not on the basis of the actual withdrawals; in this case, because the quantity of water that cannot be pumped is not negligible compared to the demand for water, the prescribed return flow is slightly over-estimated and the balance is optimistic. In fact, the return flows range between 6,720,000 m^3 and 6,560,000 m^3. The discharge from fixed heads is 3.1% of the recharge. The overflows are 0.2% of the recharge, which is negligible and also located near the draining meshes.

Table 2. Annual water balance in Maheshwaram watershed

	1/1/–31/12/2000	*1/1/–31/12/2001*	*1/1/–31/12/2002*
Recharge ($m^3.y^{-1}$)	3,521,000	6,213,000	2,372,000
Return flow ($m^3.y^{-1}$)	5,214,000	6,228,000	6,720,000
Outlet from fixed heads ($m^3.y^{-1}$)	–46,000	–110,000	–74,000
Withdrawals ($m^3.y^{-1}$)	–9,469,000	–11,293,000	–11,927,000
Groundwater overflows ($m^3.y^{-1}$)	0	–13,000	–5,000
Storage variation ($m^3.y^{-1}$)	–780,000	1,026,000	–2,912,000
Balance deviation (%)	–0.02	–0.02	0.42

Analyses of the Simulation/Calibration and Prediction

A comparison between the simulated heads and the measured ones for January 2001 under steady state conditions shows that most of the water levels are well simulated and are falling on the 450 line. The comparison between the simulated groundwater levels in the transient condition shows a satisfactory calibration as the differences (Fig. 8) are more or less in the tolerance limit.

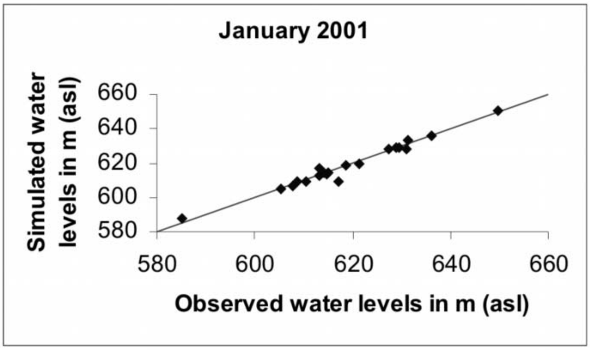

Figure 7. Comparison between simulated and calculated heads for January 2001 in Steady State Simulation.

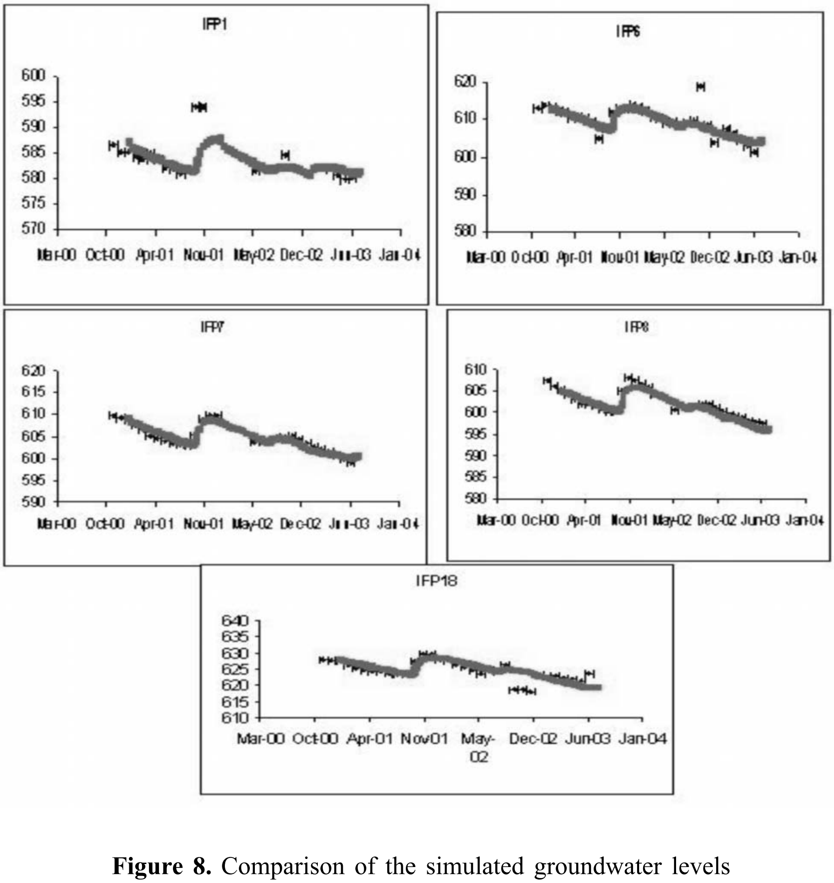

Figure 8. Comparison of the simulated groundwater levels (continuous line) and observed ones (stars).

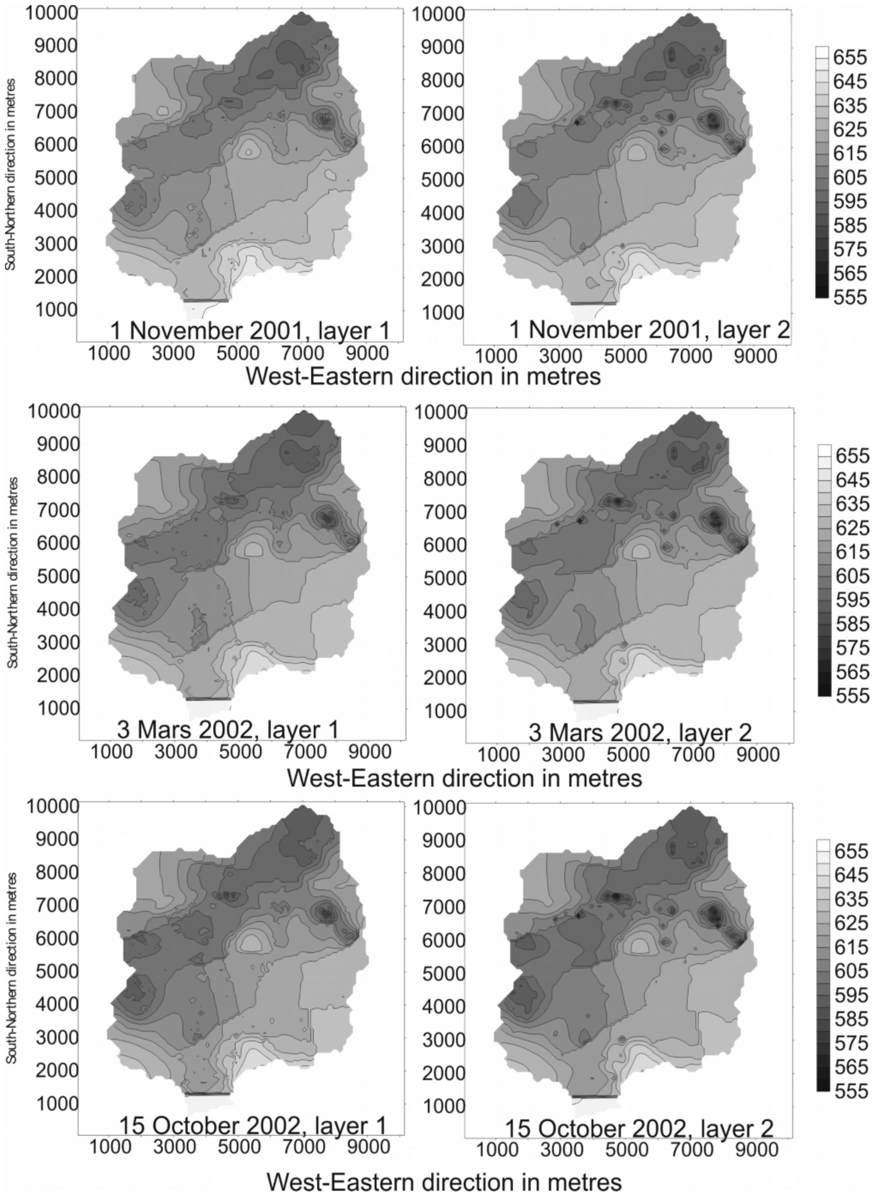

Figure 9. Simulated water levels for layers 1 and 2.

Figure 9 presents some simulated water-level maps for both layers. There is not much difference in the water levels between layer 1 and layer 2 except in the zone of large groundwater withdrawals where layer 2 shows lower hydraulic heads than layer 1.

Some predictive scenarios were tested until the year 2023 assuming:

- that the recharge was set at a constant value equivalent to the average of the recharge calculated between 1986 and 2002; and

- that the recharge varied as it had done between 1986 and 2002.

In both scenarios, the water demand was set constant and equal to the one in 2002.

If the water demand increases, the scheme is different. Figure 10 shows an extrapolation of the water demand over the next 20 years. This figure is only an example. It proposes a logarithmic increase in the water demand justified by the assumption that the yearly increase of the number of wells will decrease due to a saturation of the land use. With this figure, the number of wells located in the watershed will have increased from 709 to 1004 in January 2023.

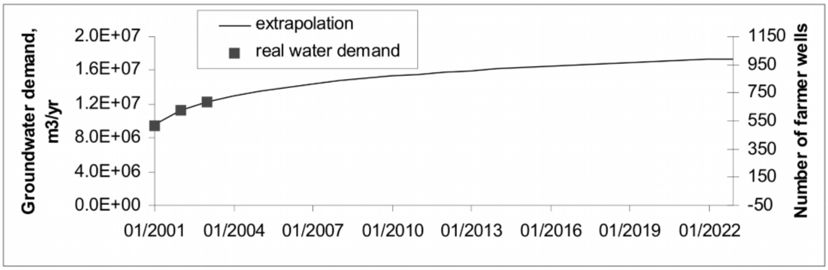

Figure 10. Anticipated water demand for the next 20 years.

Predictions were made with this new scenario. The groundwater level decreases rapidly (Figure 11). In the longer term (a few more years), the

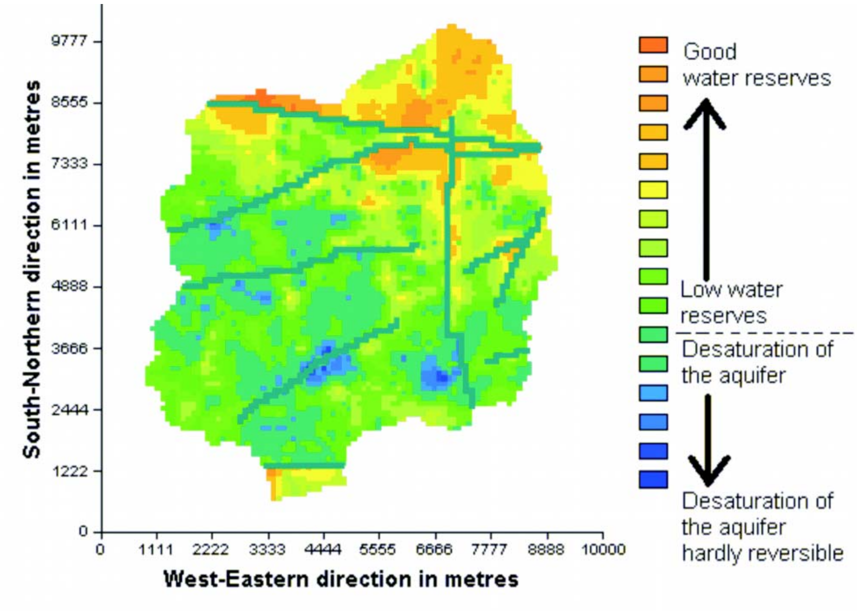

Figure 11. Groundwater status in 2023.

groundwater storage will be directly equivalent to the recharge. The monsoon will allow the aquifer to recharge but the irrigation will, within one year or less, empty the aquifer until the next monsoon season. In these conditions, the farmers will be more vulnerable to dry years than at present and may not be able to grow two or even one crop in these years. This will lead to economic instability and hardship for the farmers.

CONCLUSION

The flow in a weathered-fractured coupled system of aquifers was simulated using two layers model. Such situation is quite representative of the aquifers in granitic terrains. The special condition in this particular case has been that in most of the simulation period the aquifer in the weathered layer has been dry. In the two-layer aquifer model the upper layer being the weathered rocks was simulated as porous medium with comparatively low variability in hydraulic property but in the lower layer the weathered-fractured rocks was simulated as equivalent porous medium with highly variable hydraulic properties and contrast. The special case is also due to the fact that no separating layer exists nor is simulated between the weathered and fractured layers. For a majority of wells, hydraulic head simulations are in accordance with the water levels observed in the project wells for the years 2001 and 2002. Hydraulic heads that are not in accordance with the field observations are located in areas where the withdrawals have been intensive and are to be verified. The average hydraulic conductivity and the specific yield of the weathered-fissured layer are in accordance with those found with the "Discrete Fracture Network" model used to interpret the pumping tests in the aquifer (Bruel et al., 2002). The model has to be further improved and calibrated for the heterogeneities in the hydraulic properties by accurately estimating other input parameters. The return flow from the irrigation water is very difficult to validate. It is an approximate parameter that can also be calibrated with the model. Although the model was calibrated only for two years for which the data existed, some predictive scenarios were tested for further 20 years.

The results of the predictive model with the anticipated scenario show that if the water demand increases, the water levels in the watershed will decrease drastically everywhere. More and more wells will become dry and the groundwater storage at the beginning of a given year will be entirely dependent on the recharge of that year. In other words, there will not be any more reserves in the aquifer (Custodio, 2002) to even out the temporal variability of recharge from year to year. This will lead to difficulties for the farmers and economic instability.

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