An Operational Decision Support Tool (DST-GW) for Sustainable Groundwater Management in Semi-arid Hard-Rock Regions

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Abstract

Latest studies showed that a typical hard rock aquifer (e.g., granite, gneiss) is made of two main hydrogeological units characterized by quite homogeneous specific hydrodynamic properties, namely the saprolite and the fissured layers. Therefore, hard rock aquifers can be considered as a multi-layered system.

Based on this conceptual model of hard rock aquifer, an operational Decision Support Tool (DST-GW) designed for groundwater management in semi-arid hard rock regions has been developed. This DST-GW focuses on the impact of changing cropping pattern and artificial recharge on average seasonal piezometric levels at the scale of small watersheds (up to 100 km2). The model integrates the natural characteristics of hard rock aquifers such as the variation in specific yield with depth, the respective thicknesses of the fissured and saprolite layers, as well as variations in both natural and artificial aquifer recharges with respect to climatic conditions.

Under the project SUSTWATER sponsored by the European Commission (Asia ProEco programme), the DST-GW and related methodologies have been tested at an operational scale for policy-makers and planners in the Gajwel watershed (84 km2): the hydraulic model was calibrated with a limited number of field data over two hydrological years. The watershed is overexploited due to the intensive cultivation of groundwater-irrigated paddy fields and if no appropriate management measures are taken groundwater resources may run dry following bad monsoon years. Simulation with DST-GW indicates that a combination of supply and demand measures will bring sustainable solutions to the aquifer overexploitation.

The application of the DST-GW to Gajwel watershed shows that it is an efficient and cost-effective tool that can help policy-makers in their decision process and selection of the most appropriate groundwater management measures.

Future development of the DST-GW may include water quality, surface water- groundwater interaction, and the integration of spatial variability (hydraulic conductivity, recharge) for application at larger scale.

Keywords: Groundwater Management, Decision Support Tool, Hard-Rock, Semi-Arid Climate

Introduction

Decision Support Tools (DST) or Systems (DSS) in hydrological sciences have been developed over the past two decades to help decision-makers to perform computer generated analyses of data and take appropriate decisions combining environmental, social, and economic considerations. Existing DSTs focus mostly on surface water resources management: over rather large areas such as large river basins (e.g., Letcher and Guipponi 2005), surface water and wetlands (e.g., Sriwongsitanon 2007), surface water- groundwater interactions (e.g., Chowdary et al. 2003).

DSTs especially devoted to groundwater management are rarely described in the literature (Liu 2004, Tripathy 2007) and a specific DST for groundwater management in hard-rock semi-arid context (DST-GW) is quite unique (Dewandel et al. 2007).

Until recently, aquifers located in hard rock formations (granite, gneiss, schist) were considered as highly heterogeneous media, and adequate methodologies for groundwater management were not existent. Recent studies (e.g., Wyns et al., 1999; Maréchal et al., 2004; Dewandel et al., 2006) showed that when hard rock are exposed to deep weathering processes, as it is the case in India, the aquifer is made of two main sub-parallel hydrogeological layers, namely the saprolite and the fissured layers, forming a total thickness comprised between 50 to 100 m. These layers can be considered as homogeneous from 100 m to kilometric scale and are therefore characterized by quite homogeneous hydrodynamic properties. These new geological and hydrogeological concepts, that enable to regionalize hard rock aquifers properties, find numerous practical applications including water resources management methodologies.

This DST-GW has been developed to answer to the needs of large rural areas of southern India where groundwater overexploitation is widespread. However, this tool and associated methodologies are also applicable to many other rural areas around the world having similar climatic conditions and geology (e.g., Africa, part of SE Asia and S America).

Groundwater is a natural resource of major importance in India. From the 1960’s, this resource has been tapped at a very large scale over the entire country, as part of a radical change that became known as the Green Revolution. As a result, the number of mechanized wells and tubewells grew from less than 1 million in 1960 to 19 millions in 2000 (Shah et al. 2003). These wells pump around 150 km^3/year, which makes India the largest groundwater-user country in the world.

Presently, groundwater is a significant source of irrigation in India and accounts for more than half of the net irrigated area at the country scale. In 1970-73, the contribution of groundwater irrigated area and surface irrigated area to total agricultural output was Rs 21 billion and Rs 77 billion respectively and this has gone up to Rs 132 billion and Rs 115 billion in 1990-93 (Deb Roy and Shah 2002). Groundwater irrigation therefore can be an effective vehicle of poverty eradication as its access exists in many areas and required investments are affordable by rural communities. In 1998, Government of India estimated that the contribution of groundwater to India’s GDP is around 9%.

The major setback of the Green Revolution is that groundwater exploitation has been conducted without adequate scientifically-based guidelines so far. Since the last decade most of the States of India, and particularly in South India, suffered from drought, severe groundwater level depletion and alarming deterioration of water quality (e.g., in the states of Andhra Pradesh, Karnataka, Maharasthra, Madhya Pradesh and Rajasthan). Therefore, it is necessary to adapt groundwater abstraction to available resources and to have suitable tools to assess the aquifer water budget and to analyze and propose water resources management policies at the watershed scale.

The DST-GW presented in this paper is a first attempt to answer to the need for an appropriate groundwater management in southern India. It includes a hydraulic module where the groundwater budget of the selected watershed is computed and the hydraulic model calibrated and a module where various scenarios of groundwater demand/supply measures can be simulated: cropping pattern changes, domestic water use changes, artificial recharge, climatic change, etc. (Dewandel et al. 2007). The DST-GW simulates piezometric variations at the watershed scale for the different scenarios over the next 20 years.

For its scientific development, the DST has been implemented in a representative south Indian watershed (Maheshwaram watershed; 53 km² in area, Fig.1) characterized by a granitic basement, semi-arid climatic conditions, rural context, and groundwater overexploitation due to large amount of water pumped for the irrigation of rice, vegetables and flowers (annual groundwater abstraction about 10 Mm^3).

The presented case study is the first application of DST-GW at the operational scale, i.e. using a limited number of field data over a limited calibration time (cost-effectiveness) and a user-friendly computerized support. It is based on the results of a project supported by the European Commission, grants Asia ProEco, that was carried out in close collaboration between the Rural Development Department of Andhra Pradesh, the Andhra Pradesh Groundwater Department and the authors.

Geological and Hydrogeological Setting

The DST-GW has been calibrated for the Gajwel watershed (84 km^2) which is located 60 km NE of Hyderabad, Andhra Pradesh (Figure 1). The climate is semi-arid with an average of 810 mm yearly rainfall occurring during the monsoon period between June and October. The topography of the area is mostly flat with granitic hills in the upstream part of the watershed. The whole watershed is located in a rural context with groundwater irrigated agriculture (paddy dominated) mostly in the vicinity of villages and significant surfaces of the watershed devoted to rainfed crops (mainly cotton and maize). Surface flow occurs only during the monsoon and is limited to a few hours during storm events. This surface water is stored into tanks located along stream valleys.

The geology of the watershed is characterised by the predominance of Archean orthognessic granite (a.k.a. pink granite) and limited occurrence of leucocratic granite. A few dolerite dykes and pegmatite veins are also present. The granite is weathered with a saprolite layer thickness comprised between 10 and 30 metres with the exception of granite outcrops in the upstream part of the watershed.

The hard-rock aquifer is depleted due to intense draft caused by approximately 1200 irrigation borewells implemented in the watershed. In most places, the saprolite is totally unsaturated and the water table is located in the fissured layer of the aquifer. Farmers have said that a significant number of borewells may run dry after a bad monsoon year.

The aquifer hydrodynamics is characterized by sharp seasonal water table fluctuations with a long dry season followed by recharge during the monsoon months (Figure 2).

Groundwater budget computation

Technically speaking, the DST-GW can be described as a Column or Single-cell model. It means that the groundwater balance is calculated at the watershed scale using average values for each water budget component. The DST-GW is made of two successive parts: 1) the hydraulic model; 2) the simulations. In the first part, the hydraulic model is calibrated with field data. Then in the second part, the DST-GW will simulate the average water table inter-annual fluctuations at the watershed scale. Many different simulations can be carried out according to User-defined scenarios.

The hydraulic component of the DST-GW is based on groundwater budgets and on a computation of specific yield and annual recharge using the ‘Double Water Table Fluctuation (DWTF)’ method (Marechal et al., 2006; Dewandel et al., 2007). This approach is particularly well adapted to unconfined hard rock aquifers under semi-arid conditions with well marked dry and rainy seasons which correspond to the conditions in the selected watershed (Figure 2).

The groundwater budget method focuses on groundwater flow (Figure 3). Although groundwater flow is linked to surface flow such as precipitation, evapotranspiration and runoff, the latter do not appear directly in the budget. Changes in groundwater storage can be attributed to recharge, irrigation return flow and groundwater inflow to the basin minus baseflow (groundwater discharge to streams or springs), evapotranspiration from groundwater, pumping, and groundwater outflow from the basin:

$$R + RF + Q_{in} = ET + PG + Q_{out} + Q_{bf} + \Delta S \tag{1}$$

where R is groundwater recharge, RF is irrigation return flow, Q_{in} and Q_{out} are groundwater flow across the watershed boundaries, ET is evapotranspiration from water table, PG is the abstraction of groundwater by pumping, Q_{bf} is baseflow (groundwater discharge to streams or springs) and ΔS is change in groundwater storage.

In intensively exploited aquifers, the water table is quite deep implying that:

- There are neither springs nor contribution of groundwater to streams, consequently the baseflow is nil ($Q_{bf}=0$).
- Vegetation is not able to consume significant groundwater, and evapotranspiration ET is thus redefined as groundwater evaporation from the water table E.

As a consequence, Equation (1) can be rewritten as:

$$R + RF + Q_{in} = E + PG + Q_{out} + \Delta S \tag{2}$$

The main advantage of the groundwater budget method compared to the classical hydrological budget is that evapotranspiration, a major component, and its large associated uncertainties are not present.

The methodology used to determine the unknown groundwater storage (ΔS) is the Water Table Fluctuations method (WTF), which links the change in groundwater storage ΔS with resulting water table fluctuations Δh:

$$\Delta S = S_y.\Delta h \tag{3}$$

where S_y is the specific yield (storage) or the fillable porosity of the unconfined aquifer.

Because the water level measured in an observation well is representative of an area of at least several tens of square meters, the WTF method can be viewed as an integrated approach as compared to methods based on local data in the unsaturated zone. Techniques based on groundwater levels are among the most widely applied methods for estimating recharge rates (Healy and Cook, 2002). This is likely due to the abundance of available groundwater level data and the simplicity of estimating recharge rates from temporal fluctuations or spatial patterns of groundwater levels.

The WTF method, applicable to unconfined aquifers only, is best applied to water tables that display sharp water-level rises and declines (Figure 2). Such a configuration is observed in monsoon-type climate where recharge occurs on a limited time period and depletion continues all along the dry season. The depletion can be even accentuated due to groundwater draft in intensively exploited aquifers.

Therefore, the hydrological year can be divided into two seasons and a combined procedure of WTF and groundwater budget can be applied twice a year. This is done by combining equations Equations (2) and (3):

$$R + RF + Q_{in} = E + PG + Q_{out} + S_y \Delta h \tag{4}$$

in which two parameters, natural recharge R and specific yield Sy, are taken as unknown. The other budget components are estimated independently and piezometric fluctuations are measured using well hydrographs. Equation (4) is applied twice a year: (i) during the dry season, no recharge occurs (R=0) hence equation (1) can be solved for Sy, (ii) during the rainy season, recharge (R) is calculating using Sy obtained in step (i). The method is therefore called the “double water table fluctuation” technique (DWTF).

Watershed delineation and aquifer geometry

To accurately delineate the watershed, a DEM with a 15x15 m resolution (ASTER stereo image) has been used. The DEM has been compared with the surface drainage network from the 1:50’000 toposheet of the area and slightly modified to match perfectly the drainage network. Then watershed limits have been automatically generated using the “automatic watershed delineation” algorithm of ArcView© on the improved DEM. The watershed limit is drawn on the GIS as polygon and a total area of 83.7 km^2 is retrieved from the GIS (Figure 4). The mean topographic elevation of the watershed, calculated with the GIS based on the DEM imagery, is 569.9 m.

The mean elevations of the base of the saprolite and the base of the aquifer are obtained from geological/geophysical mapping. Granite outcrops and observations in dugwells were used to determine the saprolite thickness. Resistivity logging in 20 abandoned borewells was carried out to determine the bottom of the aquifer. These observation points were then extrapolated using SURFER© and the mean elevation calculated from the interpolated regular grid (Figure 5).

Groundwater budget components estimation

1. Water table fluctuations (Δh)

Piezometric campaigns were carried out twice a year, at the end of the dry season and at the beginning of the next dry season when recharge has taken place. Based on the piezometric data, piezometric maps are interpolated using the kriging technique (Figure 6). The maps are then critically evaluated to ensure that interpolation is satisfactory. In hard-rock areas with smooth topography, it is expected that the piezometric surface will roughly follow the topographic surface. The average piezometric elevations are calculated from the interpolated regular grid.

For year 2006, the water table elevation increase was 7.67 m for a monsoon total rainfall of 782 mm and for year 2007, the increase was 0.63 m for a monsoon rainfall of 536 mm.

2. In- and Out- flows across the aquifer boundaries (Q_{in}, Q_{out})

The watershed is delineated based on the surface topography and the hydrographic network, which limits significantly groundwater flow across watershed boundaries as the piezometric surface matches closely surface topography in this type of unconfined aquifers (i.e., groundwater divides corresponds closely to surface watershed boundaries). Moreover the high density of abstraction wells tends to capture most of the groundwater within the delineated watershed. Based on these considerations, it is inferred that groundwater outflows balance inflows, hence $Q_{in} = Q_{out}$.

3. Evaporation from the water table (E)

In semi-arid areas and when water levels are shallow, evaporation from phreatic aquifers is one of the main components of the groundwater budget (Coudrain et al., 1998).These authors showed that evaporation from phreatic aquifers in arid zones is independent of the soil characteristics and they established a relation for semi-arid climatic conditions:

$$E = 71.9 \cdot z^{-1.49} \tag{5}$$

where E is the water table evaporation [mm/y] and z, the water table depth [m]; E is the groundwater evaporation from the water table in equation (2).

This relationship can easily be applied to the watershed piezometric maps. Evaporation maps are generated, from which the average evaporation at the watershed scale is calculated.

Average values of evaporation from the water table range between 0.4 – 1.1 mm/yr. These quite low values are due to significant depth of the water table in the study area as a consequence of overexploitation.

4. Groundwater Pumping (PG)

In Gajwel watershed the largest share of groundwater abstraction is used by agriculture (mostly irrigation of paddy fields). Apart from irrigation, groundwater is also used by the local population and poultry farms.

Two land use maps, one in the dry season and one in the rainy season, were drawn based on satellite imagery (satellite IRS resourcesat, sensor LISS4, Figure 7). These maps give an estimation of the respective irrigated areas for paddy and for other irrigated crops.

Then a field cross-validation was carried out where the area of 25 paddy fields was estimated using a GPS in the dry and in the rainy seasons; for each paddy, the instant groundwater discharge applied to the field was measured with a bucket and a stopwatch. These instant discharge measurements are then used to calculate the daily water input on the field (instant discharge multiplied by the daily pumping duration). This leads to a linear relationship between paddy area and daily groundwater pumping as illustrated in Figure 8. The slope gives the representative water input (Pg_i) for the irrigated crop i in m/day. A similar approach was applied to other irrigated crops.

Once Pg_i is estimated, it is possible to compute PG for each irrigated crop at the watershed scale:

$$PG_i = Pg_i . S_i .\ t_{K,R} \tag{6}$$

where PG_i: is the groundwater abstraction for the crop 'i' in m^3, S_i the total irrigated area of crop 'i' determined from land use in m^2, and $t_{K,R}$ the number of irrigation days in dry/rainy season in days.

PG ranges between 88-112 mm/season for paddy fields and 2-18 mm/season for other irrigated crops.

Other groundwater uses (domestic and poultry farms) were estimated using a database from a similar watershed, where water consumption per capita was evaluated at 30 l/day in rainy season and 30.5 l/day in dry season (statistic based on a 4.5-year survey). These data are combined with the Gajwel population statistics to estimate the Groundwater domestic use (2.0-2.8 mm/season). The groundwater consumption by poultry farms has been estimated from a poultry farm inventory leading to a consumption of 0.16-0.22 mm/season.

5. Return flows (RF)

Irrigation return flows are estimated using a hydraulic model described in detail in Dewandel et al. (2008), which combines both saturated and unsaturated flow theory. The obtained coefficients, 47-61% for rice and 25-33% for other irrigated crops are in agreement with the ones found in the literature (e.g., Dewandel 2007).

Calibration of the hydraulic model

The hydraulic model is calibrated on two hydrological years for which field data have been acquired. Specific yields (Sy) calculated over the two depletion periods read 1.4% (2006-2007) and 1.2% (2007-2008), values in agreement with more detailed studies carried out in Maheshwaram experimental watershed (Marechal et al. 2004, 2006, Dewandel et al. 2007). Based on these values, DST-GW proposes a seven layers aquifer model (5 layers in the fissure zone and 2 layers in the saprolite) that takes into account the progressive decrease in specific yield at depth in agreement with the hard rock weathering profile (i.e., decrease of fractures density with depth) (Marechal et al. 2004, Dewandel et al. 2006).

Recharge is calculated over the two wet seasons and compared with rainfall (Figure 9). It appears that the slope of the rainfall-recharge linear relationship is slightly steeper than the one obtained with more data points in Maheshwaram experimental watershed. This difference may be at least partly due to a higher contribution of percolation tanks to recharge in Gajwel: 3.3 % of the Gajwel watershed is covered by tanks as compared to 1.3 % in Maheshwaram watershed.

However, the rainfall-recharge relationship for Gajwel watershed is based on two points only; hence it would be necessary to substantiate the role of percolation tanks with additional data.

Piezometric levels calculated by the hydraulic model can be compared with the one measured on four occasions during the piezometric campaigns (to estimate Δh) (Figure 10). The calibration is quite good as measured piezometric data are within the error bar of the model. The maximum error on the modelled piezometric data is 0.71 m (or 0.13 %).

Simulation Example

After calibrating the hydraulic model, various scenarios can be simulating with the DST-GW including climate change (variations in annual rainfall), changing cropping patterns, changes in other groundwater uses (e.g., new demands for industries, tourism, etc), additional artificial recharge. Piezometric fluctuations are simulated twice a year over 20 years starting from the beginning of the calibration period.

Figure 11 shows an example of three different scenarios: (i) the reference scenario where all groundwater demand/supply remains identical to the calibration period, the past 20 years annual rainfall are simply shifted to the next 20 years (assuming stationarity of the rainfall time series); (ii) scenario 1 where paddy areas are progressively reduced to about half of their present-day superficies; (iii) scenario 2 where paddy reduction is the same as scenario 1 but in addition artificial recharge is doubled between 2008 and 2011.

The drying up of the aquifer occurring in the reference scenario (and scenario 1) indicates that groundwater resources are overexploited and serious consequences on the livelihood of rural communities may arise if no measures are taken. It also indicates the high sensitivity of the aquifer to annual recharge due to the quite limited groundwater reserves of the aquifer (low specific yield and limited aquifer thickness). This means that reserves may become completely depleted after 1-2 bad monsoon years.

Simulated piezometric levels show that only scenario 2 is sustainable. Hence it appears that long-term management of the groundwater resources will have to combine supply measures (e.g., additional artificial recharge) with demand measures (e.g., surface reduction of irrigated paddy fields). The DST-GW may help to select the most appropriate measures that will guarantee a satisfactory balance between socioeconomic and environmental constraints.

Summary and Conclusions

The presented groundwater resource management decision support tool (DST-GW) especially developed for hard-rock aquifers in semi-arid context is cost-effective, user-friendly, yet scientifically robust. It is shown that a limited number of field data over a limited duration (two hydrological years) are sufficient to reach an adequate calibration of the hydraulic model. DST-GW is a column model and the hydraulic model is a simple water balance equation at the watershed scale using integrative groundwater budget components. This approach at watershed scale makes the DST-GW robust as calculations are not impacted by local geological heterogeneities common in hard-rock. Moreover no data subject to high spatial variability (such as K, S from pumping tests, ETR) are required because the specific yield and the recharge terms are calculated and hence represent the average value in the watershed. This approach gives robustness to the model and simulated scenarios.

Simple scenarios show that overexploitation in Gajwel watershed is a serious threat to groundwater resources. Hard-rock aquifers having quite limited resources due to their structure, they are particularly sensitive to annual recharge (i.e., monsoon intensity). Therefore, if sustainability is to be met, appropriate groundwater management measures should be implemented so that aquifer reserves are reconstituted in a way that 1-2 successive bad monsoons can be overcome (i.e., constitution of “security reserves”). These considerations may have serious impacts on rural socioeconomics in the Indian context where a large part of the community relies on groundwater for their livelihood (food and income).

In the near future, improvements of DST-GW will include a more refined module to calculate additional artificial recharge based on field experiments presently carried out (Perrin et al. 2007), options to modify future rainfall-recharge relationships to accommodate for instance climate changes effects, a new module that simulates groundwater quality (TDS, salinisation), and upscaling methodologies to work at larger basin scale. In parallel, a socio-economic module has been incorporated into DST-GW where farmers' typology, farmer incomes, changing cropping patterns per farmer groups, etc. can be considered. This part of DST-GW will be presented in another paper.

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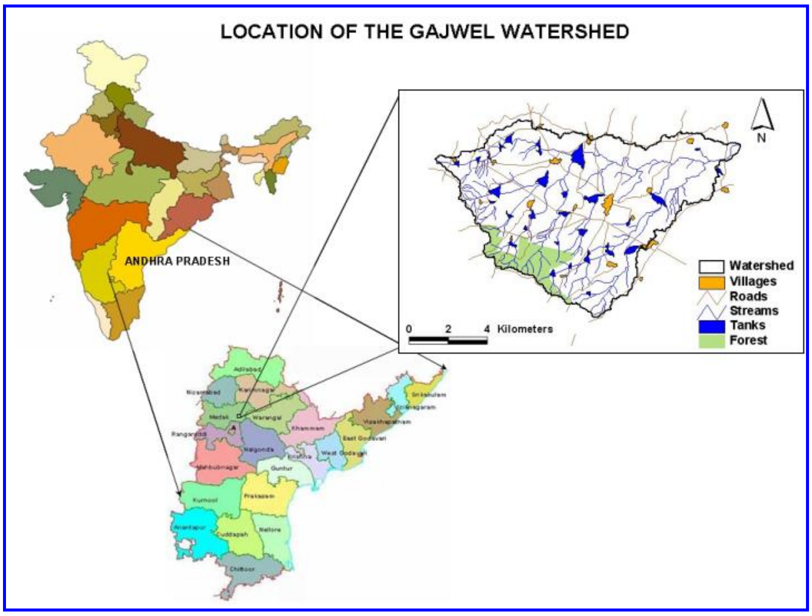

Figure 1: Location of the studied area

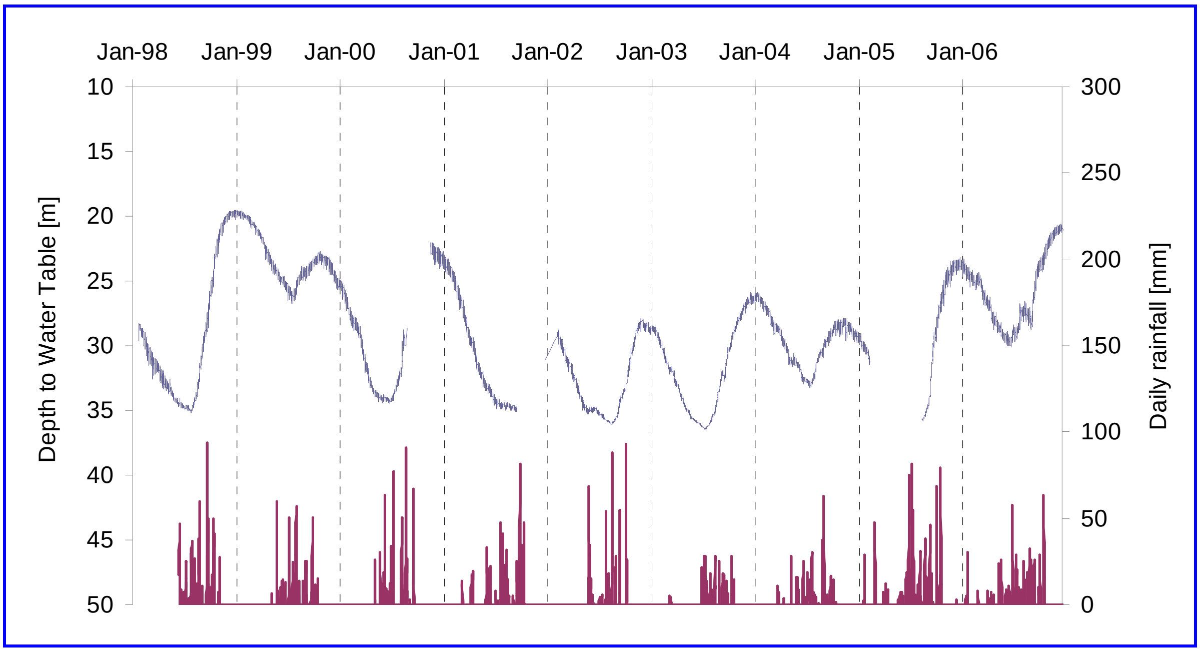

Figure 2: Water levels and rainfall in Gajwel watershed from Januray 1998 to March 2006 (source : AP Groundwater Department). Note the sharp rise and decrease due to seasonal fluctuations.

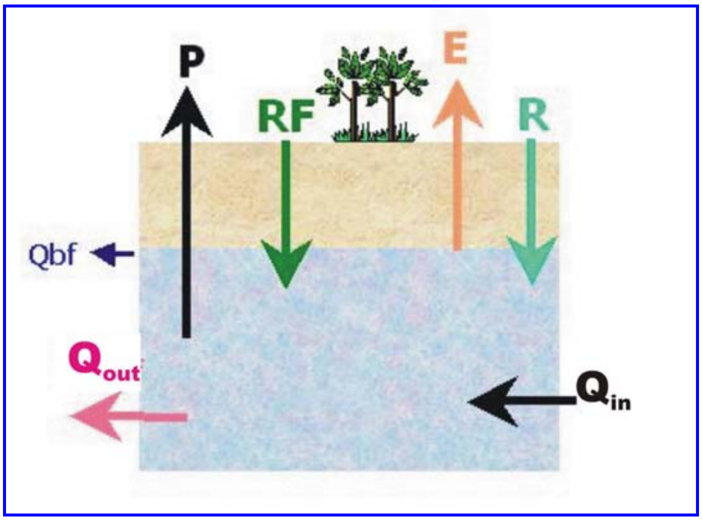

Figure 3 : Groundwater budget sketch, all components are described in the text.

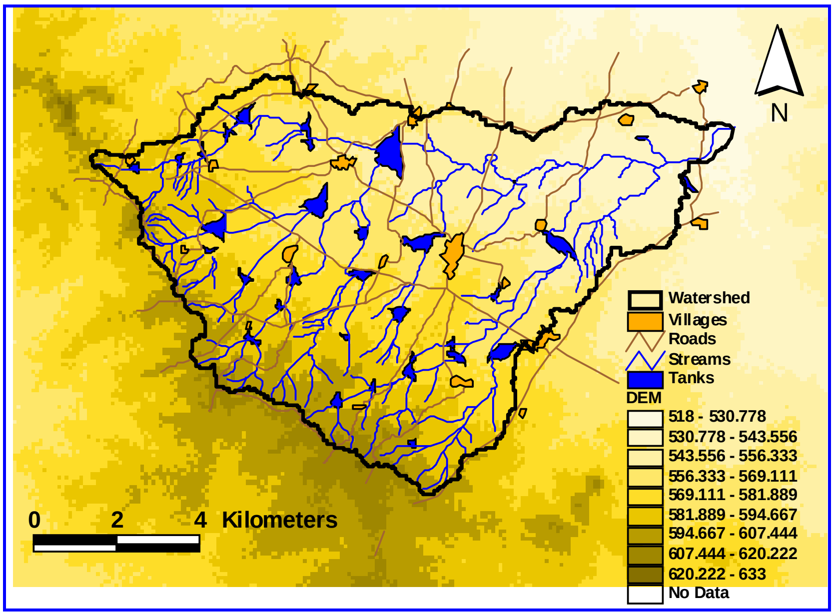

Figure 4 : Gajwel Digital Elevation Model (DEM, source: RASTER DEM, 15*15 m)

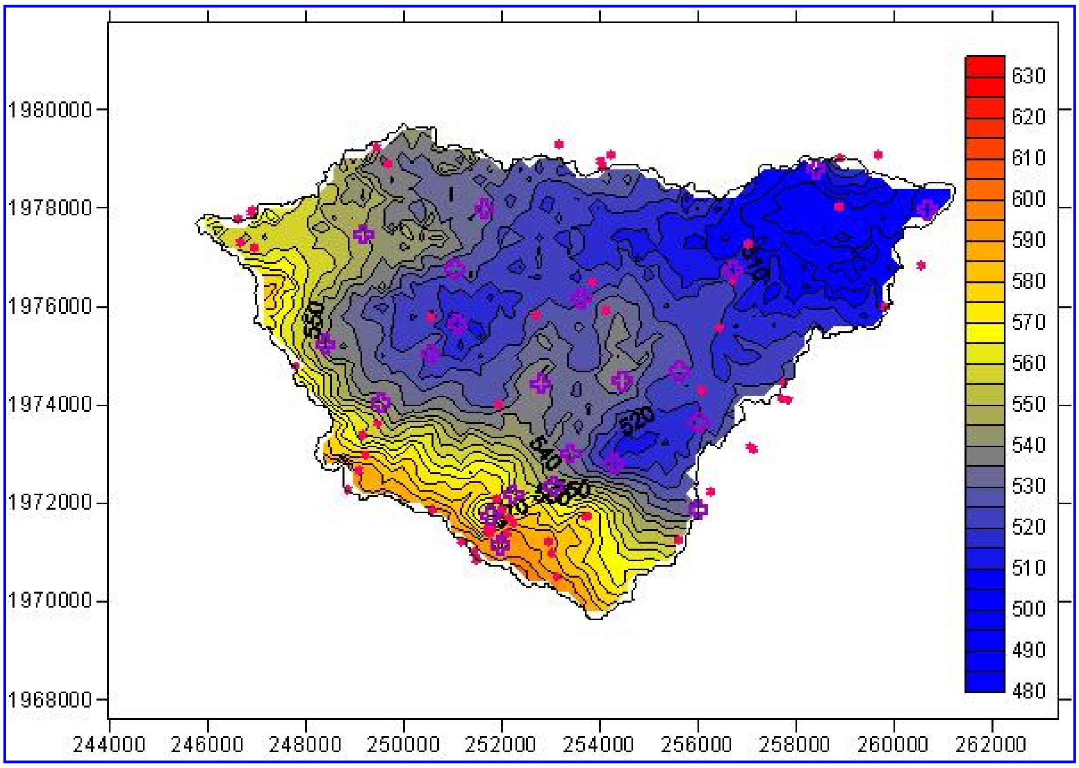

Figure 5: Map of the base of the aquifer: red dots represent abandoned borewells used for resistivity logging and pink crosses geological observations (outcrops and dugwells).

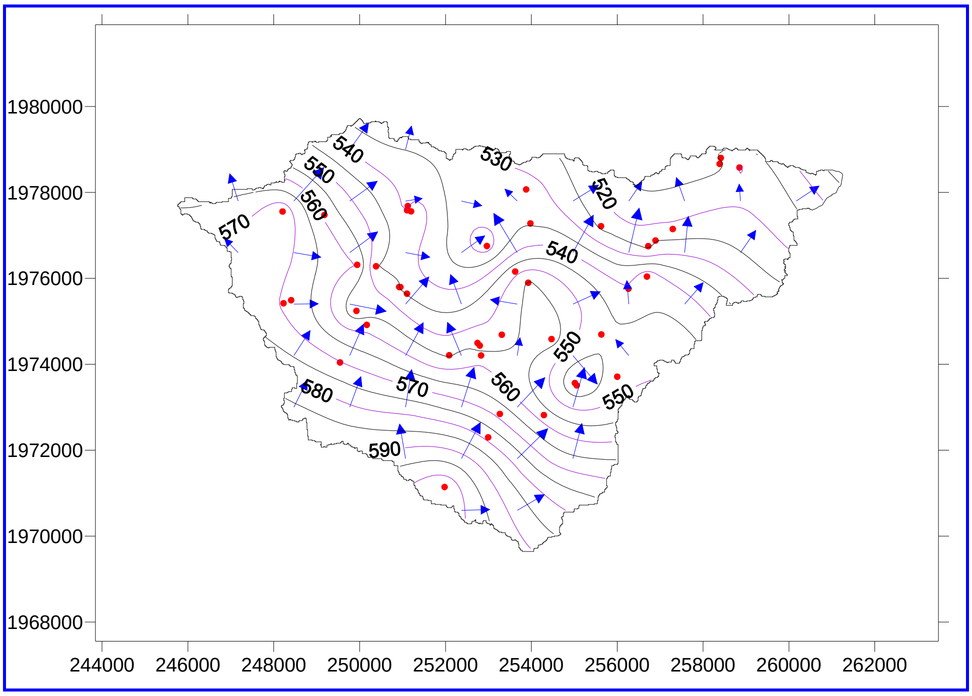

Figure 6: Gajwel piezometric map – November 2006. Arrows depict the groundwater flow direction. Average piezometric level: 551.39 masl. UTM coordinates.

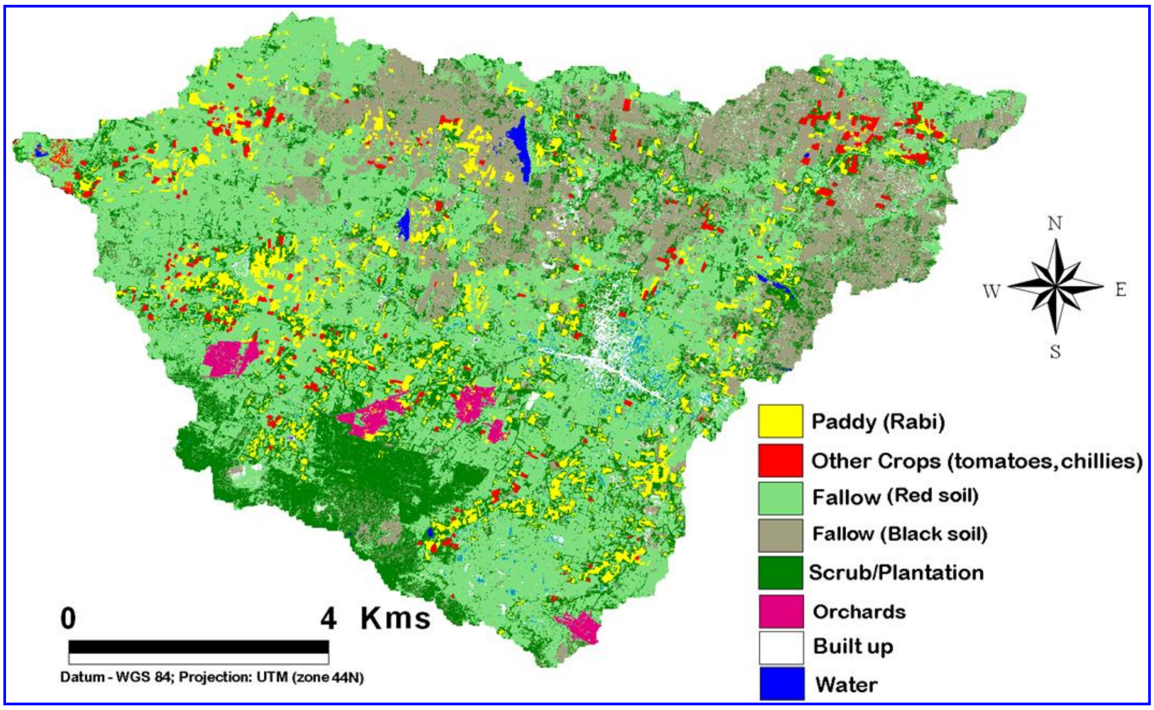

Figure 7: Land use map of Gajwel watershed, dry season 2007.

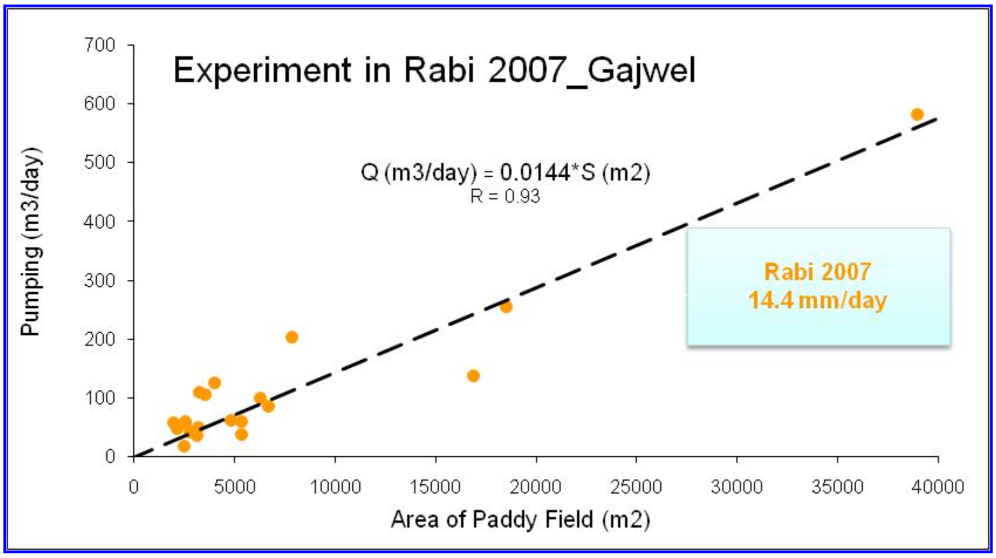

Figure 8: Field surveys on paddy fields for the dry season 2007: relationship between the water input from pumping and the irrigated area.

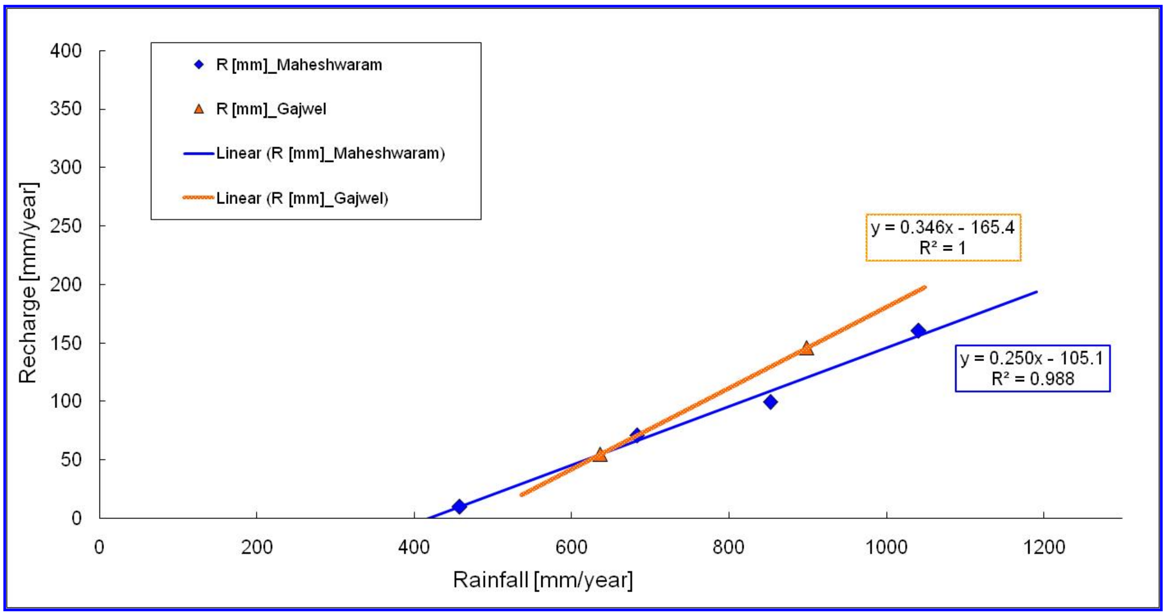

Figure 9: Rainfall-Recharge linear relationship for Gajwel watershed (brown line) and same relationship obtained for Maheshwaram experimental watershed (blue line).

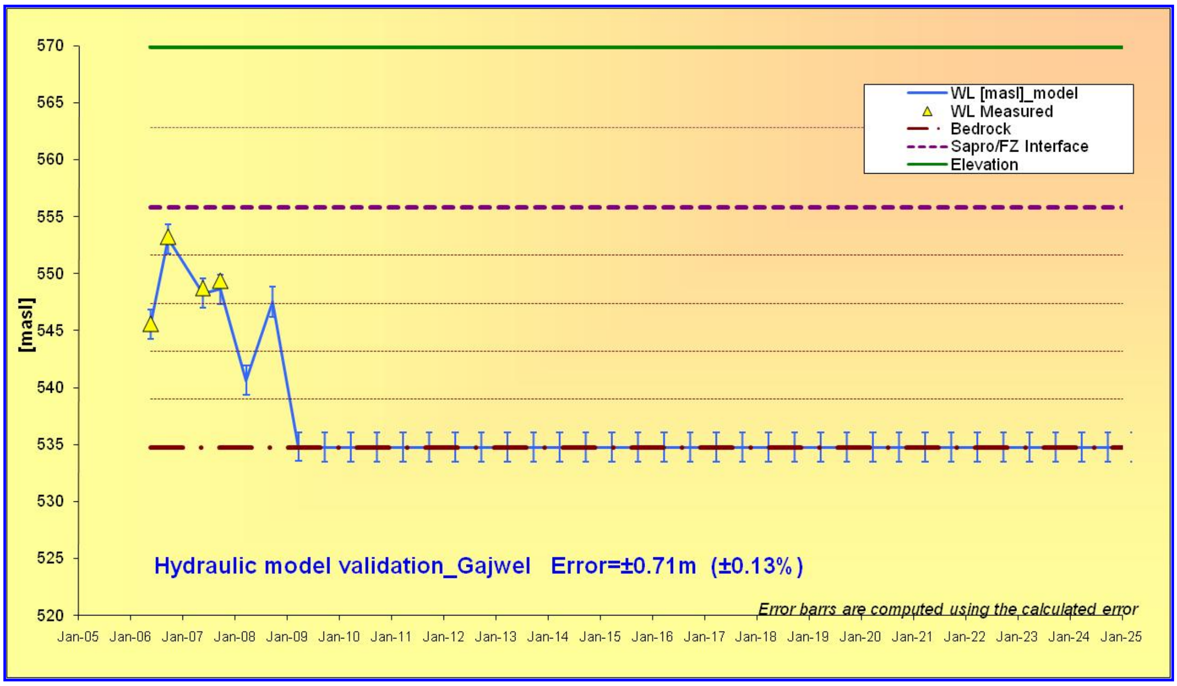

Figure 10: The hydraulic model of Gajwel watershed is calibrated over two hydrological years 2006-2008 (4 calibration points, yellow triangles, corresponding to 2 dry and 2 wet seasons).

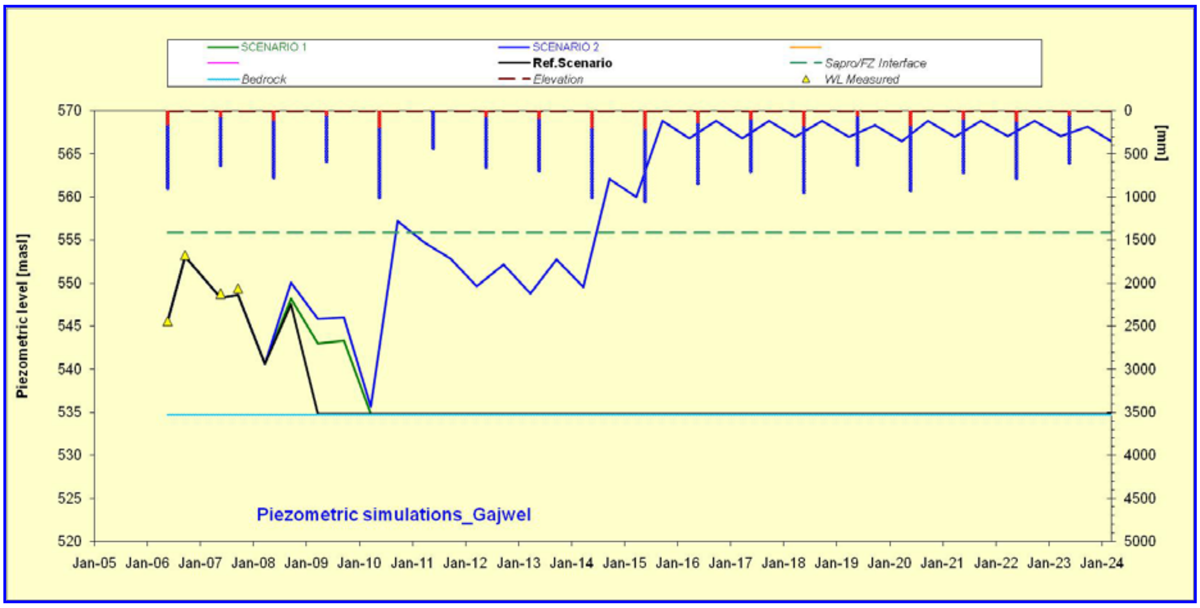

Figure 11: Example of piezometric level simulations, Gajwel watershed: in black reference scenario with calibration period (no change compared to present situation), in green Scenario 1 with cropping pattern changes (less paddy more vegetables), in blue Scenario 2 with same cropping pattern changes and additional artificial recharge (sustainable Scenario).