International Conference "Water, Environment, Energy and Society" (WEES–2009)
New Delhi, 12–16 January 2009

A Decision Support Tool (DST-GW) for Sustainable Groundwater Management in Semi-Arid Hard-Rock Regions

J. Perrin
BRGM, Water Division, Resource Assessment, Discontinuous Aquifers Unit
Indo-French Centre for Groundwater Research, Uppal Road, Hyderabad - 500 007, INDIA
E-mail: perrin@ngri.res.in

B. Dewandel[1] and P. Lachassagne
BRGM, Water Division, Resource Assessment, Discontinuous Aquifers Unit
Rue Pinville 34 000 Montpellier, FRANCE
E-mail: [1]b.dewandel@brgm.fr

H.H. Khan and S. Ahmed[2]
National Geophysical Research Institute, Indo-French Centre for Groundwater Research
Uppal Road, Hyderabad - 500 007, INDIA
E-mail: [2]shakeelahmed@ngri.res.in

ABSTRACT: Until recently, aquifers located in hard rock formations (granite, gneiss, schist) were considered as highly heterogeneous media, and adequate methodologies for groundwater management or borehole siting were non-existent. Recent studies showed that a typical hard rock aquifer 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 research work, the Indo-French Centre for Groundwater Research (BRGM-NGRI located in Hyderabad, Andhra Pradesh, India) has developed an operational Decision Support Tool (DST-GW) designed for groundwater management in hard rock area under variable agro-climatic conditions. This DST-GW focuses on the impact of changing cropping pattern and artificial recharge on the groundwater levels at the scale of small watersheds (up to 100 km^2). The DST-GW is based on the groundwater balance and the 'Water Table Fluctuation Method', well-adapted methods in hard rock and semi-arid contexts. It is a semi-automatic program developed under a MS-Excel Interface. 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. In addition to the hydraulic model, the DST-GW includes a module dedicated to future scenarios including socio-economic indicators: scenario "business as usual", implementation of supply and demand measures to mitigate over-exploitation, impact on farmer incomes, etc.

During its scientific development, the DST-GW has been implemented in a representative south Indian watershed (53 km^2) characterised by a granitic basement, semi-arid climatic conditions, rural context, and groundwater irrigation. For this watershed, the DST-GW models the basin-scale piezometric levels with an average error of less than ±0.6 m from 2001 to 2005 (calibration period); this shows the robustness of the model. Due to groundwater overexploitation (more than 700 bore wells in use), the model results showed that if no measures are taken, the water table depletion will run dry about 50% of the pumping bore wells by the year 2010. Simulations of mitigation measures with the DST-GW show that a realistic change in cropping patterns could rapidly reverse the tendency and lead to a sustainable management of the resource.

INTRODUCTION

Supplying 27 million hectares of farmland in India, groundwater now irrigates a larger area than surface water (21 million hectares). This change has been extremely rapid since the start of the 'Green Revolution' in the 1970s, when the number of borewells have shoot up from less than one million in 1960 to more than 20 million presently. In consequence, and especially in hard rock and (semi)arid areas that covers about 2/3 of the country, the groundwater resource is highly stressed due to large abstraction of water by pumping for irrigation. As a consequence, this overexploitation of the resource threatens the sustainability of water availability and agricultural development. Therefore in these areas, it is necessary, to adapt the groundwater resource exploitation to its availability.

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 most part of Africa and India, the hard rock 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. Consequently, hard rock aquifers can be considered as a composite aquifer constituted of two main layers.

Based on this new conceptual model of hard rock aquifers, the Indo-French Centre for Groundwater Research (IFCGR-Hyderabad) has developed a Decision Support Tool for sustainable groundwater management in semi-arid hard rock regions. For its scientific development, the DST-GW has been implemented in a representative south Indian watershed (Maheshwaram watershed; 53 km² in area, Figure 1) characterised 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).

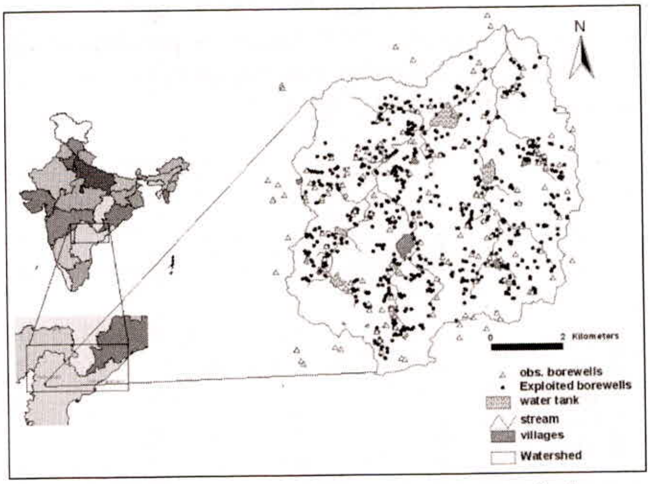


Fig. 1: Maheshwaram watershed, 700 borewells in use for the irrigation of crops.

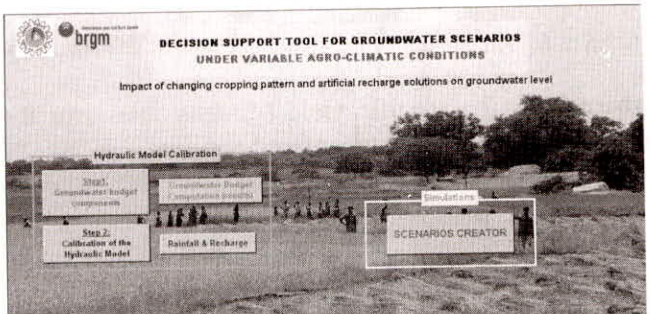
DESCRIPTION OF THE DECISION SUPPORT TOOL (DST-GW)

IFCGR has developed a Decision Support Tool (DST-GW) under MS Excel Software interface. The DST-GW is devoted to groundwater management in semi-arid hard rock areas. Scenarios including impacts of climate change and/or changing cropping patterns can be tested and the groundwater levels forecasted. The DST-GW is particularly well designed for watershed size ranging from 10 to 100 km^2.

As a main result, the DST-GW predicts mean groundwater levels at basin scale for a seasonal time-step, drying up of exploited borewells, and annual mean farmer's incomes per farmer's categories.

The DST-GW is composed of the main active windows (Figure 2):

- *Calibration and validation of the hydraulic model*, it includes, among other, the identification of the saprolite and the fissured layers, various information about the studied watershed, groundwater budget computation, etc. From these data variation in specific yield with depth and variation in groundwater recharge according to annual rainfall are deduced.
- *Creation of scenarios*, it comprises the "most probable scenario", (i.e., the one that predicts what should happen in the studied area according to agricultural, industrial, tourism, etc., policies), the creation of other scenarios different from the previous one, changing climatic conditions (i.e., annual rainfall), information on exploited borewells (i.e., aquifer thickness), and socio-economic data for simulating farmer's incomes (i.e., farmer's categories, incomes per crop, etc.). As a result, predictions of the average groundwater level at basin scale, drying up of borewells and farmer's incomes are visualized.


DECISION SUPPORT TOOL FOR GROUNDWATER SCENARIOS
UNDER VARIABLE AGRO-CLIMATIC CONDITIONS

Impact of changing cropping pattern and artificial recharge solutions on groundwater level

Fig. 2: "Menu" Page of the DST-GW

BRIEF DESCRIPTION OF THE DST-GW HYDRAULIC MODEL

The hydraulic component of the DST-GW is based on the combination of two well-known methods: i) groundwater budget computation, and the 'Water Table Fluctuation (WTF)' (Maréchal *et al.*, 2006).

This combination offers two main advantages while dealing with hard rock aquifers and a semi-arid context: 1) no assumption in hard-rock hydrodynamic behaviour, which can be quite complex in such complex aquifers; 2) precipitation or evapotranspiration components, which may be the source of large uncertainties in semi-arid climate, do not need to be estimated as the DST-GW focuses on groundwater fluxes only. The only basic requirements to use this method are that the aquifer should be unconfined and that dry and rainy seasons should be well differentiated for a proper use of the WTF method.

The basic equation governing the fluxes at the basin-scale into an unconfined aquifer (Figure 3) is adapted from (Schicht and Walton, 1961),

$$R + RF + Q_{in} = E + PG + Q_{off} + Q_{bf} + \Delta S \qquad \dots (1)$$

where R is the total groundwater recharge [mm], RF irrigation return flow [mm], Q_{in} and Q_{off} groundwater flow in and off the aquifer [mm], E evaporation from water table [mm], PG the abstraction of ground water by pumping [mm], Q_{bf} base flow (ground water discharge to streams or springs; in mm), and ΔS change in ground water storage [mm]. Due to the relatively deep water table in the Maheshwaram watershed, more than 17 m in depth, there are neither springs nor contribution of groundwater to streams, consequently the base flow is nil ($Q_{bf} = 0$).

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

$$\Delta S = S_y . \Delta h \qquad \dots (2)$$

where Sy is the specific yield (dimensionless) or the fillable porosity of the unconfined aquifer.

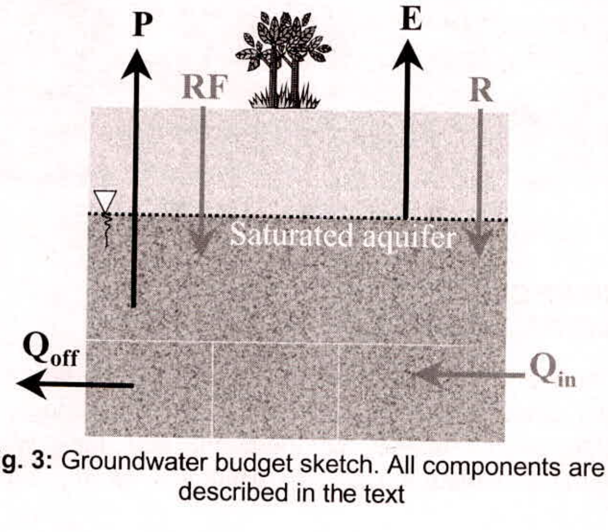


Fig. 3: Groundwater budget sketch. All components are described in the text

Due to seasonal monsoon rainfall, water levels display sharp rises and declines. Therefore, the hydrological year can be divided into two distinct seasons: dry (Rabi, November to May) and rainy (Khariff, June to October). Thus, combining the use of both groundwater budget and water table fluctuation methods twice a year allows on one hand, the estimate of the unknown parameter Sy during the dry season by assuming a nil recharge in Eqn. 1, and on the other hand the estimation of recharge during the rainy season (i.e., with known Sy in Eqn. 1).

Application of the combined method requires an accurate knowledge of all the components of the budget, except recharge and specific yield, which are considered in this approach as unknown parameters and are thus computed based on the previously described approach.

The methods for estimating the different flux components presented in Eqns. 1 and 2 (RF, PG, Q_{on}, Q_{out}, E and Δh) are not described in this paper, however the reader may refer to some of the methodologies proposed by the authors (Maréchal *et al.*, 2006; Zaidi *et al.*, 2007; Dewandel *et al.*, 2008) or select other relevant methods.

For Maheshwaram watershed, the DST-GW has been calibrated over 5 consecutive years from June 2001 to June 2005. As a result, one obtains five couples of Sy estimates versus range of piezometric fluctuations that is used to compute a Sy vs. elevation model ($Sy = f$ (elevation); Figure 4). The Sy model gives an average Sy for the fissured zone of 8.08×10^{-3}, which is quite consistent with data obtain from pumping tests (6.3×10^{-3}; Maréchal *et al.*, 2004). Once the previous model is calibrated, the DST-GW automatically computes the recharge-rainfall model (Figure 5).

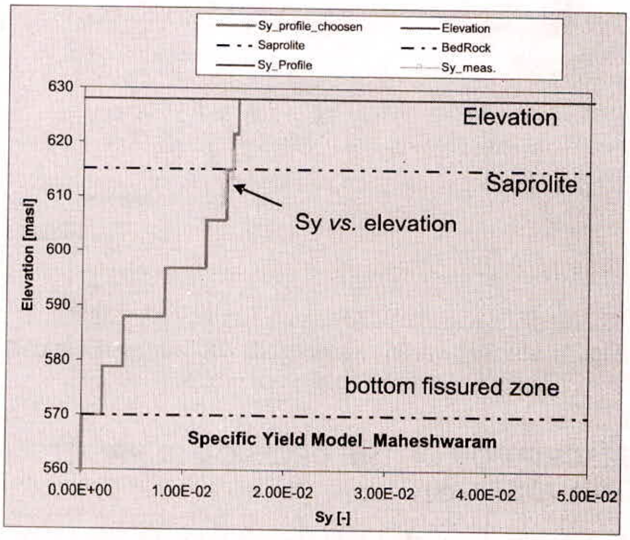


Fig.4: Automatically generated Sy *vs.* elevation model according to groundwater budget data

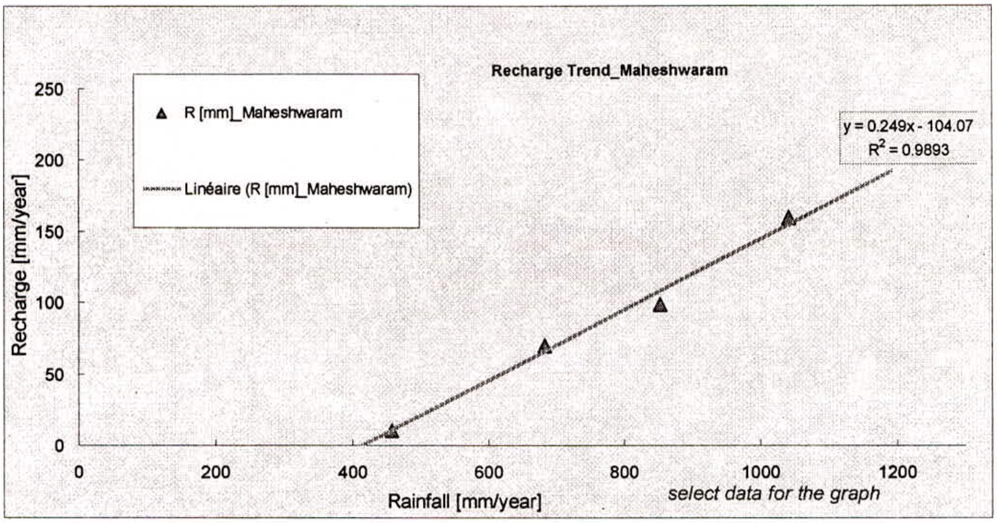


Fig. 5: Automatically generated Annual recharge *vs.* annual rainfall model according to groundwater budget data and Sy model (Figure 4)

As a final confirmation of these models, the user is conveyed to validate the calibration of the hydraulic model by checking the good match between observed and simulated average water levels (Figure 6). For this watershed, the DST-GW models the basin-scale piezometric levels with an average error of less than ±0.56 m from 2001 to 2005 (calibration period) which shows the robustness of the model. Then once the hydraulic model is validated the user may proceed to the scenario creator mode.

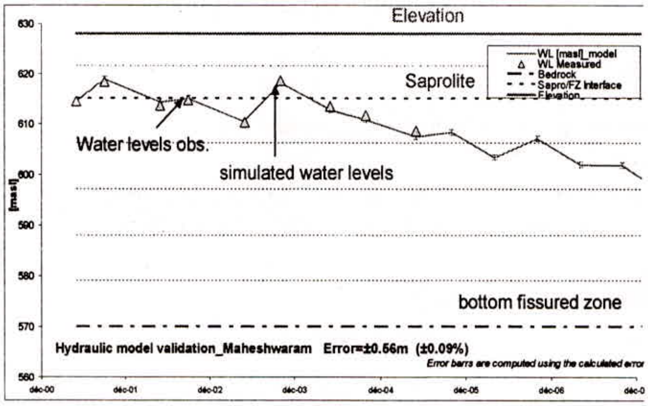


Fig. 6: Hydraulic model validation: comparison between observed and simulated average water levels; 5 years of calibration

SCENARIOS

Reference Scenario

Considering no apparent climatic changes, Figures 7a & b use the 20 previous annual rainfall data as the rainfall scenario. The groundwater resource limit at the watershed scale (or the bottom of the aquifer; horizontal dotted line in Figure 7a, below which the aquifer cannot be exploited, will be reached by the year 2012 if the groundwater exploitation by pumping continues at the present rate of development (about 1.3% per year, FAO, 1997). As a consequence about 80% of farmer's borewells will be dry at the same date (Figure 7b) with serious socio-economic consequences.

Impact of Climate Variability on the Reference Scenario

Figure 8a&b present water level simulations with the occurrence of two consecutive "low" and "good" monsoons in 2008 and 2009; 450 mm/year and 1100 mm/year respectively. One may imagine that in the case of two consecutive "low" monsoons, serious problems will start from today with a strong depletion of the aquifer. Finally, if two "good" monsoons occur for the two coming years, this will only let few years, up to 2013, to find a sustainable solution. As a result and whatever the rainfall amount provided by the monsoon, the strong depletion of the aquifer will occur sooner or later, and maybe faster than expected. Realistic solutions have to be found quickly and the DST-GW can be useful for that.

Impacts on Groundwater Levels of Changing Cropping Pattern and Artificial Recharge Solution

The DST-GW has been especially built to test the impact of changing cropping pattern solutions on groundwater levels, and on farmer's incomes. The impact of increasing or decreasing cultivated areas onto the groundwater level is predicted.

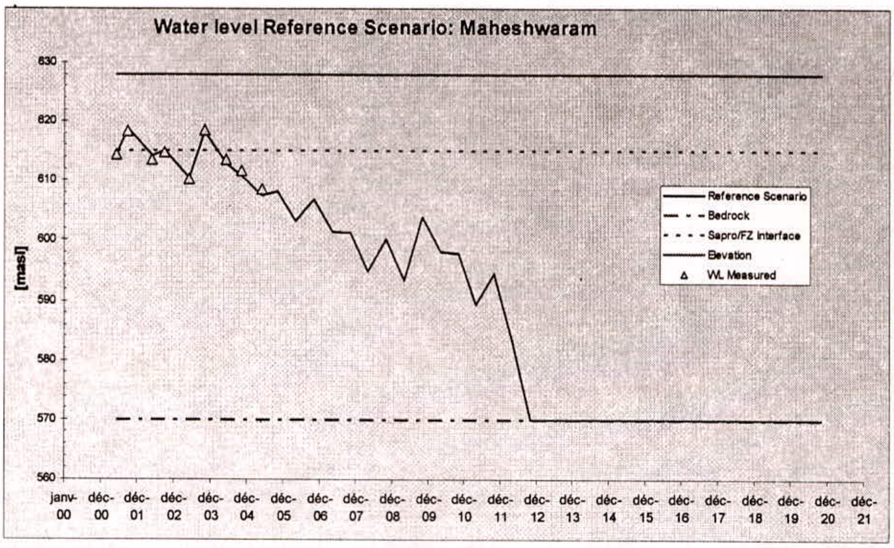


Fig.7a: Reference scenario. Simulation of water levels in Maheshwaram watershed, no climatic change and ~1.3%/year increase of irrigated area (FAO (1997). Triangles: mean annual groundwater levels during the calibration period (2001 to 2005)

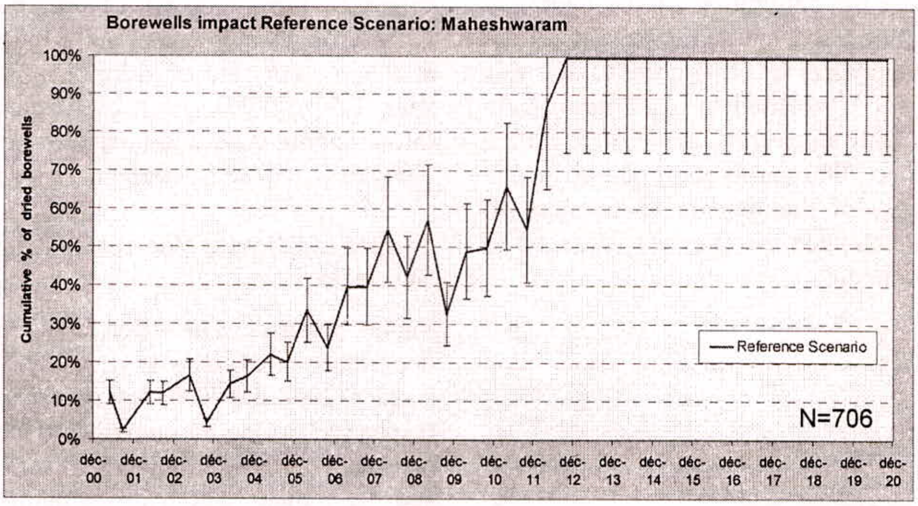


Fig. 7b: Drying-up of borewells according to the Reference scenario. The vertical bars depict the degree of uncertainty, which depends on the spatial variability of the aquifer thickness (about 25% of uncertainty)

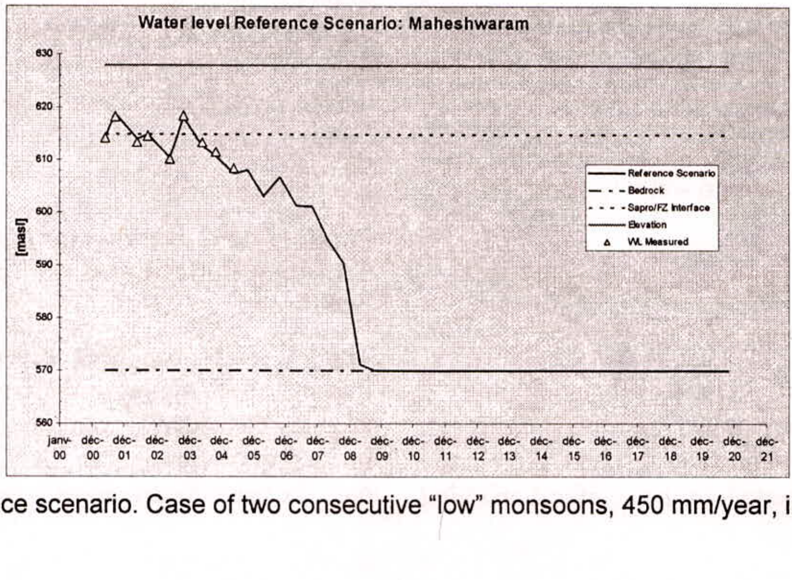


Fig. 8a: Reference scenario. Case of two consecutive "low" monsoons, 450 mm/year, in 2008 and 2009

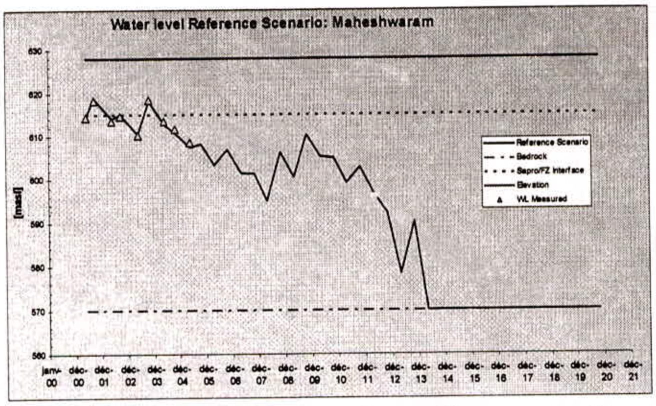


Fig. 8b: Reference scenario. Case of two consecutive "good" monsoons, 1100 mm/year, in 2008 and 2009

In order to avoid non-realistic scenarios, which may not be accepted by the farmers for profitability or socio-cultural reasons, the DST-GW has been designed to enable an action plan over several years.

For example, Figure 9a and b consider two 15 years action plan scenarios:

1. Scenario 1: 10% decrease of rice cultivated area every year from 2008 to 2017 then an annual decrease of 5% up to 2020, at the same time a 20% increase of vegetable and flower cultivated areas every year. As a result, rice cultivated area, which is about 700 ha today, will be about 220 ha in 2020 and, vegetables and flowers that cover about 70 ha today, will be about 750 ha in 2020. Thus, at the end of the plan 200 additional hectares will be cultivated.
2. Scenario 2 considers scenario 1 and the build-up of additional percolation tanks between 2008 and 2013 (+15 ha), knowing that today they cover about 80 ha in area.

In both scenarios, the water level would be more or less maintained before getting back to its original level with potential benefits for the farmer's population (+200 ha to cultivate); therefore this would bring a sustainable solution.

In addition, the scenario 2 demonstrates that artificial recharge cannot be considered as the unique measure for tackling the groundwater depletion in this area. Its contribution to improve the situation is minimal compared to changing cropping patterns. But a combination of both could seriously improve the groundwater situation. Therefore, policies aiming at sustainable groundwater management may consider a package of supply/demand measures rather than only one measure.

CONCLUSION

It is very important to assess the availability of the water resource in a quantative way and balance it with the demand. The difference could and should be managed by demand measures such as agri-changes, improving the irrigation techniques, etc. and supply measures such as artificial recharge. Decision Support Tools are a well adapted approach because users can play on the different components of the water demand/supply in an interactive way.

The developed DST-GW is especially designed for groundwater management in hard rock semi-arid regions. It is an interactive software, where the users can build-up scenarios and visualize the outcome. The DST-GW has been tested and validated in Maheshwaram watershed and the developed methodology can be applied to any other watershed in a similar context.

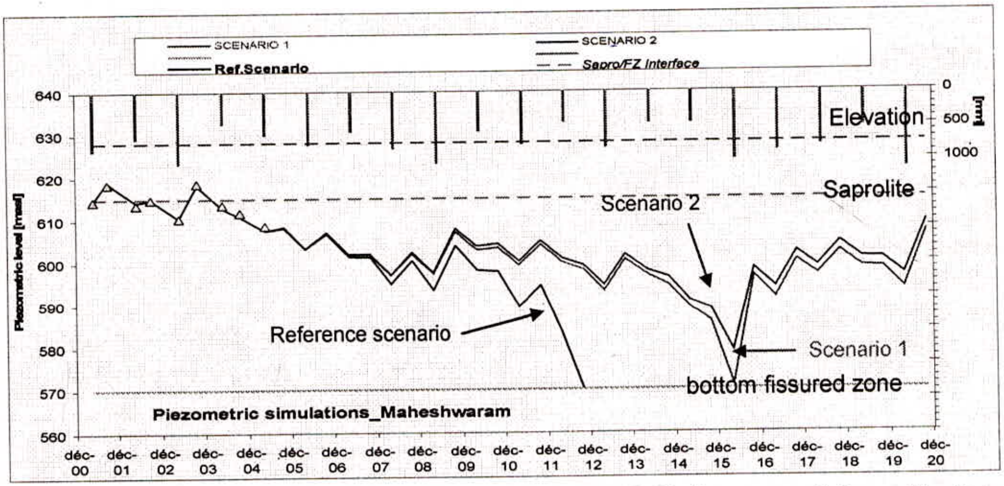


Fig. 9a: DST, testing scenarios on groundwater levels. Scenario 1: 10 % decrease of rice cultivated area every year from 2008 to 2017 then an annual decrease of 5% up to 2020, at the same time 20% increase of vegetables and flowers cultivated area every year. Scenario 2: considers scenario 1 + build-up of 15 ha of additional percolation tanks between 2008 and 2013

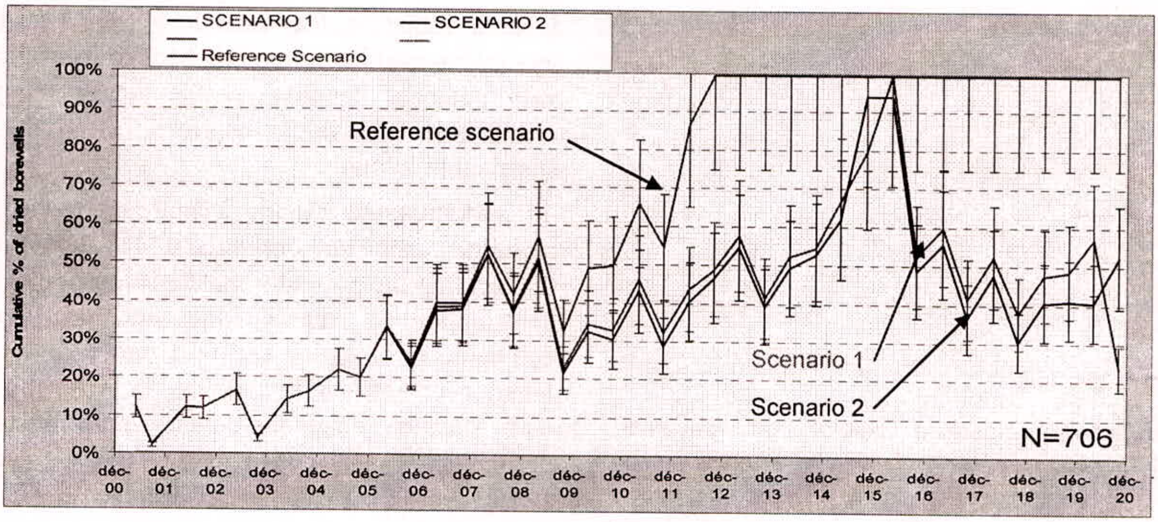


Fig. 9b: DST, testing scenarios, impact on borewells. Results of Scenario 1 and 2 (Figure 9a)

Moreover, this DST-GW is a first version and will soon incorporate the forecast of farmer's incomes.

Recently the DST-GW and the related methodologies have been implemented at an operational scale for Policy Makers and Planners in the Gajwel watershed (80 km^2) under the project SUSTWATER sponsored by the European Commission (Asia ProEco programme). This project was carried out in close collaboration with the Andhra Pradesh Rural Development Department and Groundwater Department.

The DST-GW can create an efficient link between Policy Makers and water experts. The experts help for building-up realistic scenarios, including both the socio-economic aspects and the Policy Maker's constraints. The simulation results can be criticized, optimized and validated together, and it is only afterwards that the authorities can implement actions.

ACKNOWLEDGEMENTS

The authors are grateful to the research-sponsorship from many sources such as: IFCPAR (New Delhi), BRGM (France), Embassy of France in India, NGRI (India) and the European Commission (SUSTWATER AsiaProEco Project). Colleagues from NGRI (Hyderabad), BRGM (France), Department of Rural Development, AP Govt. and AP Groundwater Department, CGWB are thanked for their fruitful comments and discussions.

REFERENCES

Dewandel, B., Lachassagne, P., Wyns, R., Maréchal, J.C. and Krishnamurthy, N.S. (2006). "A generalized hydrogeological conceptual model of granite aquifers controlled by single or multiphase weathering." *Journal of Hydrology*, 330, 260–284, doi:10.1016/j.jhydrol.2006.03.026.

Dewandel B., Gandolfi, J.M., de Condappa, D. and Ahmed, S. (2008). "An Efficient Methodology for Estimating Irrigation Return Flow Coefficients of Irrigated Crops at Watershed and Seasonal Scales", *Hydrological Processes*, in press.

FAO-Forestry (1997). "Aquasat: FAO's Information System on Water and Agriculture", available on www.fao.org/ag/agl/aglw/aquasat/countries/india.

Maréchal, J.C., Dewandel, B., Ahmed, S. and Galeazzi, L. (2006). "Combining the groundwater budget and water table fluctuation methods to estimate specific yield and natural recharge." *Journal of Hydrology*, 329, 1–2, 281–293, doi:10.1016/j.jhydrol.2006.02.022.

Maréchal, J.C., Dewandel, B. and Subrahmanyam, K. (2004). "Use of hydraulic tests at different scales to characterize fracture network properties in the weathered-fractured layer of a hard rock aquifer", *Water Resources Research*, Vol. 40, W11508, 1–17.

Schicht, R.J. and Walton, W.C. (1961). "Hydrologic budgets for three small watersheds in Illinois", *Illinois State Water Surv Rep Invest* 40, p. 40.

Wyns, R., Gourry, J.-C., Baltassat, J.-M. and Lebert, F. (1999). "Caractérisation multiparamètres des horizons de subsurface (0–100 m) en contexte de socle altéré, in *2ième Colloque GEOFCAN"*, edited by I. BRGM, IRD, UPMC, pp. 105–110, Orléans, France.

Zaidi, F.K., Ahmed, S., Maréchal, J.C. and Dewandel, B. (2007). "Optimizing a piezometric network in the estimation of the groundwater budget: A case study from a crystalline-rock watershed in southern India", *Hydrogeology Journal* 15: 1131–1145.