Development of a tool for managing groundwater resources in semi-arid hard rock regions: application to a rural watershed in South India

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ABSTRACT

Until recently, aquifers located in hard rock formations (granite, gneiss, schist) were considered as a highly heterogeneous media, and no adequate methodology for groundwater management was available. Recent research studies showed that when hard-rocks are exposed to regional and deep weathering processes and when the geology is relatively homogenous, a typical hard rock aquifer is made of two main superimposed hydrogeological layers each characterized by quite homogeneous specific hydrodynamic properties: namely the saprolite and the fissured layers. Therefore, for these cases, hard rock aquifers can be considered as a multi-layered system.

Based on these works, an operational Decision Support Tool (DST-*GW*) designed for the management of groundwater resources in hard rock area under variable agro-climatic conditions has been developed. The tool focuses on the impact of changing cropping pattern, artificial recharge and rainfall conditions on groundwater levels at the scale of small watersheds (10 to about 100 km^2 in case well-developed weathering profile). DST-*GW* is based on the groundwater balance and the 'Water Table Fluctuation Method', well-adapted methods in hard rock and semi-arid contexts.

Based on field data from an over-exploited south Indian watershed (58 km^2), the model allows calibrating, at watershed scale, the variation in specific yield of the aquifer with depth, as well as the rainfall/aquifer recharge relationship. Seasonal basin-scale piezometric levels are computed with an average deviation of ±0.56 m compared to measurements from 2001 to 2005. The model shows that if no measure is taken the water table depletion will induce the drying up of most of the exploited borewells by the year 2012. Scenarios of mitigation measures elaborated with the tool show that change in cropping patterns could rapidly reverse the tendency and lead to a sustainable management of the resource.

This work presents the developed tool and particularly the hydraulic model involved in, and its application to a case study. However, the purpose tool is applicable at watershed scale but not design for the groundwater management of a very small area or for a single bore well.

Key words: groundwater management, hard rock aquifer, overexploitation, groundwater budget, DST-*GW*

1. 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 result, 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 conducted in African, European and Indian basements (e.g., Omorinbola, 1982, 1983; Wright, 1992; Chilton and Foster, 1995; Owoade, 1995; Wyns et al., 1999; Taylor and Howard, 2000; Maréchal et al., 2004; Dewandel et al., 2006; Krásný and Sharp, 2007; Maréchal et al., 2007, Courtois et al., 2008, Courtois et al., in press, etc.) showed that when hard rocks are exposed to regional and deep weathering processes and when the geology can be considered as homogenous, the aquifer is constituted of two main sub-parallel hydrogeological layers, namely the saprolite, a clayey-sandy material, and the fissured layers, generally characterized by a dense horizontal fissuring in the first few meters and a depth-decreasing density of fissures. Usually, the total thickness of the weathering profile is comprised between 50 to 100 m. Each layer can be considered as homogeneous and is therefore characterized by quite homogeneous hydrodynamic properties (Maréchal et al., 2004, 2007; Dewandel et al., 2006). For example in hard rock areas of India and Africa, this homogeneity in term of layers thicknesses and hydrodynamic properties is shown from 100 m to kilometric scale (e.g., Dewandel et al., 2006; Courtois et al., 2008, Courtois et al., in press). Consequently, hard rock aquifers exposed to regional deep-weathering processes can be considered as a composite aquifer constituted of two main layers characterized by their own hydrogeological properties.

Based on this 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 at watershed scale (DST-*GW*). The main objective of the tool is to help stakeholders to visualise what would happen to groundwater levels under different conditions of groundwater exploitation (irrigation), implementation of artificial recharge structures, and rainfall scenarios. The hydraulic model involved in DST-*GW* is based on the water table fluctuation method and groundwater budgets performed at catchment scale (Maréchal et al., 2006). DST-*GW* predicts mean groundwater levels at seasonal and watershed scale and is thus a lumped model. However, the purpose tool is applicable at watershed scale, so it cannot be used for the groundwater management of a very small area or a single exploited borewell.

For its scientific development, DST-*GW* has been implemented in a representative south Indian watershed (Maheshwaram watershed; 58 km² in area, Fig.1) characterised by a granitic basement, a relatively flat area (from 590 to 670 masl), semi-arid climatic conditions (mean annual precipitation: 750 mm; potential annual evapotranspiration: 1800 mm; aridity index= 0.42), rural context, and groundwater overexploitation due to large amount of water pumped for the irrigation of rice (210 ha during the dry season and 500 ha during the rainy season), vegetables (15 ha), flowers (20 ha), fruit trees (47 ha) and grape (55 ha). The mean annual groundwater abstraction at catchment scale is about 10 Mm^3 (174 mm).

This work presents the developed tool and particularly the hydraulic model involved in, and its application to the Maheshwaram watershed.

2. BRIEF DESCRIPTION OF THE TOOL

Figure 2 presents the break down structure of the tool.

DST-*GW* is composed of the following main active windows:

- Input data for groundwater budget computation: groundwater fluxes at basin scale (RF, Q_{in}, Q_{off}, PG, E, watershed scale piezometric levels; see Eqs.1 and 2), mean elevation, and mean elevation of the bottom of the saprolite layer and of the bedrock (fresh basement). Input data are averages at watershed scale,

- Calibration and validation of the hydraulic model, from previous data relationships at watershed scale between elevation and specific yield as well as rainfall and recharge are established. These relationships are used to compute theoretical water levels that are compared to the ones observed. These relationships are used for computing future scenarios.

- Scenario: it comprises a modulus for creating the "most probable scenario" (i.e., the one that predicts what should happen in the studied area according to agricultural, industrial, tourism policies) and other scenarios for testing other strategies. For all the scenarios, groundwater uses can be modified as well as rainfall conditions. This window also comprises input information on exploited borewells (i.e., elevation of the base of the fissured layer), structures favouring artificial recharge and rainfall historical data.

DST-*GW* is devoted to groundwater management in semi-arid hard rock areas. Scenarios including impacts of rainfall change and/or changing cropping patterns can be tested and groundwater levels forecasted. DST-*GW* is particularly well designed for watershed size ranging from 10 to 100 km^2 where geology, layers thicknesses of the weathering profile and hydrodynamic properties can be considered as homogeneous. In addition and as a basic prerequisite, the aquifer has to be unconfined to allow proper uses of groundwater budget and water table fluctuation methods (see next section).

As a main result, the tool estimates mean groundwater levels at basin scale on a seasonal time-step (for dry and rainy seasons only; two values per year) and an estimate of the drying up of exploited borewells. Therefore, the tool is particularly well-suited for encouraging discussions between stakeholders to favour the implementation of groundwater exploitations strategies and regulations.

3. DESCRIPTION OF THE HYDRAULIC MODEL INVOLVED IN DST-*GW*

The hydraulic component of DST-*GW* is based on the combination of the well-known 'Water Table Fluctuation (WTF)' method and groundwater budget computation for estimating aquifer specific yield and annual recharge (Maréchal et al., 2003 and 2006; Saha and Agarwal, 2006.). This combination offers two main advantages while dealing with hard rock aquifers and semi-arid context: i) no use of hydrodynamic parameters in the model except for estimating some groundwater budget components, and ii) evapotranspiration from crops, which can be the source of large uncertainties particularly in semi-arid climate, does not need to be estimated as DST-*GW* focuses on groundwater fluxes only (recharge is computed with WTF method). 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 (significant water table rises and declines).

3.1 Groundwater budget equations

The basic equation governing the fluxes at the basin-scale into an unconfined aquifer is (Schicht and Walton 1961):

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

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 boundary [mm], E evaporation from water table [mm], PG groundwater abstraction by pumping [mm], Q_{bf} base flow (ground water discharge to streams or springs; in mm), and ΔS change in groundwater storage [mm]. Due to the relatively deep water table in the Maheshwaram watershed (more than 17 m), 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, which links the change in groundwater storage, *ΔS,* with resulting water table fluctuations, *Δh*:

$$\Delta S = S_y . \Delta h \quad (2)$$

where S_y is the specific yield (dimensionless), or the effective porosity of the unconfined aquifer.

Due to seasonal monsoon rainfall, piezometric levels display sharp rises and declines (see Table 1). 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 the one hand, the computation of the unknown parameter S_y during the dry season by assuming a nil recharge in Eq.1, and on the other hand the computation of recharge during the rainy season (i.e., with known S_y in Eq.1).

3.2 Estimation of the flow components

Application of the WTF 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 calculated using the combined method described above.

WTF method has been successfully applied to Maheshwaram watershed. Tables 1 and 2 summarize the seasonal and annual groundwater budget for the five studied hydrological years (2001 to 2005). The next section briefly describes how the different components have been evaluated. However, the reader may find additional information in Maréchal et al. (2006) for all components of Eq.1 and the impact of their uncertainties on the groundwater balance, *Sy* and *R* estimates, in Zaidi et al. (2007) particularly for *h* and *Δh* estimates according to various observation networks and impact on balance, *Sy* and *R*, and finally in Dewandel et al. (2008) for *RF* and *PG* estimates. Using such methods Maréchal et al. (2006) showed that the maximum expected uncertainty introduced by the fluxes components of Eq.1 on the total groundwater recharge and the annual groundwater balance is about 20%.

Precise seasonal water level fluctuations (Δh) were obtained by establishing detailed piezometric maps at the end of the dry seasons (in June) and at the end of the rainy seasons (October-November) based on up to 165 piezometers (IFCGR and non-exploited borewells; Fig.1). No measurements were perfomed in pumped wells and the rare cases of observed drawdown in the monitored wells (monitoring of IFCGR observation wells; time recording time interval: 15') are never more than 10 to 20 cm, which is little compared to water table fluctuations at seasonal scale (several meters). The relative error on the water table fluctuation has been calculated by geostatistics and logically decreases with the number of measurements (Tab.1). Mean seasonal piezometric levels were obtained from mapping and kriging of piezometric data; Figure 3 presents one of the piezometric map and Table 1 the mean seasonal piezometric levels at the catchment scale and the corresponding Δh with the relative error (±).

Groundwater abstraction (*PG* in Eq. 1) was evaluated by combining a well inventory database (i.e., discharge rate of each exploited borewell) and daily duration of pumping, which have been deduced from piezometric data influenced by exploited wells (Dewandel et al., 2008). The mean annual groundwater abstraction (Mean annual in Table 2) is 174 mm, and has been evaluated for all groundwater uses, i.e.: rice (86.8% of *PG*), vegetable (0.7%), flowers (0.8%), fruit trees (2.5%), grapes cultivation (5.2%), domestic (1.7%) and poultries (2.3%). The groundwater abstraction was found in accordance with the one evaluated from a land use map using remote sensing technique (difference of about 5%, NRSA, 2003). Table 2 presents the groundwater abstraction per season and per uses.

Irrigation return flows (*RF* in Eq. 1) were estimated for each irrigated crops, except for grapes and fruit trees, which use drip irrigation technique; for these crops *RF* was assumed nil. Irrigation return flows for rice, flowers and vegetables cultivation were estimated from a hydraulic model that combines both unsaturated and saturated flow theory and few information about the soil type, the meteorological conditions [rainfall and potential evaporation], the frequency of irrigation and the cropping calendar (Dewandel et al., 2008). The obtained irrigation return flow coefficients, i.e. the ratio of the irrigation return flow (*RF*) to the abstracted flow (*PG*), are on average 47% for rice (PG_{rice}/RF_{rice} in Tab.2), 23% for vegetables and 10% for flowers, and are similar to coefficients found in the literature (APGWD, 1977; Chen et al., 2002; Jalota and Arora. 2002). As no information about return flow from domestic and poultries uses was available, and since return flow may exist, a value of 20% was assumed. On average, mean annual return flow from pumping corresponds to about 72 mm meaning that about 42% of the groundwater abstraction returns back to the aquifer.

Groundwater evaporation, E, was estimated using an empirical relationship established for semi-arid environment that depends on groundwater level depth, z, (E=71.9$z^{-1.49}$; Coudrain, et al., 1998). In Maheshwaram watershed, it is a very small groundwater budget component, 2.3 mm/year, due to quite deep water levels (more than 17 m). Even if the proposed estimate is probably not the best because of the use of an empirical relationship its order of magnitude is outlined. In addition, because of its small amount compared to other fluxes this component will not affect significantly the groundwater budget.

Horizontal in and out flows, Q_{in} and Q_{off}, across the aquifer boundaries, were evaluated using a finite-differences model run in steady state mode (Modflow; Maréchal et al., 2006). The top of the fresh basement (Dewandel et al., 2006) and the piezometric map are used in computation. The aquifer permeability has been assumed constant at the watershed scale and equal to 4x10^{-6} m/s (Maréchal et al., 2004). Results show that Q_{in} and Q_{off} are also small components of the groundwater budget (annual balance: about -1 mm/year).

3.3 Computation of the specific yield and the recharge at the watershed scale

3.3.1 Specific yield, S_y:

According to the different groundwater fluxes (see previous section), the specific yield, S_y, is computed for each dry seasons at the watershed scale using Eqs. 1 and 2. As a consequence, a set of couple of S_y *versus* range of piezometric fluctuations (Δh) is obtained, Δh being defined by the average post- and pre-monsoon piezometric levels (see Table 1).

The bars in Fig. 4 illustrate the (S_y, Δh) couples for the dry seasons October 01-June 02 (S_y: 0.013), November 02-June 03 (S_y: 0.014), November 03-June 04 (S_y: 0.015) and November 04-June 05 (S_y: 0.014).

In the fissured zone of the weathering profile, aquifer permeability and storativity primarily depends on the degree of weathering and thus on the density of fissures, which itself decreases rapidly with depth (Acworth 1987; Wyns et al., 1999; Maréchal et al., 2004, Dewandel et al., 2006). Moreover, it has been shown that fissure properties are characterized by similar hydraulic properties whatever their location in the fissured layer (Dewandel et al., 2006). Consequently, it is proposed to model the variation in S_y vs. elevation by the variation in the percentage of fissures with the elevation. The percentage of fissures is deduced from a statistical analysis based on flowmeter tests in borewells carried out in the study area (Fig. 5; Dewandel et al., 2006). To compute the vertical variation in S_y at the watershed scale, the fissured zone is discretized in five layers of equal thickness (layers L3 to L7; Figs. 4 & 5), and the saprolite layer in two layers of equal thickness (layers L1 and L2).

First, the average specific yield of the investigated fissured zone, $S_{ypond\text{-}FZ}$, is computed using Eq. 3:

$$S_{y_{pond-FZ}} = \sum_{i=1}^{n} S_{y_i} \Delta h_i / \sum_{i=1}^{n} \Delta h_i \qquad (3)$$

where S_{yi} are S_y estimates in the investigated intervals Δh_i (see Table 1).

Then, assuming a linear relationship between $S_{ypond\text{-}FZ}$ and the percentage of fissures encountered within the same investigated zone leads to estimate the average S_y per fissure, $Ratio_{\%fiss.}$:

$$Ratio_{\% fiss.} = \frac{S_{y_{pond\_FZ}} \sum_{i=1}^{n} \Gamma_i}{\sum_{i=1}^{n} X_i \Gamma_i} \qquad (4)$$

where X_i is the percentage of fissure in the discretized layer i, Γ_i is the investigated fraction of the discretized layer i.

Therefore, Eq. 4 is used for modelling the variation in S_y vs. elevation for the entire fissured zone by multiplying the percentage of fissure of each layers by $Ratio_{\%fiss}$. For the saprolite layer, weighted values of the investigated intervals within the saprolite layer are used. Figure 4 presents the modelled S_y at the watershed scale vs. elevation deduced from the four years of records.

When all the data set (June 01 to June 05, 4 years) is used for calibrating the S_y model, it gives for the fissured zone of the Maheshwaram granite aquifer an average S_y value of 8.0×10^{-3}, which is consistent with data obtain from pumping tests, in average 6.3×10^{-3} (Maréchal et al., 2004), this validates the high elevation-decrease in S_y and shows the robustness of the methods used for modelling S_y.

However, if required the S_y model can be changed and different S_y values can be prescribed to each of the seven discretized layers. This option lets the users free to test any other hypothesis concerning the variation in specific yield with elevation.

3.3.2 Recharge, R:

Once the S_y model is established, then the recharge model is computed using Eqs. 1 and 2, and the groundwater budget components during the rainy seasons. This procedure is more accurate than the classical water table fluctuation method which usually assumed a constant S_y value for the entire aquifer thickness. It is why recharge values estimated in Maréchal et al. (2006) are slightly different (Jun 02 - Nov 02: 70.5 against 70.8* mm; Jun 03 - Nov 03: 156.5 against 160.4* mm; * this study).

Based on the analysis of the complete data set (four years of records) and on the previously defined S_y model, a linear relationship between recharge and annual rainfall is found (Fig. 6). This model is thus applied to rainfall values for modelling the recharge at the watershed scale. However even if the linear character of this relation is consistent with other studies carried out in granitic areas of south India that use tritium as recharge tracer (Fig. 6; Rangarajan and Athavale, 2000; Sukhija et al., 1996), the model computes higher values. Because of the use of the WTF method, DST-*GW* computes an estimation of the total recharge at the basin-scale while the tritium technique, a local approach, gives only the minimum recharge ('direct' recharge) and does not take account of both 'indirect' recharge, the percolation through rivers and tanks beds, and 'localized' recharge through local geological or topographic variations (Lerner et al., 1990; Maréchal et al., 2006). This is why values from DST-*GW* are higher. In turn, this difference gives the maximum expected percolation at the watershed scale through the tanks located in the study area that cover about 80 ha. The difference between the two trends (positive value only) is used for estimating the maximum expected artificial recharge from the tanks under variable rainfall conditions.

Once S_y and recharge models are calculated, the annual groundwater balance can be computed for each hydrological year (Tab. 2).

For the Maheshwaram aquifer, the groundwater balance from 2001 to 2005 is very often negative which illustrates the overexploited status of this aquifer. Only the year 2003 was a 'positive' year due to high and quite exceptional rainfall (1041 mm). On average (see Mean annual in Tab. 2), annual depletion of groundwater levels is 1.5 m with a negative balance of about -20 mm. This shows that even if rainy year may provide a significant increase of groundwater levels, their frequency is too low to counterbalance the negative balance induced by the pumping during 'normal' and 'weak' rainy years.

3.4 Computation of piezometric level and model sensitivity

3.4.1. Computation of piezometric levels

Piezometric levels computation either for validating the model or forecasting groundwater levels under different abstraction and/or rainfall conditions, makes use of the S_y model, the recharge model, and the variation in aquifer storage, ΔS which depends on the different groundwater fluxes (see Eq. 1).

Computed piezometric level, h_{t+1}, at time $t+1$ that corresponds to the next season can be written as follows,

for $\Delta S \geq 0$:

$$h_{t+1} = h_t + \frac{1}{S_{y_{i+1}}} \left[\Delta S_{t+1} - \sum_{i=1}^{n} (Y_{i+1} - h_t) S_{y_i} + (Y_{i+1} - Y_i) S_{y_i} \right] \tag{5a}$$

and for $\Delta S < 0$:

$$h_{t+1} = h_t + \frac{1}{S_{y_{i-1}}} \left[\Delta S_{t+1} - \sum_{i=1}^{n} (h_t - Y_i) S_{y_i} + (Y_i - Y_{i-1}) S_{y_i} \right] \tag{5b}$$

where h_t is the piezometric level at time t, h_{t+1}, piezometric level at time $t+1$, S_{yi}, specific yield of the discretized layer i, ΔS_{t+1}, storage variation at $t+1$,Y_i= bottom of the discretized layer i.

3.4.2. Sensitivity of the hydraulic model to the duration of the calibration period

Sensitivity of the hydraulic model has been evaluated through calibrations of S_y and recharge models from different periods, i.e., from one year to four years of calibration (Fig. 7 a and b).

During these tests, *Sy* and recharge models are generated from the different prescribed calibration periods (1, 2, 3 and 4 years), and sets of piezometric levels are computed with these models for the entire available data set (June 2001 to June 2005; Fig. 7c). Finally, the computed levels are compared to the ones observed and the piezometric observations beyond the calibration period are used for validating the model. The deviation between observed and computed water levels is expressed as follow:

$$Dev.[m] = \sum_{i}^{n} \overline{\left| h_{obs,i} - h_{sim,i} \right|} \qquad (6)$$

where $h_{obs,i}$ and $h_{sim,i}$ are observed and computed piezometric levels respectively.

Figures 7 a and b show that with the analysed data set 3 years of calibration period are necessary to obtain similar recharge and *Sy* models. Consequently, the difference between observed and computed water levels is low for the models calibrated on 3 and 4 years of records (Fig. 7c). One may thus assumed that continuing calibration beyond for 4 years, and thus continuing to compute all groundwater fluxes components of Eq.1, should not drastically change the these models. However, the calibration on 4 years is sensibly better (dev.=±0.56 m against ±0.95 m for the 3 years calibration period; Fig. 7c) because during the fourth year of record water levels were the deepest which has for consequence to improve the S_y estimate of the deepest aquifer compartment, i.e. the fissured zone.

In the following sections, the hydraulic model established from the calibration on the entire data set (4 years) is kept for further calculation. For this watershed, DST-*GW* models the basin-scale piezometric levels with an average deviation of ±0.56 m from 2001 to 2005, which shows the robustness of the model.

Once the hydraulic model is achieved, the user may proceed to the scenario creator modulus.

4. SCENARIOS

The scenario module, in addition to feed the model with additional data (borewell database, historical rainfall data), is especially devoted to create a ‘reference scenario’ (i.e., business as usual scenario) as well as additional scenarios. The ‘reference scenario’ or ‘most probable scenario’ describes the future evolution of a site according to changes that are expected through strategies planned at national or regional levels. The scenario module allows creating theoretical scenarios in order to test the impact of different management measures upon the groundwater resource. For every scenarios, the DST-*GW*'s user may *i)* change the abstraction of the existing groundwater uses at seasonal time-step, or add new ones, *ii)* change future annual rainfall, or /and *iii)* change the number or efficiency of artificial recharge structures.

As an example, two alternative scenarios are presented to help visualise and discuss their impacts on the groundwater resource. However, these scenarios are theoretical and issued from an optimisation approach that is not socio-economically sound since the development of the socio-economic module (e.g., computation of farmer's net returns) is not yet available.

4.1. Reference scenario

In this scenario, no climatic change is considered, and the rainfall scenario uses the past 20 years annual rainfall data for the next 20 years (Fig. 8a & b). Results show that if the groundwater exploitation by pumping continues at the present rate of development (about 1.3% per year, FAO, 1997) the groundwater resource limit at the watershed scale (i.e., the bottom of the aquifer materialized by the horizontal dotted line in Fig. 8a), below which the aquifer cannot be exploited, will be reached by the year 2012-2013. As a consequence, yields of numerous farmer's borewells will hazardously decrease or will be dry at the same date with serious socio-economic consequences; according to the model about 80% of farmer's borewells should dried up in 2012-2013 (Fig. 8b). To estimate the drying up of borewells, a database containing all exploited borewells and the borewell-specific aquifer bottom elevation is compared with simulated average piezometric levels. A borewell gets dry when the piezometric level is equal or below the aquifer bottom elevation.

4.2. Impact of rainfall or climate variability on the Reference scenario

Figure 9 presents water level simulations with the occurrence of two consecutive "low" (450 mm/year) and "good" (1100 mm/year) monsoons in 2009 and 2010. Two consecutive "low" monsoons result in a strong depletion of the aquifer with a total depletion excepted in 2009-2010. With two consecutive "good" monsoons, the consequences of overexploitation are delayed by a few years and total depletion should occur by year 2014-2015. As a result and whatever the rainfall amount provided by the monsoon, the strong depletion of the aquifer will occur sooner or later, and may be faster than expected. Realistic solutions have to be found quickly and DST-*GW* can be useful for testing and selecting the most appropriate solutions (demand/supply measures).

4.3. Impacts of changing cropping patterns and artificial recharge on piezometric levels

DST-*GW* has been especially built to test the impact of changing cropping pattern measures on piezometric levels and on exploited borewells. The impact of increasing or decreasing cultivated areas onto groundwater levels is predicted.

In order to avoid unrealistic scenarios, which may not be accepted by the farmers for profitability or socio-cultural reasons, DST-*GW* has been designed to enable an action plan over several years where each groundwater uses can be changed at a seasonal scale.

For example, Figures 10a & b consider two 15-years action plan scenarios:

i) Scenario 1: 10 % decrease of rice cultivated area every year from 2009 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.

ii) Scenario 2: the same cropping pattern changes as scenario 1 and the build-up of additional percolation tanks between 2009 and 2013 (+15 ha), knowing that today they cover about 80 ha in area.

In both scenarios, the piezometric 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 since today the existing tanks capture most of surface run off (tanks: 14% of total 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-directional measures such as recharge augmentation.

5. CONCLUSION

The present study reinforces that simple techniques like groundwater budget and water table fluctuation methods can be very useful for evaluating the groundwater fluxes balance in hard-rock areas in addition to some watershed scale parameters like hydrodynamic parameters (efficient porosity) or recharge from rainfall. The presented methodology is adapted to unconfined aquifer, hard-rock formations relatively homogenous in term geology and exposed to regional deep-weathering processes, i.e., where the weathering profile is characterized by thick sub-horizontal and stratiform layers, and well-differentiated dry and rainy seasons. As a consequence these methods are particularly well designed for watershed size ranging from 10 to 100 km^2, where geology, layers thicknesses of the weathering profile and hydrodynamic properties can be considered as homogeneous. The presented methods are suitable to other similar geological and climatic context around the world such as in Africa where evidence of deep-weathering and stratiform hard rock aquifers have been reported, e.g. in Malawi (Chilton and Foster, 1995), Uganda (Taylor and Howard, 2000), Burkina Faso (Courtois et al., in press). However, where high spatial variations in the weathering profile thickness, or a highly heteregeneous geology, characterizes the area (e.g., in mountainous areas, areas densely fractured/faulted), the methodology will be not applicable.

The developed DST-*GW* is based on groundwater budget and water table fluctuation methods at basin-wide scale, and is especially designed for groundwater management in hard rock area experiencing semi-arid conditions. The present tool is able to estimate groundwater levels and drying-up of borewells at the catchment scale at seasonal time-step. It is a tool where the stakeholders can build-up scenarios (i.e., changing the groundwater uses or climatic conditions, testing artificial recharge solutions, etc.) and visualize the outcome at the watershed scale. DST-*GW* is thus an interactive tool useful to provoke discussion between community and policy makers, which should help the implementation of sustainable solutions to reduce or control the stress imposed by human activities on aquifers.

The tool has been tested and validated in Maheshwaram watershed (Andhra Pradesh, India) and it shows that if no adequate measures are taken, alarming depleted groundwater levels will be reached soon due to overexploitation. Solutions exist (e.g., scenarios with changing cropping patterns and additional artificial recharge) but they need to be validated by a socio-economic study. In addition to this water shortage and because of the closed character of the studied aquifer, a deterioration of the groundwater quality due to a enrichment of elements by evapotranspiration is also expected, e.g. increase of water salinity, of contents in pesticide or in other contaminants.

This tool is a first version and for its future development it is planned to include socio-economic parameters (e.g., farmers categories, net return of crops, etc.), and hence to forecast farmer's incomes according to different groundwater management scenarios. This will be tested within a new case study in Andhra Pradesh. Socio-economic parameters and census data at basin scale will be integrated to DST-*GW*. This should give more information on the impact of land use changes over the farmers' average income per farmers' categories. This new development will help to propose more economically-sounded solutions, and should facilitate the acceptability and the implementation of groundwater resource management strategies.

Today and particularly in India where groundwater resource suffer the consequence of an uncontrolled exploitation, it is very important to assess the availability of the water resources in a quantitative way and balance it with the demand. The difference could and should be managed by demand measures such as changes in agricultural practices (cropping patterns, 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.

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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. The two Journal's referees, J. Krásný and an unknown reviewer, are thankful for their fruitful remarks and comments that improved the quality of the paper.

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Table caption:

Table 1: Mean piezometric levels post and pre-monsoon from June 2001 to June 2005 (*h, in masl*), corresponding water table fluctuation (*Δh in m*), and number of observation wells (IFGCR borewells and abandoned wells) used for the establishment of piezometric maps (e.g., Fig.3). * ± : relative error (deduced from geostatistics), ** from 2002 to 2005, 90 borewells have a common location. masl: meters after sea level. Catchement area: 58 km^2.

Table 2: Groundwater fluxes (see Eq.1) and groundwater budget from June 01 to June 05, Maheshwaram watershed 58 km^2. * not used in the groundwater budget computation, and annual recharge (Rech.) is computed using the *Sy vs.* elevation model (see text for explanation). Veg.: vegetables, Flow.: flowers, Grap.: grapes, Dom.Use: domestic use, Poul.: poultries, Sum GW abstr.: sum of all groundwater abstraction and Sum GW RF: sum of all return flows.

Figure caption:

Figure 1: Maheshwaram watershed, 700 borewells in use for irrigation and up to 165 observation wells used for establishing piezometric maps.

Figure 2: Breakdown structure of the DST-*GW*.

Figure 3: Example of piezometric map (June 05, 165 observations); average piezometric level: 608.5 m. The insert presents the variogram used for data interpolation.

Figure 4: Calibrated vertical distribution of the specific yield with elevation at basin-wide scale (or mean ground level) for the Maheshwaram watershed. S_y is deduced from dry seasons October 01-June 02 (S_y: 0.009), November 02-June 03 (S_y: 0.014), November 03-June 04 (S_y: 0.015), November 04-June 05 (S_y: 0.013) and modelled S_y according to variation in % of fissures *vs.* elevation (Fig. 5).

Figure 5: Variation in percentage of fissures with elevation (or vs. mean ground level) in the fissured zone for Maheshwaram aquifer, deduced from flowmeter measurements (Dewandel et al., 2006).

Figure 6: Computed annual recharge at the watershed scale *vs.* annual rainfall model according to groundwater budget data and S_y model (Fig. 4). Is also plotted the rainfall-

recharge relationship estimated with tritium techniques in hard rock aquifers of India (Rangarajan and Athavale, 2000; Sukhija et al., 1996).

Figure 7: (a) Variations in S_y model according to the duration of the calibration period, (b) variations in recharge model according to the duration of the calibration period, and (c) Right axis: observed and computed piezometric levels according to the duration of the calibration period. Left axis: deviation between observed and computed piezometric levels according to the duration of the calibration period.

Figure 8: (a) Reference scenario. Simulation of water levels in Maheshwaram watershed, no climatic change and ~1.3%/year increase of irrigated area (FAO, 1997). Triangles: mean seasonal piezometric levels during the calibration period (2001 to 2005) and (b) 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). The interrogated borewell database contains 706 borewells.

Figure 9: Reference scenario. Case of two consecutive "low" (450 mm/y) and "good" (1100 mm/y) monsoons in 2009 and 2010.

Figure 10. (a) DST-*GW*, testing scenarios on groundwater levels. Scenario 1: 10 % decrease of rice cultivated area every year from 2009 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, and (b) impact on borewells. Results of Scenario 1 and 2 (fig. 10a).

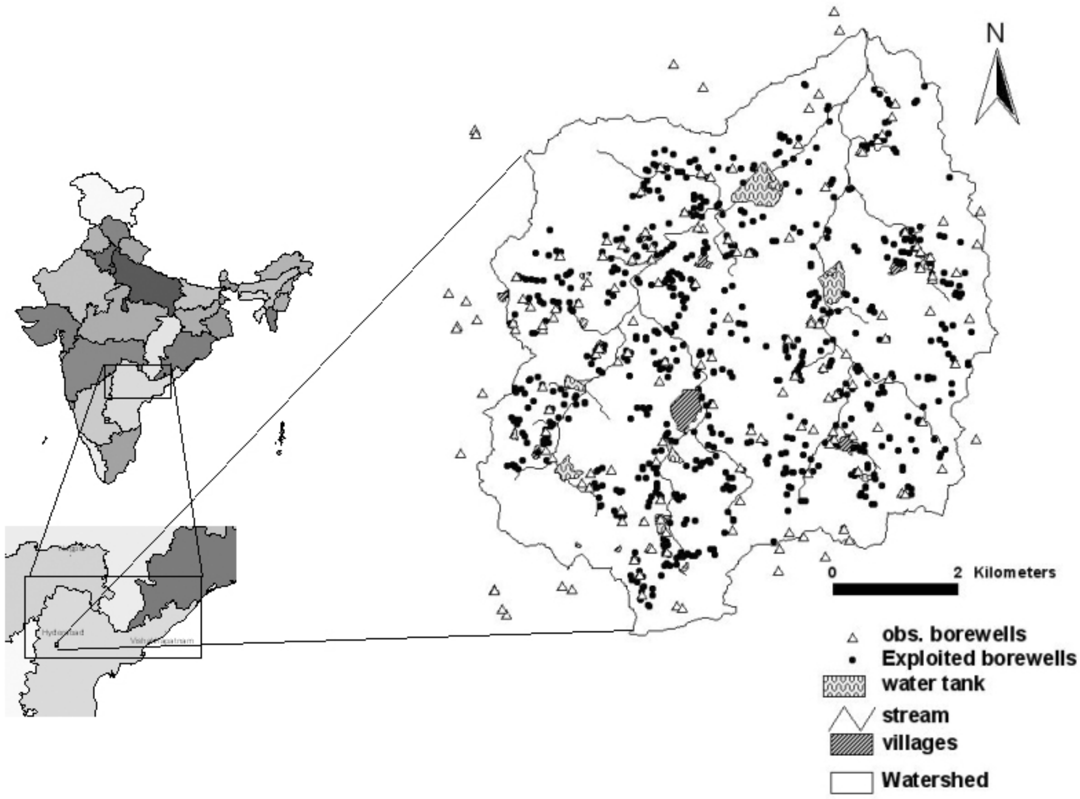

N
0
2 Kilometers
obs. borewells
Exploited borewells
water tank
stream
villages
Watershed

Fig. 1

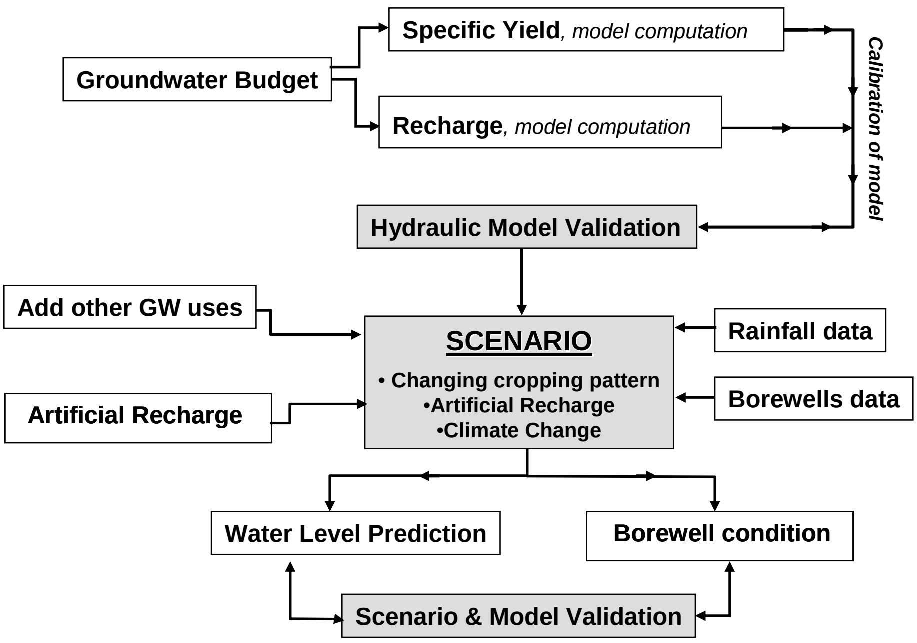
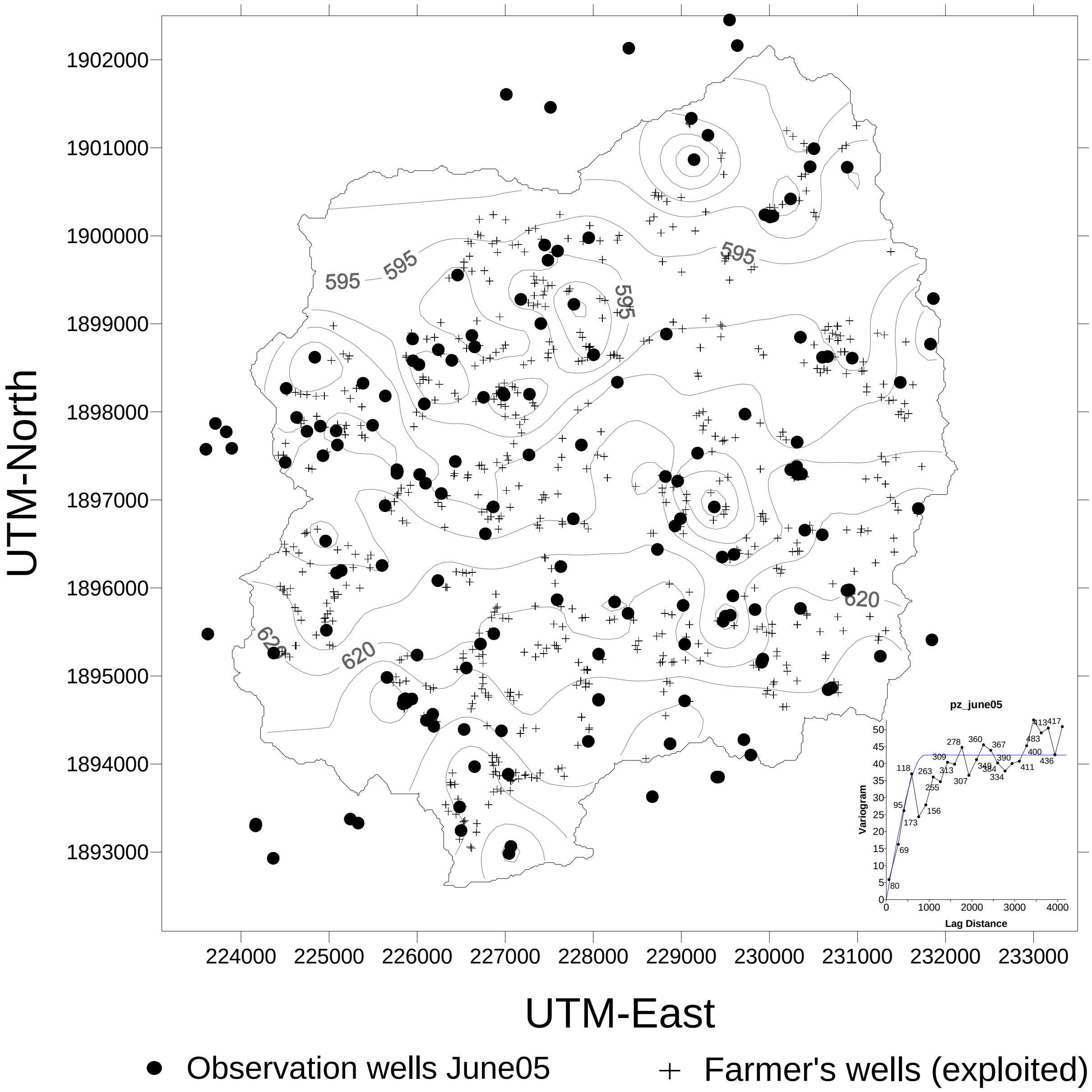
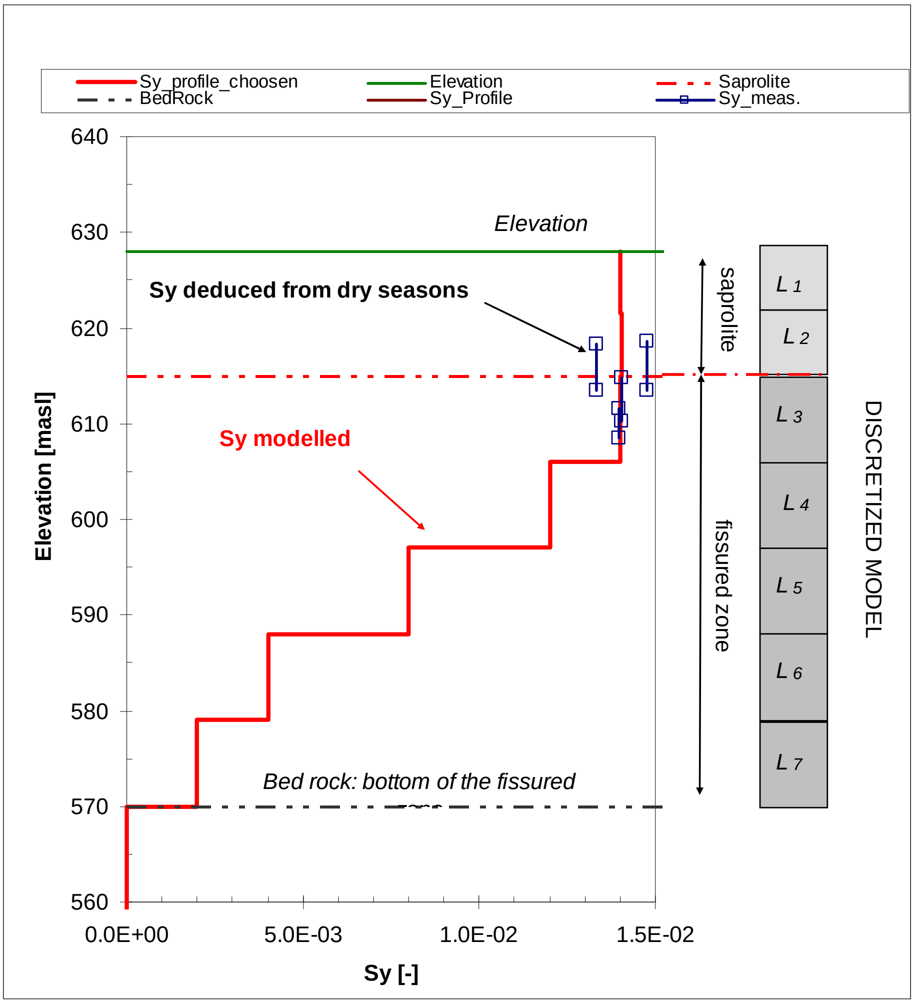

Groundwater Budget
Specific Yield, model computation
Recharge, model computation
Calibration of model
Hydraulic Model Validation
Add other GW uses
Artificial Recharge
SCENARIO
• Changing cropping pattern
•Artificial Recharge
•Climate Change
Rainfall data
Borewells data
Water Level Prediction
Borewell condition
Scenario & Model Validation

Fig.2



1902000
1901000
1900000
1899000
1898000
1897000
1896000
1895000
1894000
1893000
UTM-North
224000
225000
226000
227000
228000
229000
230000
231000
232000
233000
UTM-East
595
620
pz_june05
Variogram
Lag Distance
Observation wells June05
Farmer's wells (exploited)

Fig. 3



Sy_profile_choosen
BedRock
Elevation
Sy_Profile
Saprolite
Sy_meas.
Elevation
Sy deduced from dry seasons
Sy modelled
Bed rock: bottom of the fissured zone
saprolite
fissured zone
L 1
L 2
L 3
L 4
L 5
L 6
L 7
DISCRETIZED MODEL
Elevation [masl]
640
630
620
610
600
590
580
570
560
0.0E+00
5.0E-03
1.0E-02
1.5E-02
Sy [-]

Fig.4

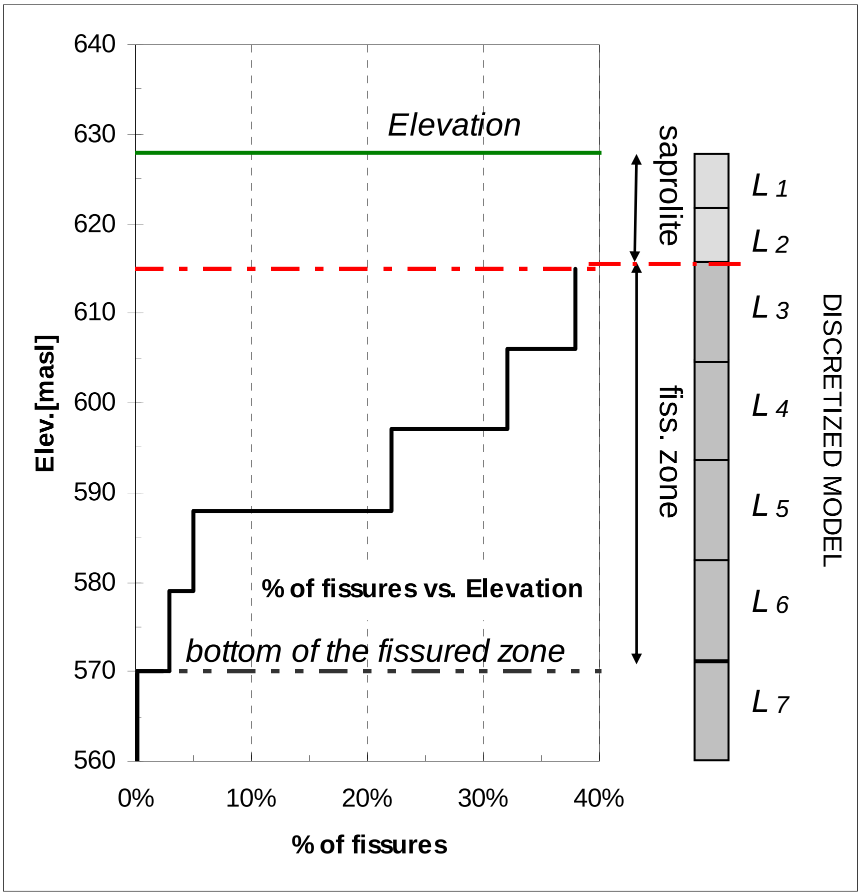

Elevation
saprolite
L 1
L 2
L 3
L 4
L 5
L 6
L 7
DISCRETIZED MODEL
fiss. zone
% of fissures vs. Elevation
bottom of the fissured zone
Elev.[masl]
640
630
620
610
600
590
580
570
560
0%
10%
20%
30%
40%
% of fissures

Fig. 5

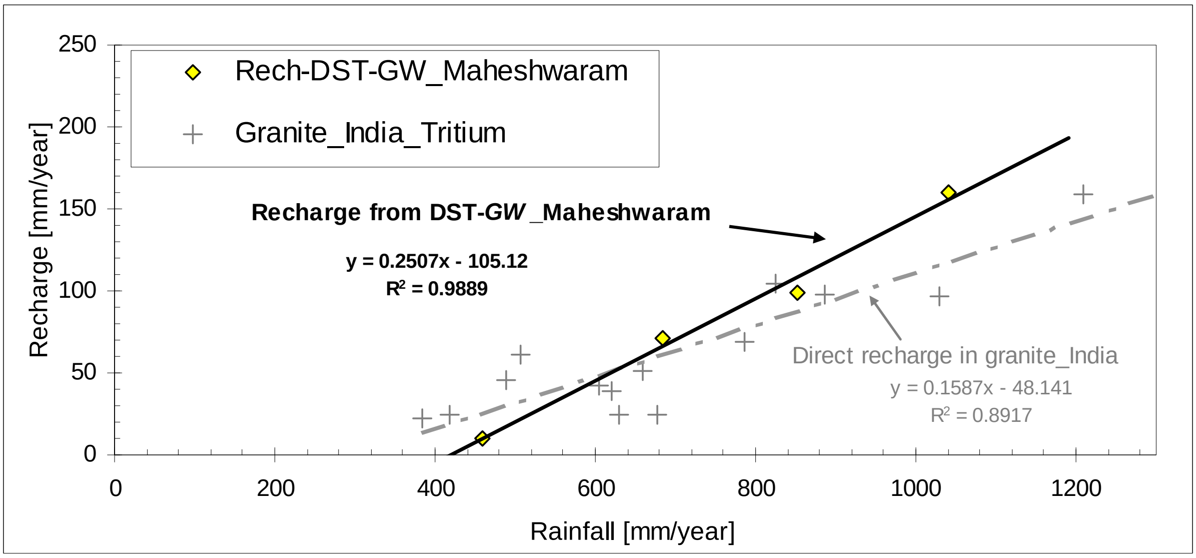
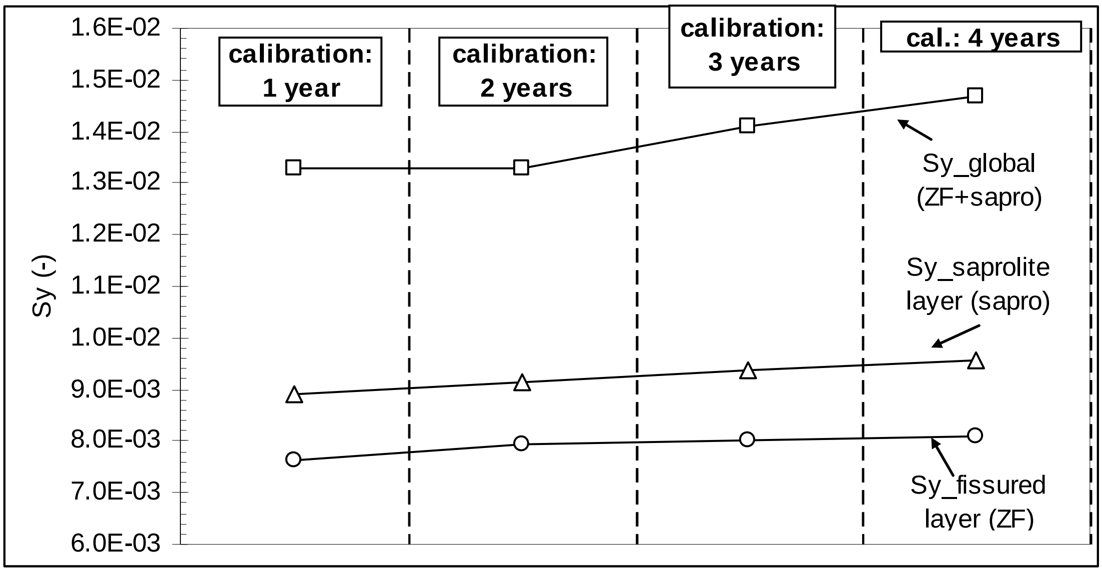
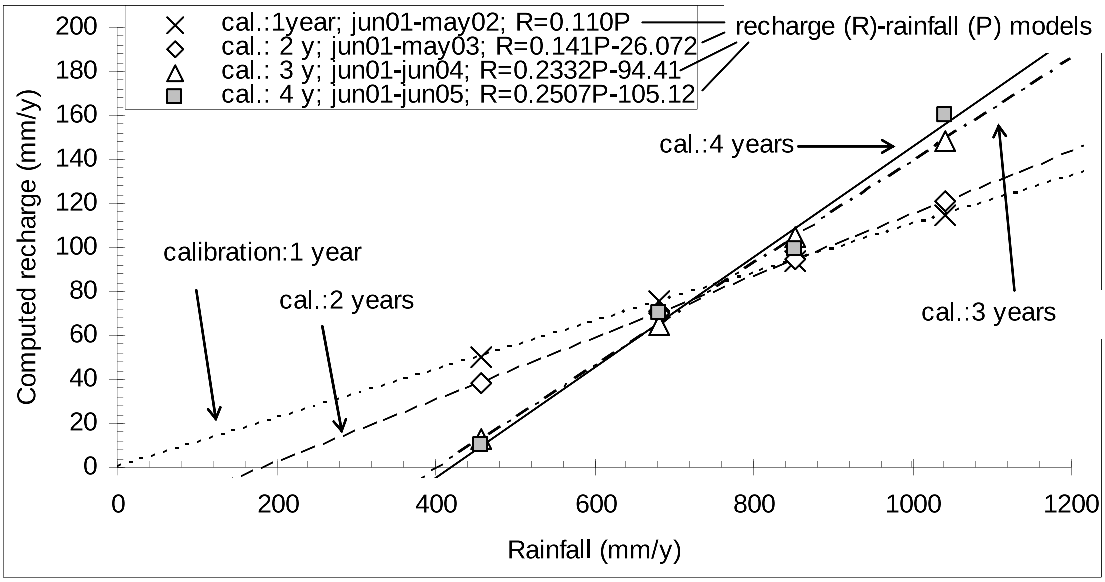

Rech-DST-GW_Maheshwaram
Granite_India_Tritium
Recharge from DST-GW_Maheshwaram
y = 0.2507x - 105.12
R² = 0.9889
Direct recharge in granite_India
y = 0.1587x - 48.141
R² = 0.8917
Recharge [mm/year]
250
200
150
100
50
0
0
200
400
600
800
1000
1200
Rainfall [mm/year]

Fig. 6



calibration: 1 year
calibration: 2 years
calibration: 3 years
cal.: 4 years
Sy (-)
1.6E-02
1.5E-02
1.4E-02
1.3E-02
1.2E-02
1.1E-02
1.0E-02
9.0E-03
8.0E-03
7.0E-03
6.0E-03
Sy_global (ZF+sapro)
Sy_saprolite layer (sapro)
Sy_fissured layer (ZF)

Fig. 7a



cal.:1year; jun01-may02; R=0.110P
cal.: 2 y; jun01-may03; R=0.141P-26.072
cal.: 3 y; jun01-jun04; R=0.2332P-94.41
cal.: 4 y; jun01-jun05; R=0.2507P-105.12
recharge (R)-rainfall (P) models
cal.:4 years
calibration:1 year
cal.:2 years
cal.:3 years
Computed recharge (mm/y)
Rainfall (mm/y)
0
20
40
60
80
100
120
140
160
180
200
0
200
400
600
800
1000
1200

Fig. 7b

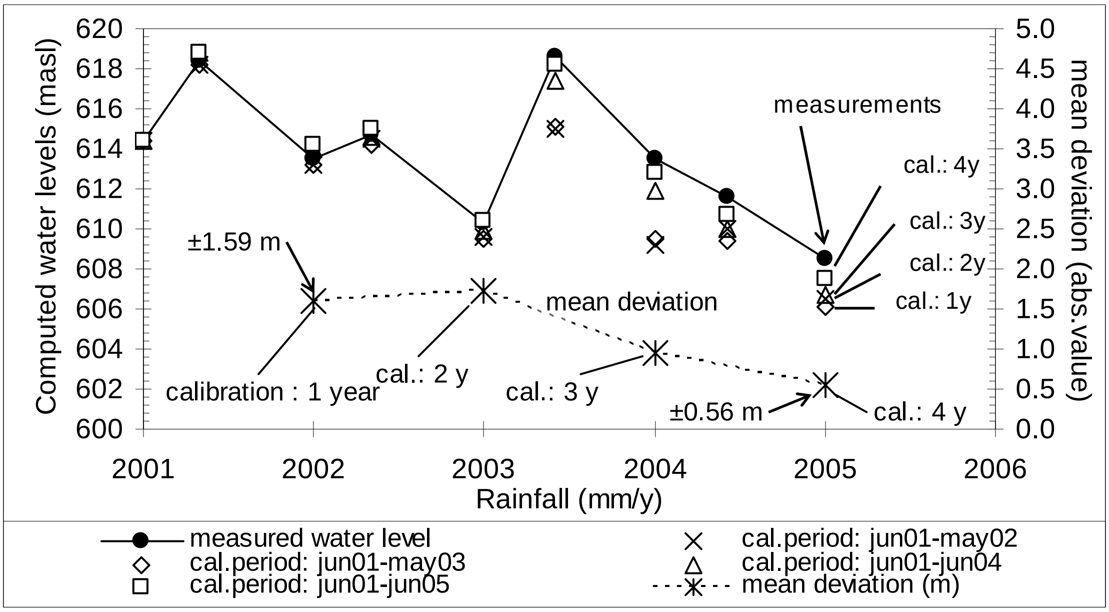

Computed water levels (masl)
mean deviation (abs.value)
measurements
cal.: 4y
cal.: 3y
cal.: 2y
cal.: 1y
±1.59 m
mean deviation
calibration : 1 year
cal.: 2 y
cal.: 3 y
±0.56 m
cal.: 4 y
Rainfall (mm/y)
measured water level
cal.period: jun01-may03
cal.period: jun01-jun05
cal.period: jun01-may02
cal.period: jun01-jun04
mean deviation (m)

Fig. 7c

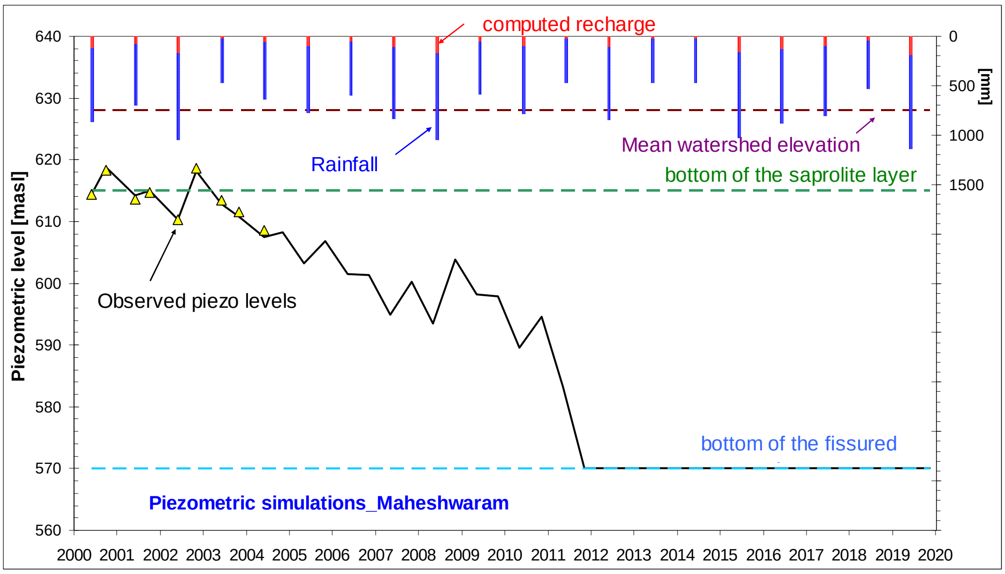
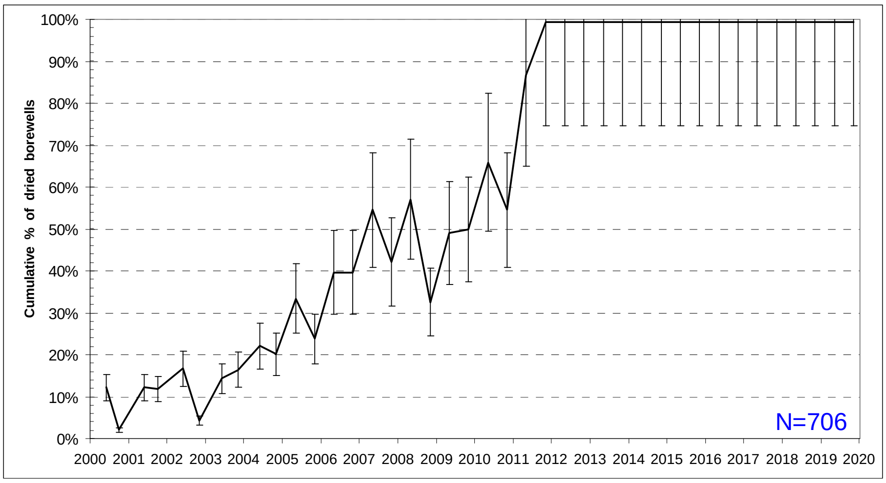
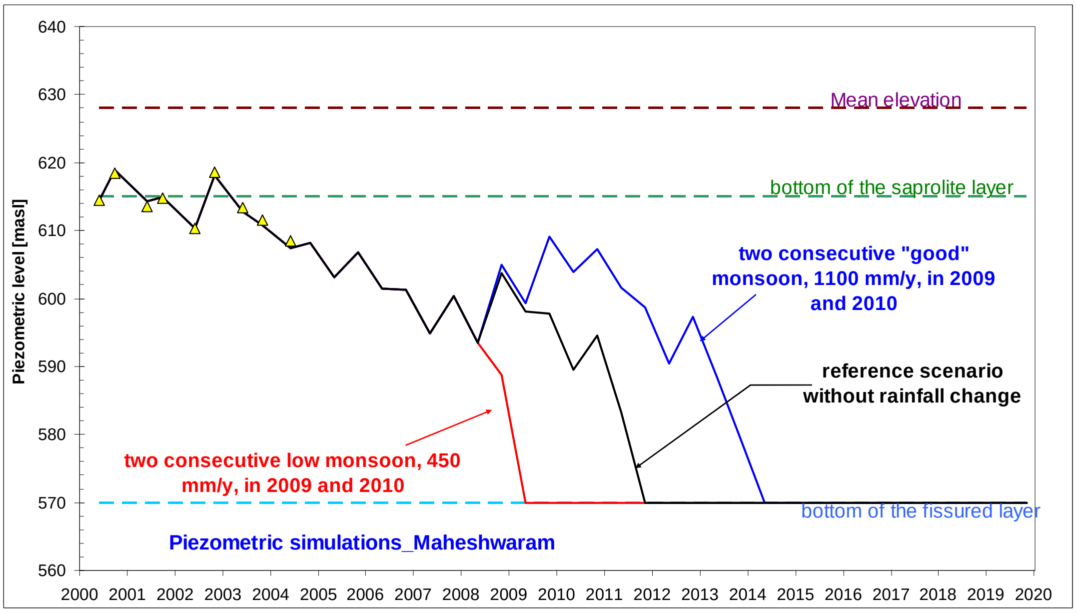

computed recharge
Rainfall
Mean watershed elevation
bottom of the saprolite layer
Observed piezo levels
bottom of the fissured
Piezometric simulations_Maheshwaram
Piezometric level [masl]
[mm]

Fig.8a



Cumulative % of dried borewells
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
N=706
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Fig 8b



Piezometric level [masl]
640
630
620
610
600
590
580
570
560
Mean elevation
bottom of the saprolite layer
two consecutive "good" monsoon, 1100 mm/y, in 2009 and 2010
reference scenario without rainfall change
two consecutive low monsoon, 450 mm/y, in 2009 and 2010
bottom of the fissured layer
Piezometric simulations_Maheshwaram
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020

Fig. 9

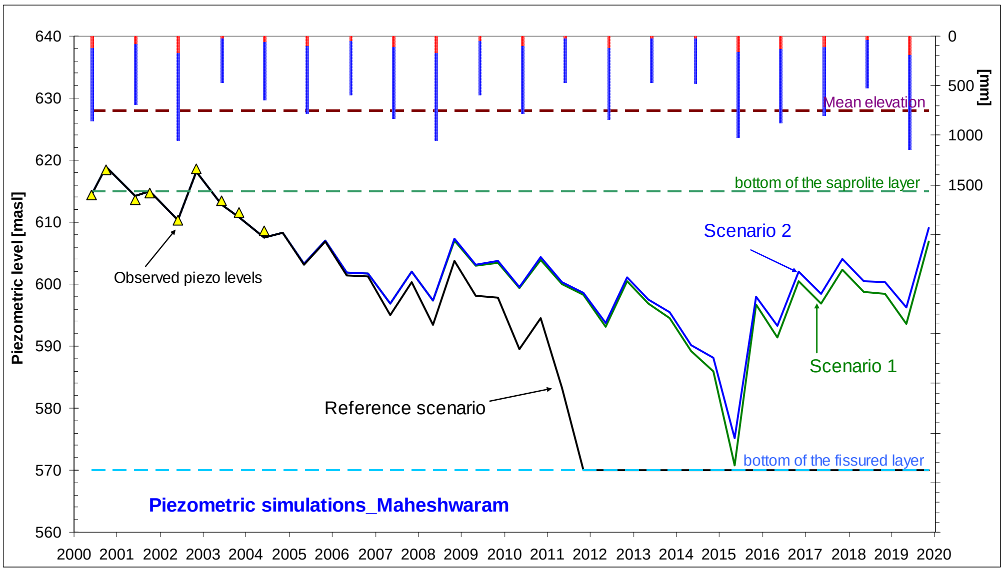


Fig. 10a

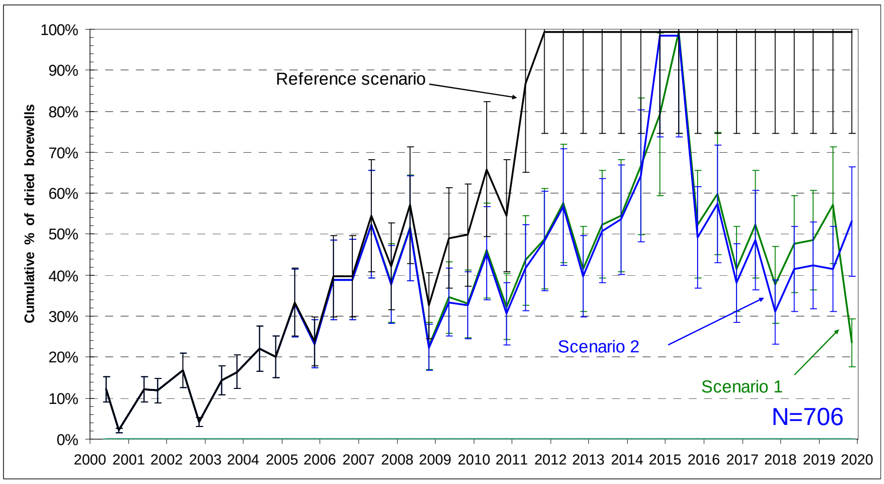


Fig. 10b

TABLES

		h (m.a.s.l)	*Δh (m)**	Nb.obs**
end dry season	Jun 01	614.4	-	40
end rainy season	Oct 01	618.4	3.9 ± 1.20	40
end dry season	Jun 02	613.5	-4.8± 0.56	99
end rainy season	Nov 02	614.7	1.2± 0.27	107
end dry season	Jun 03	610.3	-4.4± 0.35	114
end rainy season	Nov 03	618.6	8.3± 0.32	155
end dry season	Jun 04	613.5	-5.1± 0.23	134
end rainy season	Nov 04	611.6	-1.8± 0.30	147
end dry season	Jun 05	608.5	-3.1± 0.24	165

Table 1

				Groundwater abstraction in [mm]								Return flows in [mm]										
Year 1	Δh [m]	In+Out [mm]	E [mm]	Rice	Veg	Flow.	Fruits	Grap.	Dom. Use	Poul.	Sum GW abst.	Rice	Veg	Flow.	Fruits	Grap.	Dom. Use	Poul.	Sum GW RF	Rech. [mm]	Annual Balance [mm]	Rainfall [mm] *
Jun 01 - Oct 01	3.9	0.7	1.5	67.2	0.4	0.3	0.0	4.0	1.3	1.7	75.0	33.6	0.1	0.1	0.0	0.0	0.3	0.3	34.4	99.1		789.5
Oct 01 - Jun 02	-4.8	0.3	2.1	96.3	0.8	1.0	5.5	6.3	1.9	2.6	114.5	50.7	0.2	0.1	0.0	0.0	0.4	0.5	51.9			63.0
Annual data	***-0.9***	***1.0***	***3.6***	***163.5***	***1.2***	***1.3***	***5.5***	***10.4***	***3.2***	***4.3***	***189.4***	***84.3***	***0.3***	***0.2***	***0.0***	***0.0***	***0.6***	***0.9***	***86.3***		***-6.7***	***852.5***
Year 2																						
Jun 02 - Nov 02	1.2	0.0	0.5	75.8	0.6	0.7	0.0	4.1	1.3	1.7	84.2	30.2	0.1	0.1	0.0	0.0	0.3	0.3	31.0	70.8		613.0
Nov 02 - Jun 03	-4.4	-0.3	0.6	83.4	0.8	1.0	4.4	5.6	1.8	2.4	99.3	36.9	0.1	0.0	0.0	0.0	0.4	0.5	37.9			70.0
Annual data	***-3.2***	***-0.3***	***1.1***	***159.2***	***1.3***	***1.7***	***4.4***	***9.6***	***3.1***	***4.2***	***183.5***	***67.1***	***0.3***	***0.1***	***0.0***	***0.0***	***0.6***	***0.8***	***68.9***		***-45.4***	***683.0***
Year 3																						
Jun 03 - Nov 03	8.3	-1.2	0.8	62.5	0.5	0.7	0.0	3.8	1.4	1.9	70.8	31.4	0.1	0.1	0.0	0.0	0.3	0.4	32.3	160.4		823.6
Nov 03 - Jun 04	-5.1	-0.6	1.3	108.7	0.7	0.9	4.4	5.2	1.7	2.3	124.0	49.5	0.2	0.1	0.0	0.0	0.3	0.5	50.5			217.4
Annual data	***3.2***	***-1.8***	***2.1***	***171.3***	***1.2***	***1.6***	***4.4***	***9.0***	***3.2***	***4.2***	***194.8***	***80.9***	***0.3***	***0.2***	***0.0***	***0.0***	***0.6***	***0.8***	***82.8***		***43.7***	***1041.0***
Year 4																						
Jun 04 - Nov 04	-1.8	0.0	0.6	55.1	0.5	0.7	0.0	3.7	1.2	1.7	63.0	26.8	0.1	0.0	0.0	0.0	0.2	0.3	27.6	9.8		205.0
Nov 04 - Jun 05	-3.1	-2.0	0.5	53.4	0.5	0.6	3.0	3.5	1.1	1.5	63.6	22.3	0.1	0.1	0.0	0.0	0.2	0.3	23.0			253.0
Annual data	***-4.9***	***-2.0***	***1.1***	***108.5***	***1.0***	***1.3***	***3.0***	***7.2***	***2.4***	***3.2***	***126.6***	***49.1***	***0.2***	***0.1***	***0.0***	***0.0***	***0.5***	***0.6***	***50.5***		***-69.0***	***458.0***
Mean annual	**-1.5**	**-0.8**	**2.0**	**150.6**	**1.2**	**1.5**	**4.3**	**9.1**	**3.0**	**4.0**	**173.6**	**70.4**	**0.3**	**0.2**	**0.0**	**0.0**	**0.6**	**0.8**	**72.1**	**84.9**	**-19.4**	**758.6**

Table 2