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

Users' Manual

Demo Version

Foreword

Groundwater resources need to be managed with appropriate methods in regions where existing or future demand for groundwater may exceed renewable reserves. This issue is especially critical in regions with limited water resources such as areas combining dry climatic conditions and groundwater resources located in aquifers with low storage capacity. This situation occurs in southern India which is mainly composed of hard rock (granite and gneiss) aquifers under semi-arid climatic conditions. The present DST-GW (Decision Support Tool) has been developed especially for this southern Indian context but can also clearly be applied to other regions in the world with a monsoon type of climate (recharge occurring over a limited time period) and hard rocks.

The DST-GW and associated methodologies have been developed at the Indo-French Centre for Groundwater Research (IFCGR) based in Hyderabad (Andhra Pradesh, India) that concretises a scientific collaboration between the National Geophysical Research Institute (NGRI, Hyderabad, India) and the French Geological Survey (BRGM, France). The present version of the DST-GW could be developed with the support of the European-funded project SUSTWATER (*Towards sustainability of water management: implementation of a Decision Support Tool*, Programme AsiaProEco, 2006-2008).

This Users' manual is especially dedicated to water specialists (hydrogeologists, water engineers) from administrations (State government, Central government, water authorities), NGOs active in watershed management, consulting companies, and research institutions. For an adequate use of the DST-GW, a prior training that will present methods for the estimation of water budget components, uncertainties, and limitations of the DST-GW is strongly recommended. This manual presents only the software in a step by step process and shows how to enter basic information on the watershed, water budget components, socio-economic characteristics, and how to simulate future scenarios and retrieve the simulation results. Associated methodologies have been published in the scientific literature and no additional information is presented in this manual.

In an appendix, the watershed studied during the SUSTWATER project is presented as a case study and a demo version of the DST-GW is also available on the IFCGR website.

It is the hope of the Partners of the SUSTWATER project that this DST-GW will correspond to the needs of the End-Users; therefore any comment by future users of the DST-GW will be most appreciated.

Last but not least, IFCGR will continue working in developing a new version of the DST-GW that can accommodate larger scale watersheds, water quality issues, more sophisticated agronomic advisory, or complex socio-economic scenarios. These new developments will be advertised on the IFCGR website, so do not hesitate to follow up and ask for further detail

We wish you great success in the application of the DST-GW to your case studies and do not hesitate to send us feedbacks.

Dr Jerome Perrin, Hydrogeologist BRGM
SUSTWATER project leader

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Acronyms

- APGWD: **A**ndhra **P**radesh **G**roundwater **D**epartment
- BRGM: **B**ureau de **R**echerche **G**éologique et **M**inières
- CGWB: **C**entral **G**round **W**ater **B**oard
- CU: **C**harles **U**niversity (Czech Republic)
- DEM: **D**igital **E**levation **M**odel
- DST: **D**ecision **S**upport **T**ool
- DWTF : **D**ouble **W**ater **T**able **F**luctuation
- GIS : **G**eographical **I**nformation **S**ystem
- IFCGR: **I**ndo-**F**rench **C**entre for **G**roundwater **R**esearch (BRGM-NGRI)
- IWMI: **I**nternational **W**ater **M**anagement **I**nstitute
- NGRI: **N**ational **G**eophysical **R**esearch **I**nstitute (India)
- NRSA: **N**ational **R**emote **S**ensing **A**gency (India)
- RDD: **R**ural **D**evelopment **D**epartment of Andhra Pradesh

1. Introduction and definitions

In this chapter, some important concepts lying behind the DST-GW are defined as well as the first steps to be taken in the application of the DST-GW to a specific area.

The DST-GW is a tool designed to help its User to manage groundwater resources in a bounded geographical area. The main targeted Users are engineers and water scientists from State and Central Governments, NGOs active in water management, and water consultants. The "spirit" of the DST-GW is to be a practical tool, that is relatively easy to use with limited field investigations and field data ("cost-effective"), but at the same time reliable and robust in the sense that it is based on a thorough understanding of the geological structure of the aquifer and its hydrodynamic functioning.

The DST-GW has been tailored to the specificities of hard-rock aquifers in semi-arid regions. This specific context is typical of southern India but also of large areas of Africa and South America. The terms "hard-rock" includes granite and metamorphic rocks such as gneiss and schists. Recent studies (e.g., Dewandel et al. 2006) 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 multi-layered systems.

The aquifers in hard-rock are unconfined and their piezometric surface generally follows the surface topography. Therefore, there is a good match between surface drainage watershed and groundwater watershed.

The DST-GW is developed for semi-arid climatic conditions because a significant water table fluctuation between the wet and the dry season is needed to calculate the groundwater balance. These conditions occur generally under a monsoon-type climate where a large part of the annual rainfall occurs during a few months only (the rainy season), the rest of the year being mostly dry (the dry season).

The DST-GW has been mainly developed for watersheds that are delineated on the basis of the surface topography (e.g., using a DEM). However, it is also possible to use the DST-GW for watershed delineation based on administrative boundaries or geological boundaries for instance. In this case, the In- and Out-flows across the watershed boundaries have to be estimated (see Chapter 2).

Technically speaking, the DST-GW can be described as a **Column, Single-cell or Lumped model**. It means that the groundwater balance is calculated at the watershed scale using average values for each budget component. This makes the DST-GW simpler to use compared to classical groundwater modelling package such as MODFLOW for instance, but the main limitation is that the DST-GW will not lead to spatially distributed results.

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 interannual fluctuations at the watershed scale. Many different simulations can be carried out according to User-defined scenarios.

Definitions

Column Model: A numerical model in which solutions depend only on the vertical coordinate and time.

Decision Support Tool: Process that provides a consistent and reproducible basis for making decisions

Groundwater balance: governed by the equation comparing the sum of the out-flows with the sum of the in-flows in a groundwater system

Groundwater budget: synonym of groundwater balance

Hard Rock: includes granite and metamorphic rocks such as gneiss and schists. This definition does not include sedimentary rocks or eruptive rocks (that are also hard).

Kharif: Indian term synonym of rainy season

Maheshwaram: pilot watershed located nearby Hyderabad used by IFCGR for the development of methodologies and the development of DST-GW

Most probable scenario: see “Reference scenario”

Net Pumping: Total pumping minus irrigation return flow

Rabi: Indian term synonym of dry season

Saprolite: the weathered layer capping the fissured zone of hard-rock aquifers. It is generally composed of a sandy regolith layer capping a laminated regolith layer.

Watershed: a defined geographic surface area whose water drains into a particular watercourse (synonym to catchment area or river catchment)

Advices to use the DST in an appropriate manner:

Watershed size: 10-100 km^2

Geology: hard-rock

Climate: semi-arid

Calibration time: minimum two hydrological years of field data

Technical requirement: Microsoft Excel 2003 or XP with enable macros option

2. Groundwater balance – a methodology

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 et al., 2007, 2008). This approach is particularly well adapted to unconfined hard rock aquifers under semi-arid conditions with well marked dry and rainy seasons. The following section describes briefly the DWTF methodology.

Theoretical Background

The methodology used for assessing the groundwater balance is a combination of the ground water-budget and water-table-fluctuations procedures, both well adapted to the specific structure and hydrodynamic properties (mainly storage) of hard-rock aquifers (Marechal et al., 2006).

The groundwater budget method focuses on groundwater flow (**Figure 1**). 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:

$$R + RF + Q_{on} = ET + PG + Q_{off} + Q_{bf} + \Delta S \qquad \textit{Equation 1}$$

where R is groundwater recharge, RF is irrigation return flow, Q_{on} and Q_{off} are groundwater flow onto and off the basin, 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.

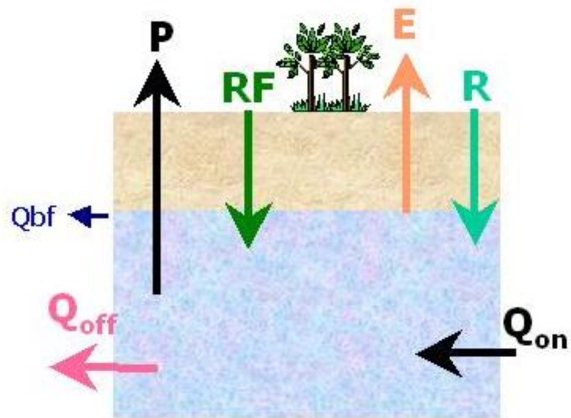

***Figure 1** : Groundwater budget sketch, all components are described in the text.*

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:

$$R + RF + Q_{on} = E + PG + Q_{off} + \Delta S \qquad \textit{Equation 2}$$

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:

$$\Delta S = S_y . \Delta h \qquad \textit{Equation 3}$$

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.

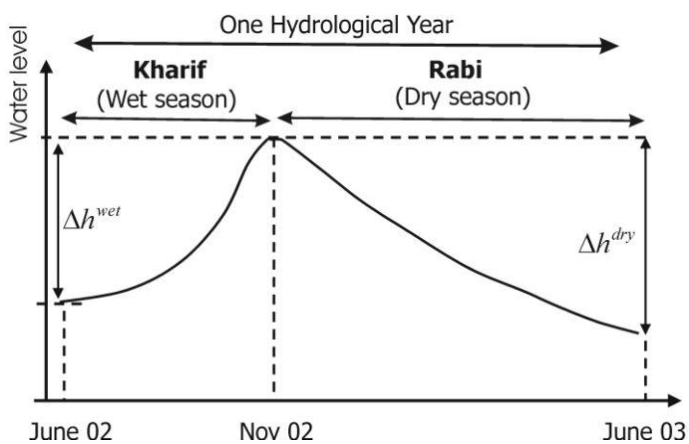

Figure 2 *: Idealized well hydrograph in the study area with seasonal water table fluctuations*

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):

$$R + RF + Q_{on} = E + PG + Q_{off} + S_y \Delta h \qquad \textit{Equation 4}$$

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, during the dry and rainy seasons, in order to determine the unknown values *R* and *Sy*. The method is therefore called the “double water table fluctuation” technique (DWTF).

Dry season groundwater budget: determination of the specific yield (*Sy*)

During the dry season, which is characterized by the absence of recharge but significant draft, the recharge term *R* can be neglected and the groundwater budget (equation 2) can be written:

$$RF^{dry} + Q_{on}^{dry} = E^{dry} + PG^{dry} + Q_{off}^{dry} + \Delta S^{dry} \quad \textit{Equation 5}$$

where ΔS^{dry} is negative. Combining equation (3) and equation (5), the specific yield of this unconfined aquifer is obtained:

$$S_y = \frac{RF^{dry} + Q_{on}^{dry} - E^{dry} - PG^{dry} - Q_{off}^{dry}}{\Delta h^{dry}} \qquad \textit{Equation 6}$$

All the terms of equation (6) are estimated for the dry season of the hydrological year. This method for estimating *Sy* is known as the “water-budget method” (Healy and Cook, 2002). The water budget method is the most widely used technique for estimating *Sy* in fractured-rock systems, probably because it does not require any assumptions concerning flow processes. Using this method, the obtained specific yield corresponds to a regional value at the aquifer scale.

Rainy season groundwater budget: estimation of natural recharge (*R*)

Recharge *R* is estimated by combining equation (2) for the wet season and equation (3) with *Sy* obtained during the dry season (equation 6). Therefore, recharge is estimated using:

$$R = \Delta h^{wet}.S_y - RF^{wet} - Q_{on}^{wet} + E^{wet} + PG^{wet} + Q_{off}^{wet} \quad \textit{Equation 7}$$

All the terms of equation (7) are are estimated for the rainy season of the hydrological year and the obtained value of *R* corresponds to an average recharge at the watershed scale.

As a summary, combining the use of both groundwater budget and water table fluctuation methods twice a year allows firstly the estimation of the unknown parameter *Sy* during the dry season by assuming a nil recharge in equation (1), and secondly the estimation of the recharge during the rainy season (i.e., with a known *Sy*). The main advantage of this method is that *Sy* and *R* are estimated for the study area itself without any hypothesis on (i) the flow processes, and (ii) on the other parameters of equation (1). Moreover, *Sy* is computed at the basin-scale and do not need to be estimated through hydraulic tests where *Sy* estimates may, and particularly in the case of discontinuous aquifers, be highly variable and may not take account of localized macro-porous structures.

3. Methodologies for estimating groundwater budget components

This chapter describes briefly the developed methodologies that can be used for the estimation of the groundwater budget components of equation (2). It is to the User to decide whether to apply one of the methodologies proposed here or to develop its own methods (e.g. to fit available data or to account for the specificities of the studied watershed). More information on existing methodologies can be found in the literature (e.g., Marechal et al. 2006, Dewandel et al. 2007, 2008).

The DST-GW works as a column model (single cell) and each groundwater flow component are taken as an average value for the entire catchment. Average values are required twice a year: once at the end of the dry season and once at the end of the rainy season/beginning of the dry season.

A case study is given as an Appendix and can be referred to for more information on specific methods.

Water levels (Δh)

The DWTF method requires a very good knowledge of the piezometric level over the entire basin. In southern India, this can be achieved by using the dense observation network provided by defunct or abandoned farmer’s borewells.

A geostatistical analysis of a dense piezometric network has shown that a number of 50 piezometers is optimal for a wateshed area comprised between 50-60 km^2 (Zaidi et al. 2007). Piezometers have to be measured twice a year, once near the end of the dry season and once at the end of the rainy season when recharge has taken place (Marechal et al. 2006, Dewandel et al. 2007).

The most accurate way to calculate the average water table elevation is to interpolate field piezometric data using the kriging technique (e.g. SURFER© package or an open source software such as SAGA) and then calculate the average value based on the interpolated regular grid.

For a correct estimation of ΔS, it is necessary to have a detailed geological map of the watershed, so it possible to know in which portion of the aquifer are the water table fluctuations taking place. In fact, the base of the saprolite layer and the base of the aquifer (bottom of the fissured layer) have to be mapped. From these two maps, it is then possible to obtain the mean elevation for both contacts. Methods to map the aquifer include geological observations at the surface and in defunct dug wells as well as geophysics (e.g., resistivity logging, electrical tomography).

Groundwater abstraction (PG)

Groundwater abstraction (PG) corresponds to groundwater pumped for agriculture ($PG_{agriculture}$) as well as for industrial ($PG_{industry}$) and domestic ($PG_{domestic}$) use. In rural areas, the largest share is for the agriculture sector. $PG_{agriculture}$ is defined as the total pumping and not the net pumping. The first method to estimate $PG_{agriculture}$ is to realise a borewell inventory with the instant discharge of each borewell. Then information on daily pumping duration (may be recorded by the electricity provider) and number of pumping days during the dry/rainy season (may be provided by farmers or crop calendar).

A faster method for the estimation of $PG_{agriculture}$ is to obtain a land use map from satellite imagery that will give the total irrigated area in the watershed. Then, field validation should be carried out and a relationship between irrigated surface and groundwater draft established. This relationship is used to extrapolate the draft to the entire watershed (Marechal et al. 2006, Dewandel et al. 2007).

For the estimation of $PG_{agriculture}$, it may also be possible to use flow-meter data if borewells are equipped accordingly or electricity consumption data.

For the estimation of $PG_{domestic}$, the easiest way is probably to make use of census data for population and livestock and then use daily consumption standard norms usually provided by governments. For the estimation of $PG_{industry}$ if present, a field investigation may be required.

Irrigation return flows (RF)

Irrigation return flow (RF) is defined as the excess of irrigation water that is not evapotranspirated or evacuated by direct surface drainage, and that returns to the aquifer. Irrigation return flow coefficient is defined as the ratio between the irrigation return flow and the abstracted flow: $C_f=RF/PG$. It varies from more than 50% for rice cultivation to about 15% for sugarcane cultivation, and is usually non-existent when drip irrigation techniques are used. Thus, RF can be a significant component of the groundwater balance particularly in the case of intensively irrigated areas and need to be accurately assessed for the groundwater balance.

A specific methodology for estimating irrigation return flow coefficients has been developed by Dewandel et al. (2008). This methodology is based on: (i) data collected at the basin scale, such as duration of pumping, climatic conditions, local farming practices, and typical regional soil characteristics values, (ii) and on a hydraulic model that combines both water balance technique and concepts of unsaturated/saturated flow processes at the field scale.

RF from domestic and industrial uses may be difficult to estimate. The administration in charge of water distribution may have some data. Otherwise, some fixed percentage may be assumed. In rural area as domestic and industrial use of groundwater is small component of the budget, their RF has also a very limited impact on the budget.

In and out flows across the watershed boundaries (Q_{on}, Qo_{ff})

In- and out-flows correspond to the water fluxes that could exist across the watershed boundaries, i.e. the in-flows entering the watershed and the out-flows leaving the watershed.

In hard-rock aquifers, the regional water table is sub-parallel to regional topography and this implies that the groundwater watershed matches the surface water watershed. Depending on how the watershed is delineated, the User will follow two different methods to estimate in- and out-flows across the watershed boundaries.

1) **Natural watershed**: the watershed delineation is based on the surface topography (i.e. match between groundwater and surface water watersheds).

   In this case, the watershed is bounded by no flow boundaries in the upstream part (in-flows=0) and out-flow in the downstream part shall contribute to base flow of surface stream/river. However as indicated in Chapter 2, no base flow occurs in over-exploited aquifers (out-flow=0).

2) **Administrative watershed**: in this case the watershed delineation is based on administrative limits (or other limits that do not correspond to natural boundaries) and in- and out-flows across the boundaries are expected. It is necessary to estimate these two components of the groundwater budget either by running a groundwater flow numerical model of the watershed (may be time consuming) or using simplified approaches (piezometric map including the outskirts of the watershed and application of Darcy law all along the limit of the watershed).

Evaporation from 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. They propose a relation for semi-arid climatic conditions: annual evaporation flux is expressed as an inverse power function of the water table depth below the surface, independently of the soil characteristics:

$$E = 71{,}9\, z^{-1{,}49} \qquad \textit{Equation 8}$$

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 is illustrated in **Figure 3** where the evolution of evaporation with water table depth shows that evaporation becomes significant (> 10 mm/year) for shallow aquifers only (water depth < 3.7 m).

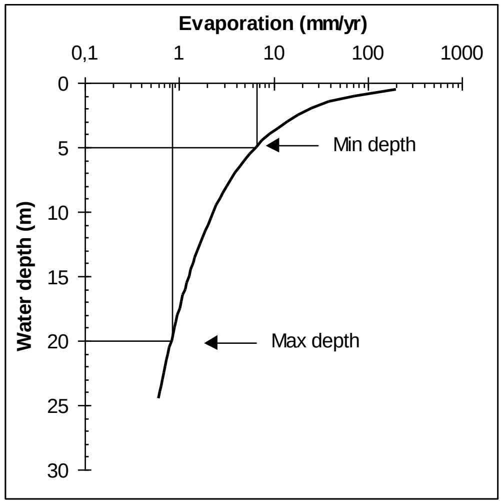

***Figure 3** : Evaporation – water table depth relationship (Coudrain et al., 1998).*

This relationship can easily be applied to the watershed piezometric maps (for instance using SURFER© or an open source software). Evaporation maps are generated, from which the average evaporation at the watershed scale is calculated.

4. The DST-GW: a step by step process

!! Note: the demo version available online (www.ifcgr.net) and on the CD given at the SUSTWATER final workshop has limited attributes: no models for specific yield-depth, neither for rainfall-recharge, nor for artificial recharge. Cropping pattern changes per year cannot be taken into account and simulations are limited to water table fluctuations (yearly) and % of drying borewells. The full version DST-GW 1.0 may be requested to IFCGR.

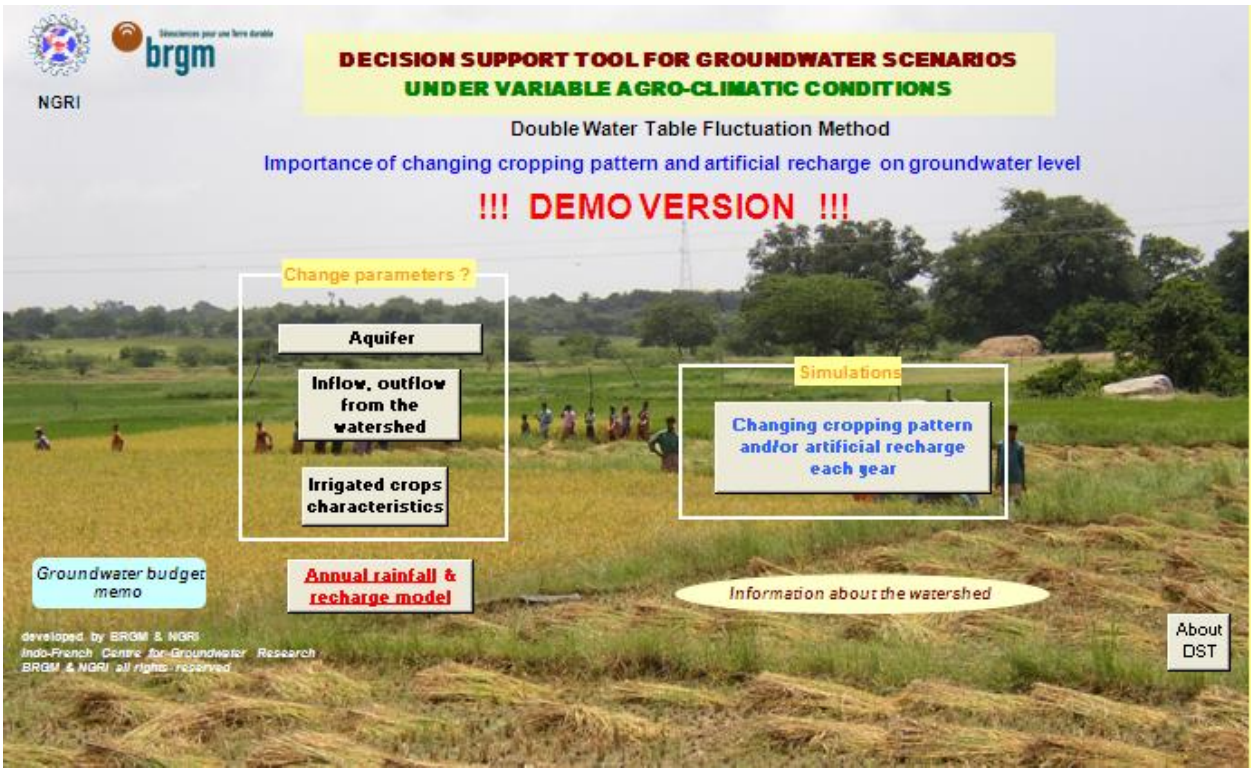

***Figure 4** : Main page of the groundwater management DST-GW (Demo version)*

Several active windows open from the main page (**Figure 4**):

The buttons "**groundwater budget memo**", "**annual rainfall & recharge model**", "**information about the watershed**", and "**About DST**" access to information windows. In the following, only the "**Change parameters"** and "**Simulations**" sections will be presented in detail as they form the core of DST-GW.

Change Parameters

- **Aquifer characteristics**: the User can define the average specific yield of the aquifer, the watershed area, the groundwater resource limit (i.e., the bottom of the aquifer), and the mean topographic elevation of the watershed. Maheshwaram watershed values may be used by default.

- **In, outflow from the watershed**: the User can enter the value Q_{inflow}-$Q_{outflow}$ in mm/yr. Maheshwaram watershed value may be used by default.

- **Irrigated crops characteristics**: the groundwater consumption for up to five crops can be entered for both Kharif season and Rabi season. Similarly the groundwater consumption for domestic use and poultry can be entered. For each defined groundwater use, the corresponding return flow has to be entered. Maheshwaram watershed values may be used by default.

Simulations

In this section, up to five scenarios of groundwater use and supply can be defined. First each scenario is defined in a specific table (**Figure 5**) and next the simulation results are viewed as a graph piezometric level vs time (**Figure 6**) by clicking button "**water level simulations**". It is also possible to see the groundwater budget components in mm/yr for the simulation period by clicking "**groundwater budget**".

The scenario can include change in cropping patterns for the up to five crops defined in the previous section (window "**Irrigated crops characteristics**"), change in domestic uses and poultry groundwater consumption, as well as an increase or decrease in artificial recharge (in mm/year).

Increase or decrease the crop areas (>0: increase, <0: decrease) in percentage of the previous year

(i.e. +5% in 2009= (1+0,05)*surf in 2008)

Information:
- Paddy 210 ha - vegetables 15 ha- flowers 20 ha - fruits 47 ha -

Results: Water level simulations | Groundwater budget

Menu

SIMULATION 1

period (1to10y.)	1	change every 'X' year	period (1to10y.)	1	change every 'X' year	period (1to10y.)	1	change every 'X' year	period (1to10y.)	1	change every 'X' year	period (1to10y.)	1	change every 'X' year	period (1to10y.)	1	period (1to10y.)	1		
Variations in surface [%]															Variation in activity [%]				Arificial recharge	
Date	**Rice**	area [ha]	**Date**	**vegetable**	area [ha]	**Date**	**flowers**	area [ha]	**Date**	**fruits**	area [ha]	**Date**	**grappes**	area [ha]	**Date**	**chicken**	**Date**	**domestic**	**Date**	**[mm/year]**
2001		252	2001		15	2001		20	2001		47	2001		55	2001		2001		2001	
2002		252	2002		15	2002		20	2002		47	2002		55	2002		2002		2002	
2003		252	2003		15	2003		20	2003		47	2003		55	2003		2003		2003	
2004		252	2004		15	2004		20	2004		47	2004		55	2004		2004		2004	
2005	-7.0%	234	2005	25.0%	19	2005	25.0%	25	2005		47	2005		55	2005		2005		2005	
2006		234	2006		19	2006		25	2006		47	2006		55	2006		2006		2006	
2007	-7.0%	218	2007	25.0%	23	2007	25.0%	31	2007		47	2007		55	2007		2007		2007	
2008		218	2008		23	2008		31	2008		47	2008		55	2008		2008		2008	
2009	-7.0%	203	2009	25.0%	29	2009	25.0%	39	2009		47	2009		55	2009		2009		2009	
2010		203	2010		29	2010		39	2010		47	2010		55	2010		2010		2010	
2011	-7.0%	189	2011	25.0%	37	2011	25.0%	49	2011		47	2011		55	2011		2011		2011	
2012		189	2012		37	2012		49	2012		47	2012		55	2012		2012		2012	
2013	-4.0%	181	2013	12.0%	41	2013	12.0%	55	2013		47	2013		55	2013		2013		2013	
2014		181	2014		41	2014		55	2014		47	2014		55	2014		2014		2014	
2015	-4.0%	174	2015	12.0%	46	2015	12.0%	61	2015		47	2015		55	2015		2015		2015	
2016		174	2016		46	2016		61	2016		47	2016		55	2016		2016		2016	
2017	-4.0%	167	2017	12.0%	51	2017	12.0%	69	2017		47	2017		55	2017		2017		2017	
2018		167	2018		51	2018		69	2018		47	2018		55	2018		2018		2018	
2019	-4.0%	160	2019	12.0%	58	2019	12.0%	77	2019		47	2019		55	2019		2019		2019	
2020		160	2020		58	2020		77	2020		47	2020		55	2020		2020		2020	
2021		160	2021		58	2021		77	2021		47	2021		55	2021		2021		2021	
2022		160	2022		58	2022		77	2022		47	2022		55	2022		2022		2022	
2023		160	2023		58	2023		77	2023		47	2023		55	2023		2023		2023	
	Area diff.	-92		Area diff.	43		Area diff.	57		Area diff.	0		Area diff.	0						0

Example of scenario: changing cropping patern | Clear

Next simulations

***Figure 5**: Table used to define scenario 1: in this scenario the surface of paddy is decreased regularly whereas the cultivated surface for vegetables and flowers is increased. These changes in cropping pattern are expressed in % of the existing irrigated area.*

The graph "**Simulation of piezometric level**" (**Figure 6**) presents for a twenty years period, the piezometric trend if no change occurs in the watershed (black curve), the piezometric trend if agriculture development follows the existing evolution based on FAO report (red curve 1), and then the User-defined scenarios results (up to five curves).

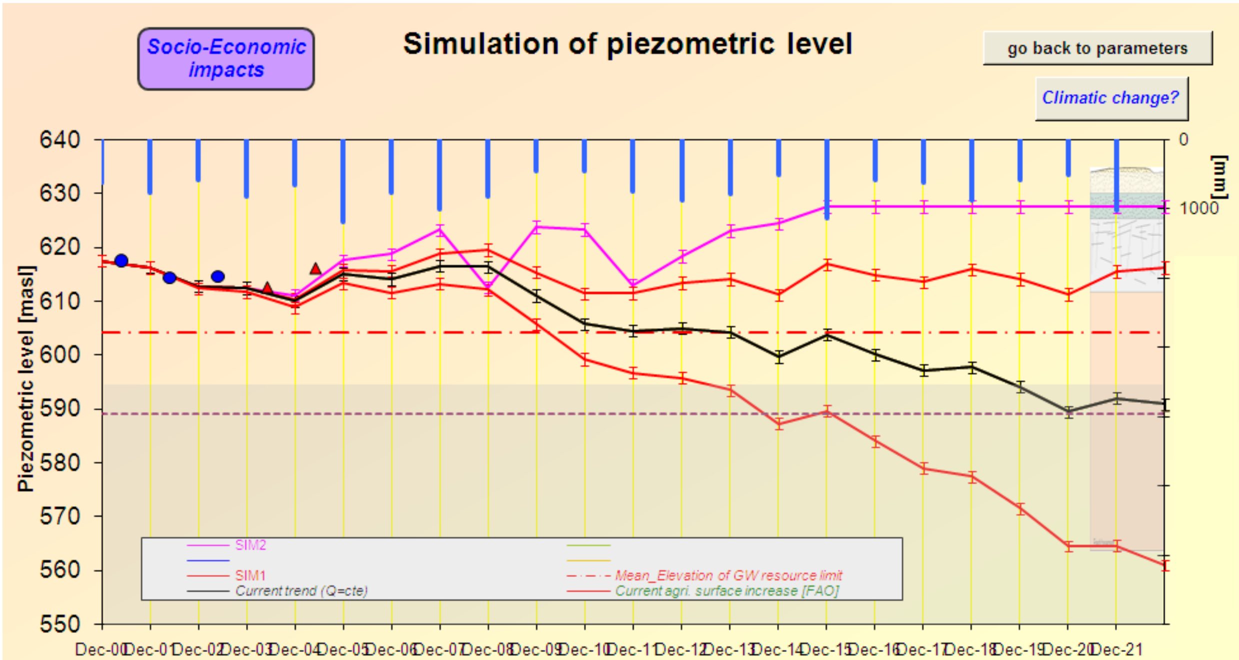

***Figure 6**: Simulation results for two User-defined scenarios (red curve SIM1 and pink curve SIM2). SIM1 corresponds to a scenario 1 defined in Figure 5 (decrease in paddy, increase in vegetables and flowers) whereas SIM2 corresponds to the same cropping pattern changes with additional artificial recharge.*

From the **Simulation of piezometric level** window, several other windows are accessible:

Socio-economic impacts: shows the % of drying borewells for the various scenarios. This is calculated from the borewell database of Maheshwaram watershed and may not be applicable to other waterheds.

Climatic Change?: the User can define his own future annual rainfall in order to simulate for instance the effect of consecutive bad monsoons.

Go back to parameters: this button connects back to the tables where the scenarios are defined.

5. Selected list of publications

Coudrain-Ribstein A., Pratx B., Talbi A., and C. Jusserand. 1998. Is the evaporation from phreatic aquifers in arid zones independent of the soil characteristics ? **C.R. Acad. Sci. Paris**, Sciences de la Terre et des Planètes 326: 159-165.

Dewandel, B, Lachassagne, P, Wyns, R, Maréchal, JC, Krishnamurthy, NS. 2006. A Generalized 3-D Geological and Hydrogeological Conceptual Model of Granite Aquifers Controlled by a single or Multiple Weathering. **Journal of Hydrology** 330:260-284.

Dewandel B., Gandolfi J-M., Ahmed S. and Subrahmanyam K, 2007. A Decision Support Tool for sustainable Groundwater Management in semi-arid Hard-Rock areas with variable agro-climatic scenarios. **Current Sciences of India**, vol. 92, 1093-1102.

Dewandel, B., Gandolfi, J-M., de Condappa, D., and S. Ahmed, 2008. An efficient methodology for estimating irrigation return flow coefficients of irrigated crops at watershed and seasonal scale. **Hydrological Processes.** doi: 10.1002/hyp.6738.

Healy, R.W. and P.G. Cook. 2002. Using ground water levels to estimate recharge. **Hydrogeology Journal** 10: 91-109.

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.

Maréchal, JC, Dewandel, B, Ahmed, S, Galeazzi, L, Zaidi, FK. 2006. Combined estimation of specific yield and natural recharge in semi-arid groundwater basin with irrigated agriculture. **Journal of Hydrology** 329: 281-293. doi:10.1016/j.jhydrol.2006.02.022.

Rangarajan, R, Athavale, R.N.,2000. Annual replenishable groundwater potential of India – an estimate based on injected tritium studies. **Journal of Hydrology** 234: 38–53.

Sukhija, B.S., Nagabhushanam, P., Reddy, D.V. 1996. Groundwater recharge in semiarid regions of India: An overview of resultsobtained using tracers. **Hydrogeology Journal** 4: 50–71.

Zaidi, FK, Ahmed, S, Maréchal, JC, 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.

6. Useful addresses and links

NGRI: National Geophysical Research Institute; Uppal Road, Hyderabad 500007, India. **www.ngri.org.in**

BRGM: French Geological Survey; 3, avenue Claude Guillemin - BP 36009 - 45060 Orléans Cedex 2, France. **www.brgm.fr**

IFCGR: Indo-French Centre for Groundwater Research; Groundwater Building, NGRI, Uppal Road, Hyderabad 500007, India. **www.ifcgr.net**

IWMI: International Water Management Institute; 127, Sunil Mawatha, Pelwatte, Battaramulla, Sri Lanka. **www.iwmi.cgiar.org**

Charles University (CU): Faculty of Science, Alberto 6, Prague 2, 128 43 Czech Republic. **www.cuni.cz**