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Importance of irrigation return flow on the groundwater budget of a rural basin in India

J. C. MARÉCHAL, L. GALEAZZI, B. DEWANDEL

BRGM, Water Department, Water Resources, Discontinuous Media Unit, Indo-French Centre for Groundwater Research, NGRI, Uppal Road, Hyderabad 500 007, India

marechal@ngri.res.in

S. AHMED

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

Abstract In many areas of India, the assessment of groundwater balance at the basin scale is a very important challenge for better management of this resource that is stressed by high exploitation through pumping for irrigation. A methodology is presented and applied to a case study in a hard-rock area. The methodology is based on the relationship between the water balance over a given period and resulting water level fluctuations (Water Table Fluctuation method). It is found that the main positive term of the budget is the return flow from paddy fields irrigation. From June 2001 to June 2002, despite normal rainfall, the annual balance is a little bit negative, inducing a general water level depletion of 1.18 m. Decreases of the pumping rate, or water harvesting measures and artificial recharge of the basin are necessary to reverse this deficit and to ensure sustainable management of the groundwater resource.

Key words budget; hard-rock; India; irrigation; overexploitation; recharge; water table

INTRODUCTION

Supplying 27 million hectares of farmland in India, groundwater now irrigates a larger total area than surface water (21 million hectares). This means it sustains almost 60% of the country's irrigated land. This change in usage in India has been extremely rapid since the 1970s. In just two decades, the groundwater-irrigated lands of India have increased by 105%. In contrast, the areas of surface-water irrigated land rose by only 28% over the same period (1970–1994). A count of mechanized wells and tube wells also illustrates how quickly groundwater irrigation has spread. Numbers of wells have rocketed in the last 40 years, from less than one million in 1960 to more than 19 million in the year 2000.

Great stress is put on groundwater, especially in (semi)arid areas such as Andhra Pradesh where surface water is not available. Therefore, it is necessary to adapt the exploitation of groundwater to its availability. For that purpose, it is indispensable to have suitable tools able to assess either the water budget of the aquifer and/or its renewable reserve.

In this paper, a methodology for water budget evaluation using a database of borewells under a Geographical Information System is presented and applied to a case study in a granitic basin in a semiarid context centred on the village of Maheshwaram in Ranga Reddy district, Andhra Pradesh, India (Fig. 1).

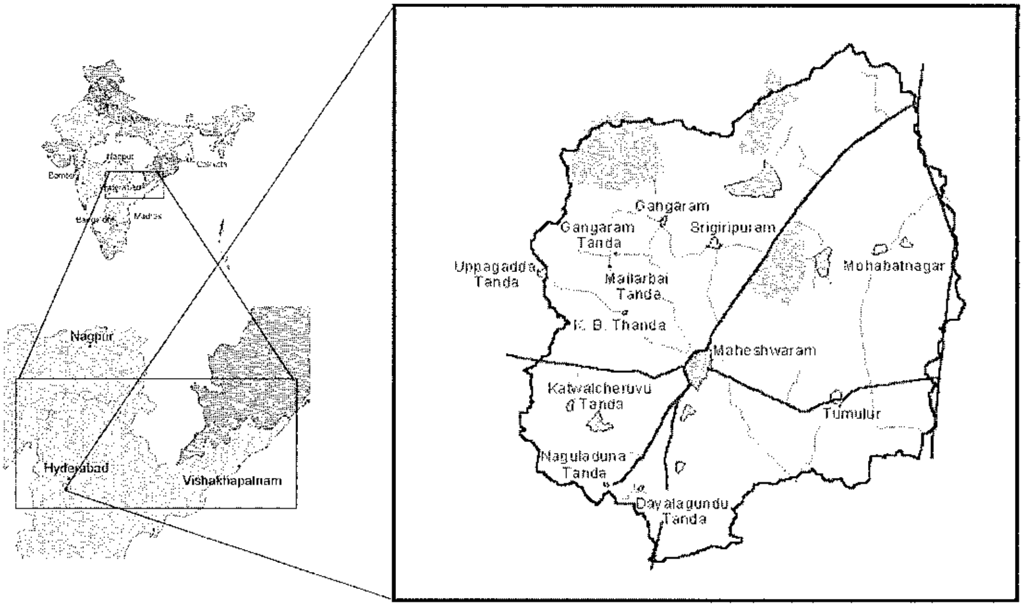

Fig. 1 Location of the study basin.

COMPONENTS OF THE GROUNDWATER BUDGET

Changes in subsurface water storage can be attributed to recharge, irrigation return flow, and groundwater flow into the basin minus baseflow, evapotranspiration from groundwater, pumping, and groundwater flow out of the basin (adapted from Schicht & Walton, 1961):

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

where R is groundwater recharge; RF is the irrigation return flow; Q_{on} and Q_{off} are groundwater flow into and from the basin, ET is evaporation from the saturated zone; 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. Due to the deep water table in the Maheshwaram basin, no spring is present and there is no groundwater contribution to streams, consequently the baseflow can be neglected in equation (1); also vegetation is not able to consume groundwater and evapotranspiration should be redefined as evaporation from groundwater, thus, the term ET is replaced by E: evaporation.

Equation (1) can be written:

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

The methodology used to determine the components of the budget is the Water Table Fluctuations (WTF) method that links the change in groundwater storage ΔS with resulting water table fluctuations Δh:

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

Pumping flow

Paddy fields and other crops (vegetables and fruits) are irrigated using groundwater for practical reasons: low rate of drilling and electricity costs, possibility of getting water near the crop, etc. A database of the borewells present in the basin was developed between June 2002 and September 2002. Exactly 929 wells were located using portable GPS and the discharge rate of each was measured. Information about the daily duration of pumping and annual number of pumping days was gathered in order to assess annual abstracted volume. The daily duration of pumping is dependent on power availability. Automatic water level recorders installed in three observation wells in the basin allow us to observe water level fluctuations due to pumping cycles and to identify an annual average of 6 h of pumping per day for 365 days.

Horizontal flow across the boundaries of the basin

Because the weathered covering of the geological profile is dry, and the permeability of the fresh basement is very low, horizontal flows in these layers of the aquifer can be neglected. Flows only occur in the fissured layer of the aquifer. These flows are dependant on the horizontal permeability, thickness of saturated zone, and local hydraulic gradient. They were computed using a finite differences model in order to obtain a spatial distribution on a grid of squared cells. A MODFLOW model was used with a kriged grid of the altitude of the top of the fresh basement, forming the bottom of the aquifer, along with the grid of the water table. Hydraulic potentials were imposed on the four limits of the modelled domain, far away from the basin. Flows are computed for a few days with an average horizontal permeability $K = 0.87 \times 10^{-5}$ m s^{-1} determined by upscaling (from slug-test scale to 200 × 200 m cells scale) using a DFN (Discrete Fractures Network) model, on the basis of 25 slug-tests.

The balance between horizontal in- and out-flows is positive (especially during the pre-monsoon period) due to the capture of water from outside induced by pumping.

Evaporation from the groundwater table

This component is evaluated using the relation developed by Coudrain *et al.* (1998). Evaporation flux is expressed as an inverse power function of the piezometric depth below the soil surface, independently of the soil characteristics. It was calculated for both pre- and post-monsoon periods. Due to the great depth of the depleted water table, the average value is only about 1.7 mm year^{-1}, much less compared to other components of the water budget.

Return flow from irrigation

Most of the pumped water in the basin is used for irrigation. A large part of this volume returns back to the aquifer by direct infiltration in the irrigated lands. This can be written as: $RF = C \times PG$ where C is the return coefficient ($0 < C < 1$). Because the return coefficient is different from paddy fields to other crops, the global return coefficient C is weighted by the repartition of crops. In the granite areas of Andhra Pradesh, the coefficient for paddy fields was evaluated as 0.60 (APGWD, 1977). For other crops, the proposed coefficient is $C_{OTHER} = 0.20$ (CGWB, 1998). With 79% of paddy fields and 21% of other crops, the final value is $C = 0.516$.

SPECIFIC YIELD AND DRY SEASON GROUNDWATER BUDGET

The hydrological year studied (June 2001 to May 2002) was divided into two parts: the wet season (from June to November 2001) corresponds to the monsoon influence with recharge reaching the aquifer, while the dry season (from November 2001 to June 2002) starts after the monsoon and, by definition, is characterized by the absence of recharge. Following this definition, recharge can be neglected during the dry season and the groundwater budget (equation (2)) of the basin can be written:

$$RF^{dry} + Q_{on}^{dry} = E^{dry} + PG^{dry} + Q_{off}^{dry} + \Delta S^{dry} \quad (4)$$

where ΔS^{dry} is negative. Applying the WTF method to the dry budget, the porosity of this unconfined aquifer is obtained by introducing equation (3) into (4):

$$\Phi = \frac{RF^{dry} + Q_{on}^{dry} - E^{dry} - PG^{dry} - Q_{off}^{dry}}{\Delta h^{dry}} \quad (5)$$

All the terms of equation (5) are listed above, and were estimated for the full hydrological year. Consequently, considering that the duration of the dry season is five months, the flows for this period are estimated as a ratio (5/12) of the total year. The application of this technique allows us to estimate the specific yield of the aquifer (Table 1). The specific yield obtained is realistic for such fissured granite and is consistent with values found using pumping tests (Maréchal *et al.*, 2002) or global modelling (Engerrand, 2002).

RECHARGE AND WET SEASON GROUNDWATER BUDGET

Accurate recharge estimation is difficult, especially in (semi)arid areas where spatial and temporal variability are high. The chosen technique is a combination of the WTF and groundwater budget techniques. Contrary to classical water budget techniques, the groundwater budget technique is not dependent on uncertainties in the evapotranspiration component. Furthermore, because of the good quality observation network, the WTF method can be applied at the basin scale. Thus, combining equation (2) for the wet season and equation (3), the recharge is estimated:

$$R^{wet} = \Delta h^{wet}.\Phi - RF^{wet} - Q_{on}^{wet} + E^{wet} + PG^{wet} + Q_{off}^{wet} \quad (6)$$

Application of this equation is illustrated at Table 2. The estimated recharge flow includes all recharge types (direct, indirect and localized recharge).

Table 1 Groundwater budget during the dry period (flow terms are in mm year^{-1}).

RF^{dry}	Q^{dry}	E^{dry}	$Q_{on}^{dry} - Q_{off}^{dry}$	Δh^{dry} (m)	Φ (–)
69	135	1.0	4.9	–6.88	0.0089

Table 2 Groundwater budget during the wet period (flow terms are in mm year^{-1}).

RF^{wet}	PG^{wet}	E^{wet}	$Q_{on}^{wet} - Q_{off}^{wet}$	Δh^{wet} (m)	R^{wet}
49.6	96.1	0.7	3.5	+5.70	94.5

Table 3 Annual groundwater budget (flow terms are in mm year^{-1}).

R	RF	PG	E	$Q_{on} - Q_{off}$	ΔS	Δh^{tot} (m)
94.5	119	231	1.7	8.4	–10.5	–1.18

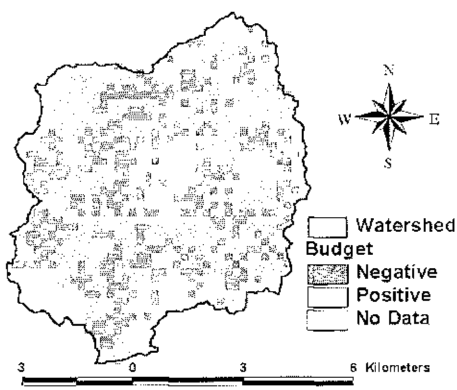

Fig. 2 Spatial annual budget

ANNUAL GROUNDWATER BALANCE

The annual groundwater balance was calculated from June 2001 to June 2002 (Table 3). Considering the uncertainty on the flow components, this indicates that the budget is more or less balanced. However, the total balance is a little bit negative, in accordance with an average water level decrease of about 1.18 m on the basin over this period, in spite of a normal monsoon (603 mm of rainfall). This clearly shows that, with such an abstraction rate from the basin, any bad monsoon, as for example the monsoon of 2002, will induce a significantly negative balance followed by a depletion of the water table. The map of water budget (Fig. 2) shows that negative balance areas only correspond to pumping areas due to the fact that pumping flows and return flows are respectively the main negative and positive components of the budget. In spite of the fact that spatially they represent only 25% of the 1324 cells, the whole balance is negative.

CONCLUSIONS

The annual groundwater budget of Maheshwaram basin was calculated from June 2001 to June 2002. The groundwater balance of the whole basin was a little bit negative, inducing a depletion of 1.18 m for the water table, in spite of the occurrence of a normal monsoon. This means that high rate of pumping leads to overexploitation of groundwater resource at the basin scale. The importance of irrigation return flow has arisen in such a typical rural basin in semiarid southern India.

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