Journal of Hydrology 398 (2011) 144–154

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Solute recycling: An emerging threat to groundwater quality in southern India?

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ARTICLE INFO

Article history:
Received 30 November 2009
Received in revised form 6 December 2010
Accepted 20 December 2010
Available online 25 December 2010

This manuscript was handled by P. Baveye, Editor-in-Chief

Keywords:
Solute recycling
Southern India
Hard-rock aquifer
Irrigation
Reservoir model
Salinisation

SUMMARY

Groundwater from crystalline aquifers is abstracted at large rates for paddy irrigation in southern India resulting in widespread over-exploitation of the resource. Detailed field studies at watershed scale have shown that basin closure is happening (i.e., groundwater contribution to base flow has stopped) and irrigation return flow can contribute to as much as half of the aquifer recharge. Studies in other semi-arid regions have shown that irrigation return flow, through a process known as solute recycling, can contribute significantly to aquifer salinisation. To evaluate the impact of this process in the southern India context, a lumped reservoir model has been designed in order to simulate long-term trends of piezometric levels and solute concentrations at watershed scale. The model is applied to the well studied watershed of Maheshwaram (53 km^2), located 40 km South of Hyderabad. It can reproduce qualitatively watershed-average groundwater levels and chloride concentrations inferred since 2001 that shows a progressive buildup. Simulation of the period 2010–2044 indicates that forecasted reservoir concentrations are very sensitive to aquifer mixing efficiency. In the case of complete mixing, base flow that activates after rainy years may export significant solute mass and level off aquifer concentration to acceptable levels. In the more realistic case of incomplete mixing, diluted base flow will export less solute and progressive solute mass buildup continues throughout the simulation period to end up with concentrations close to the ones that makes water no longer suitable for irrigation. Final aquifer concentrations may become even higher with scenarios that accelerate the lowering of the water table such as higher pumping rates, decrease in daily rainfall or increase in daily evaporation.

These simulations show that solute recycling may have a significant negative impact on groundwater quality in southern India, especially in aquifers located in semi-arid hard-rock areas where the main source of irrigation is provided by groundwater.

1. Introduction

Groundwater is a natural resource of major importance in India. From the 1960s, exploitation of this resource has increased drastically in large areas of the country, and contributed to a radical change known as the Green Revolution. As a result, the number of mechanized wells and tubewells increased from a small fraction of 1 million in 1960 to 19 millions in 2000 (Shah et al., 2003). These wells pump around 150 km^3/year, which makes India the largest groundwater-consuming country in the world.

Presently, groundwater is a significant source of irrigation and accounts for more than half of net irrigated area in the country. Groundwater irrigation can be therefore an effective vehicle of poverty eradication as its access exists in many areas and required investments are affordable by rural communities. According to the World Bank and the Ministry of Water Resources, the contribution of groundwater to India's GDP is around 9%. With only surface water irrigation, less than 20% of the country's farmland would be irrigated and the Green Revolution would not have achieved the wide and even spread success that it has.

This intensive use of groundwater resources resulted in over-exploitation, particularly in semi-arid hard-rock regions of southern India (Maréchal et al., 2006a; Dewandel et al., 2007), and a deterioration of groundwater quality (Maréchal et al., 2006b).

In this paper we investigate the potential negative impact of solute recycling by irrigation return flow (IRF) on groundwater quality. IRF, especially from paddy fields, is one of the major groundwater budget components in semi-arid hard-rock watersheds. For instance, Maréchal et al. (2006a) showed that in a typical southern India watershed, IRF at watershed scale accounts for 70–90 mm/year which is in the same range as natural recharge from rainfall (55–124 mm/year at the watershed scale) even though the total irrigated area covers only 4–9% of the total watershed. This situation is quite widespread in southern India where

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doi:10.1016/j.jhydrol.2010.12.024

paddy fields are cultivated extensively and irrigated with groundwater (with the noticeable exception of surface water irrigation from nearby large rivers).

IRF can have a serious impact on groundwater quality due to progressive mineralization/salinisation as shown by several studies in semi-arid areas around the world (Konikow and Person, 1985; Bouwer, 1987; Close, 1987; Beke et al., 1993; Prendergast et al., 1993; Milnes and Renard, 2004).

To our knowledge, in India the role of IRF on groundwater resources salinisation has been overlooked so far. The majority of studies on groundwater salinisation have focused on coastal areas (e.g., Sukhija et al., 1996; Choudhury et al., 2001; Violette et al., 2009).

The objective of this paper based on field observations from one typical watershed located in semi-arid hard-rock southern India is twofold. First, it aims at presenting a reservoir model simulating piezometric levels and solute concentrations and investigating its suitability to compute long-term concentration trends. Second it discusses the key factors that may affect the groundwater quality at the horizon 2020–2045 according to different scenarios of global change.

2. Solute recycling model

Hard-rock (granite, gneiss) aquifers originate from weathering processes (secondary porosity) which give a specific structure characterized by two layers: a high-storage low permeability layer on top known as saprolite, and a low-storage high permeability layer below known as the fissured zone (e.g., Dewandel et al., 2006). These unconfined aquifers have a thickness limited by the depth of weathering, usually less than 100 m, except in the vicinity of geological discontinuities. The water table follows generally the surface topography, so that surface watershed limits and groundwater divides match closely.

In semi-arid climatic conditions, recharge occurs during a few monsoon months (direct and indirect infiltrations from rainfall). Hence in natural conditions, fluid and mass fluxes will be controlled by recharge events (in-flows) and baseflow to surface streams (out-flows) as sketched in Fig. 1i. With the exponential increase in the number of borewells in southern India over the past 20 years, the aquifer functioning changed drastically (Fig. 1 ii): water tables have dropped (down to alarming levels in over-exploited aquifers), baseflow to streams has stopped as deep water tables are disconnected from stream beds, and borewells capture most of the recharge fluxes. Moreover, IRF constitute an important recharge component in addition to rainfall sources and IRF fluxes are active all year round as compared to natural recharge that is limited to the monsoon months.

These aquifer systems presented in Fig. 1i and ii can be reproduced in a simple way by a reservoir model with the aim to simulate long-term fluid and mass fluxes (and piezometric levels and solute concentrations trends). Such a reservoir model is easier to calibrate than a distributed model because it does not require hydraulic and transport parameters that may be difficult to assess in heterogeneous hard-rock aquifers. However the model is appropriate for reproducing long-term evolutions of average piezometric levels and average aquifer solute concentrations.

In over-exploited aquifers, groundwater flow across the aquifer boundaries is limited and out-flows balance in-flows as shown by Maréchal et al. (2006a) so that these terms of the groundwater balance can be neglected. However this may no longer be a valid assumption for mass balance since groundwater solute concentration in the out-flow may be very different from concentration in the in-flow. A term for groundwater solute mass export (M_{gwout}) is added to the reservoir model.

The model is designed as a lumped reservoir model at the watershed scale. This reservoir model is sketched in Fig. 1iii where the aquifer reservoir is divided into seven horizontal layers of identical thickness and with specific yield (typical values between 0.002 and 0.02) progressively increasing from bottom to top to reproduce the general decrease in porosity with depth observed in the aquifer (Dewandel et al., 2006).

Water and mass stored in the reservoir are computed on a daily time step (t) according to:

Water storage:

$$V_{aqu}(t) = V_{aqu}(t-1) + V_R(t-1) + V_{IRF}(t) - V_P(t-1) - V_{out}(t-1) \quad (1)$$

with

$$V_{R,IRF,P,out} = \int Q_{R,IRF,P,out}(t)dt \approx \sum Q_{R,IRF,P,out}(t)\Delta t$$

$$Q_{out} = V_{aqu}(t-1) - V_{\max} \quad \text{if } V_{aqu}(t-1) > V_{\max}$$

$$Q_{out} = 0 \quad \text{if } V_{aqu}(t-1) \leqslant V_{\max}$$

And V is the water volumes, Q the water fluxes; subscripts *aqu* is the reservoir, R the natural recharge, *IRF* the irrigation return flow, P the pumping, *out* the base flow, and V_{max} is the maximum storage capacity of the reservoir.

Piezometric levels can be computed by:

$$h(t) = h(t-1) + \frac{[V_{aqu}(t) - V_{aqu}(t-1)]/A}{S_y^*} \quad (2)$$

With A is the surface area of the reservoir and S_y^* is the average specific yield for the corresponding piezometric level.

Mass storage:

$$M_{aqu}(t) = M_{aqu}(t-1) + M_R(t-1) + M_{IRF}(t) - M_P(t-1) - M_{out}(t-1) \quad (3)$$

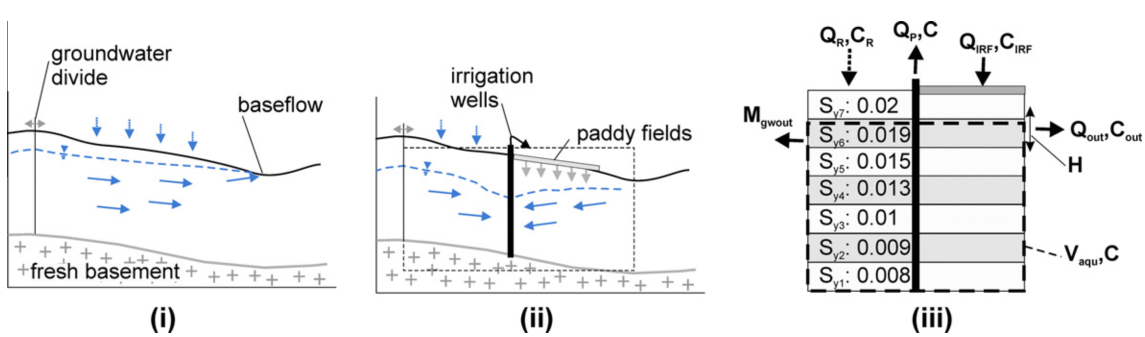

Fig. 1. (i) Conceptual model of hard-rock aquifer in southern India under natural conditions where natural recharge contributes to base flow; (ii) the same aquifer currently intensively pumped for paddy irrigation: the water table gets depleted and base flow is cut off; and (iii) sketch of the solute recycling reservoir model representing the aquifer within the dashed rectangle in (ii).