Water Quality Evolution During Managed Aquifer Recharge (MAR) in Indian Crystalline Basement Aquifers: Reactive Transport Modeling in the Critical Zone

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Water quality evolution during managed aquifer recharge (MAR) in Indian crystalline basement aquifers: reactive transport modeling in the critical zone.

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Abstract

The present study investigates the role of MAR (Managed Aquifer Recharge) on groundwater quality overexploited crystalline aquifers in semi-arid context (South India). A 1D transient reactive transport model was conceived to simulate the infiltration of a recharge tank through the critical zone. The model takes into account hydrodynamics, evaporation, kinetic weathering of minerals (precipitation/dissolution), adsorption, cationic exchange. Results show the beneficial effect of MAR on groundwater quality, in particular on Fluoride accumulation, a widespread problem in the Indian context, strongly depending on seasonal climatic variations.

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Keywords: MAR; overexploited crystalline aquifers, Fluoride accumulation, critical zone, reactive transport modelling.

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1. Introduction

The overexploitation of crystalline aquifers in India due to the green revolution in the 1970s, has lead to not only to a general water level drawdown but also to the degradation of water quality [1]. In the Maheshwaram watershed (Andra Pradesh, Southern India), groundwater is largely used for irrigation. Fluoride (F^-) progressively accumulated in the irrigation return flow (IRF) because of strong evaporation in the paddy fields together with mineral dissolution of primary minerals containing F- (fluorapatite, biotite, epidote) [2,3].This accumulation is enhanced by calcite precipitation reducing Ca^{2+} activity and also by Ca^{2+} removal through cation exchange with Na^+ on clay minerals, thus hindering fluorite (CaF_2) precipitation the only mechanism efficiently controlling F^- concentrations [4]. High concentrations of F^- are therefore typically accompanied by a Na-HCO_3^- water type [5] and areas of alkaline soils increase in India due to poorly managed irrigation projects [7,8,9].

Managed Aquifer Recharge (MAR) through percolation tanks is often presented as a promising technique to increase groundwater availability and eventually enhance water quality, but is rarely estimated (Boisson et al., 2014). Currently there are three percolation tanks located within the Maheshwaram watershed and the monitored one, is close to Tumulur village (Fig. 1), has been monitored over 2 years. Instrumentation monitoring equipment of the Tumulur tank is described in detail by [10].

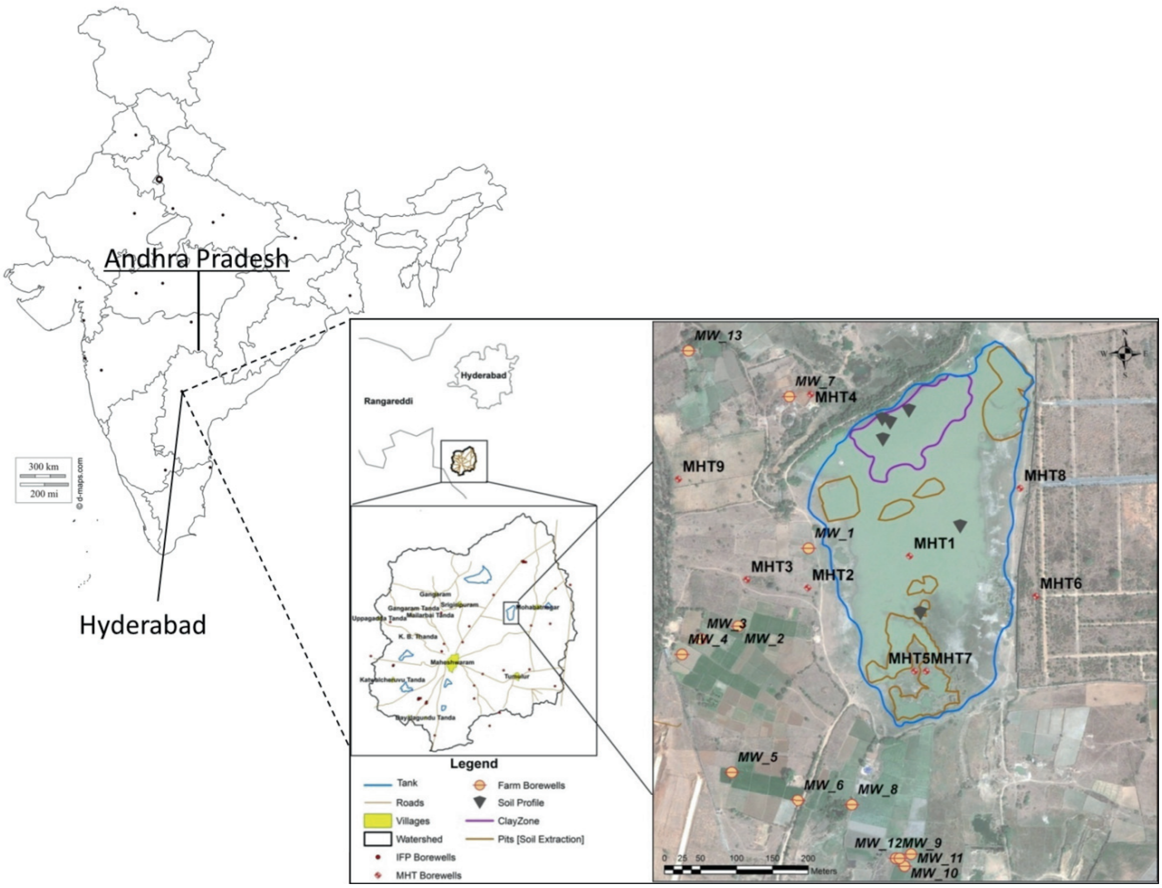

Fig. 1. Location of the Maheshwaram watershed and Recharge tank near the Tumulur village.

The aim of the geochemical modelling presented here is to quantify the water-rock interactions processes during the recharge and to investigate the corresponding impact on groundwater quality at the watershed scale. Results of hydrogeological models, including recharge scenarios are used to establish water budget as input to the reactive transport model [10]. The global objective is to evaluate the beneficial or adverse effect of managed recharge upon soil salinization and fluoride accumulation under the particular conditions of the Maheshwaram aquifer. The geochemical model of solute recycling developed for paddy field irrigation [3] using a 1D PHREEQC reactive-transport column [11] was adapted to the MAR problem, on the basis of new monitoring data in order to test the conceptual geochemical model of MAR (Fig. 2).

2. Methods

The system can be conceptualized at watershed scale considering the daily amount of tank water infiltration impacted by evaporation and the mixing processes, within the aquifer, of infiltrated water from the tank with natural recharge using a seasonal water balance approach [10]. The simulations were run for two contrasted climatic period (monsoon and dry period) during 110 days, using actual Tumulur tank data (i.e. water chemistry and meteorological data). The pore water velocities for the three layers of the percolation profile (soil, sandy regolith and laminated layer) are calculated using a 2D model of variably saturated vertical flow in a 10 m thick layer model using the MARTHE code [12,13,14,15]. Steady-state condition is established rapidly and the entire profile is quasi-saturated with infiltration water (>90%).

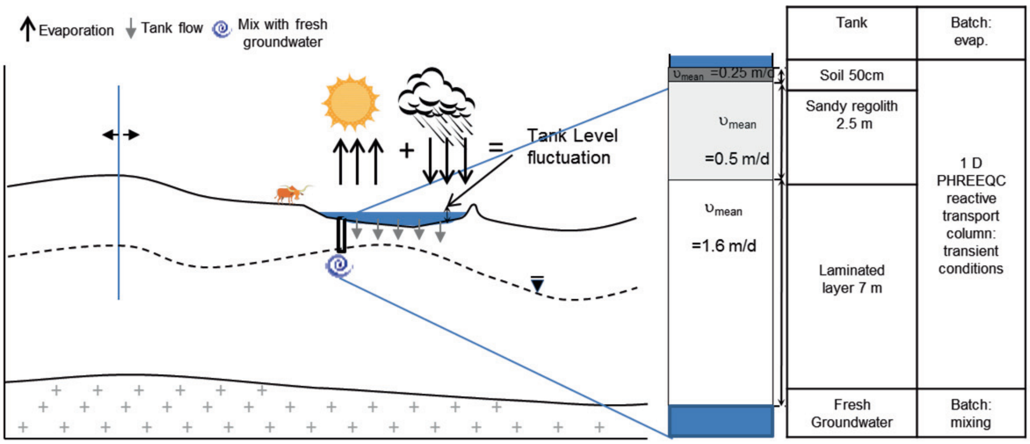

Fig. 2. Conceptual model of hard-rock aquifer in southern India with Managed Aquifer Recharge (MAR) through an infiltration tank used for the development of a1D Phreeqc reactive column model. υmean is the mean pore flow velocity.

Reactive transport modelling is performed during 110 days using a 1D PHREEQC column with calculated pore flow velocity (Fig. 3). The reactive transport model takes into account:

- The mineral composition of the 3 distinct layers of altered biotite granite determined by XRD analysis [3],
- Cation Exchange Capacity (CEC) of the weathering profile determined by cobalt hexamine chloride solution [3],
- Initial groundwater composition determined using ion chromatography and ICP-MS [3].

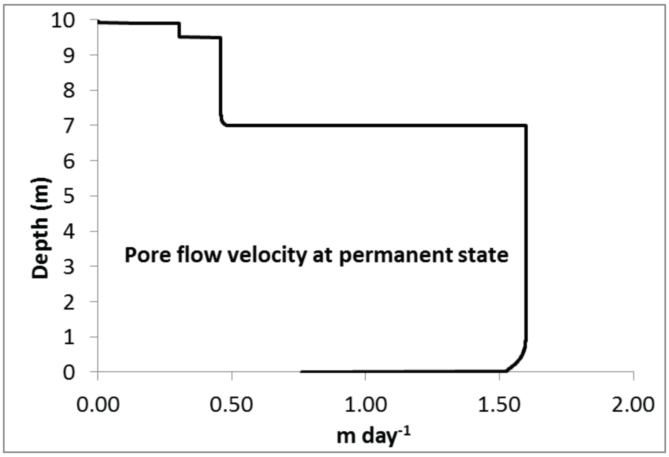

Fig. 3. Simulated steady-state pore flow velocity with 2 D variably saturated model.

The processes integrated in the reactive transport model are:

- The thermo-kinetic dissolution of primary aluminosilicate phases based on [16] and [17] formulation (Transition State Theory, TST; [18],),
- The possible precipitation of secondary mineral phases [19],
- The adsorption on Fe hydroxides following the [20] theory, [21] and [22] for surface site characteristics,
- The cationic exchange processes.

The groundwater geochemistry is calculated with batch reaction at a daily time step mixing the solution taken at the outlet of the column with the evolving groundwater composition. The ratio of mixing (MAR water volume/aquifer volume) is fixed to 0.01%.

3. Results and Discussion

Fig. 4 shows the results of modeling in terms of solute evolution (chloride and fluoride) in Maheshwaram groundwater for several climatic conditions (dry and monsoon periods) and land uses contexts. Perrin et al. [1] has shown that the observed increasing TDS can be reproduced with the help of a solute recycling model (SRM) since the start of irrigation pumping. Pettenati et al. [3] used a geochemical reactive transport model to simulate the impact of IRF on groundwater chemistry and F^- accumulation. This model including water/rock interaction in the Critical Zone and climatic parameters highlights the joint effect of dissolution of F^--bearing minerals (fluorapatite/allanite/biotite) and of evaporation as principal trigger of F^- enrichment in the return flow and the aquifer.

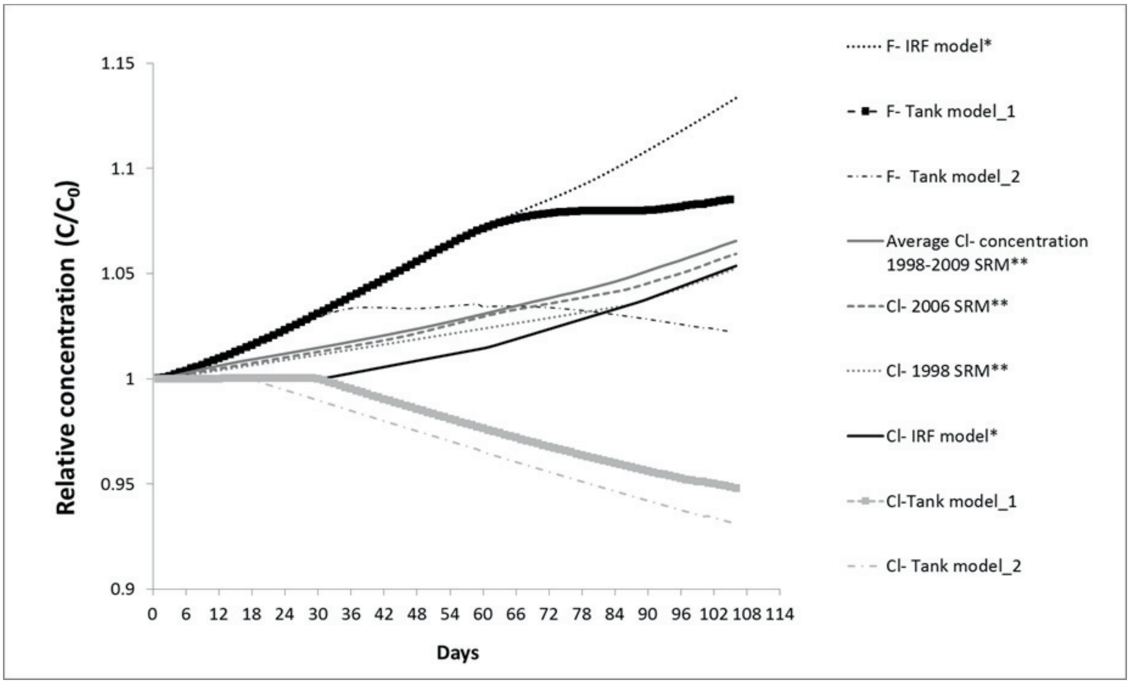

Fig. 4. Comparison between the relative aquifer solute concentration of chloride (Cl^-) simulated by the solute recycling model SRM ([1]**) and by the PHREEQC model for chloride (Cl^-) and fluoride (F^-) over one cycle of paddy field irrigation (dry season, [3]*) and one cycle of Tank infiltration (Tank model_1 = dry conditions 01/2006 to 04/2006; Tank model_2 = monsoon conditions 07/2012 to 10/2012).

Based on these previous works, the MAR model applied to the critical zone shows that tank infiltration can have a beneficial effect on the decrease of aquifer fluoride concentration (F^- Tank model_2) under monsoon period (tank filling). As illustrated by the decreasing concentration of non-reactive chloride, this effect is due to a dilution effect compensating the evaporation processes. But results obtained considering another dry period (tank drainage) illustrate that, even if F^- accumulation is delayed (F^- Tank model_1) compared to the IRF model (paddy field context) there is still an increase of F^- over the duration of managed recharge. This tendency is due to a higher degree of evaporation over the dry period combined with the weathering of F^--bearing matrix minerals within the critical zone during tank water percolation.

4. Conclusions

This research investigated the role of managed aquifer recharge under variable climatic conditions and its impact on groundwater chemistry. Based on a previous model which reproduced satisfactorily the solute behavior in Maheshwaram groundwater, the reactive transport model of the Tumulur tank infiltration through the critical zone helps to understand the evolution of Fluoride enrichment or depletion in groundwater when MAR is implemented in a watershed. Results of the first scenarios simulation show that the beneficial effect of MAR may be variable over the year being strongest during monsoon whereas during the dry period, F accumulation occurs.

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