Chapter 7

Percolation tanks as managed aquifer recharge structures in crystalline aquifers – An example from the Maheshwaram watershed

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7.1 INTRODUCTION

Managed aquifer recharge (MAR) through percolation tanks is a promising technique to increase local water availability. However, authors such as Dillon *et al.* (2009) point out the lack of data available for an accurate assessment and note that little evidence exists on the positive impact at local scale. Some authors even point out the possible negative impact at the watershed scale due to the enhancement of local water extraction (Calder *et al.* 2008; Glendenning *et al.* 2012; Sakthivadivel, 2007).

In the following study, a percolation tank located in the Maheshwaram watershed in Andhra Pradesh (India) is monitored to quantify its impact on water availability and quality. The objectives are to assess the potential of percolation tanks as managed aquifer recharge structures by:

1) quantifying the volume of water recharged to the aquifer by a percolation tank
2) developing a simple methodology for prediction of yearly benefits to the aquifer from percolation tanks
3) defining the hydrodynamic and hydrochemical specificities of percolation tanks in crystalline aquifers
4) assessing the impact of percolation tanks on the ground water quality

An overview of major results is presented in this chapter. More detailed information on methodologies and detailed results can be found in related publications (Boisson *et al.* 2014a; Boisson *et al.* 2014b; Pettenati *et al.* 2014; Alazard *et al.* 2015).

7.2 SITE DESCRIPTION

7.2.1 Maheshwaram watershed

The study was carried out in the Maheshwaram watershed, located 35 km south of Hyderabad (Andhra Pradesh State, India). This typical watershed is a good example of a south Indian context with semi-arid climate and crystalline aquifers. Moreover, previous hydrogeological studies in the watershed provided good baseline data (Dewandel *et al.* 2006; Maréchal *et al.* 2004, 2006; Wyns *et al.* 2004; Perrin *et al.* 2011). The watershed covers an area of 53 km^2 (Figure 7.1) and has a relatively flat topography ranging from 590 to 670 m above mean sea level. The climate is semi-arid with annual monsoon rains (rainy or 'Kharif' season from June to October). Mean annual precipitation is about 750 mm, of which more than 90% falls during the monsoon season (Maréchal *et al.* 2006). The mean annual temperature is about 26°C although during the summer

(‘Rabi’ season from October to May), maximum temperature can reach 45°C (Maréchal *et al*. 2006). The resulting potential evapotranspiration is 1,800 mm/year. Due to the rapid growth of Hyderabad city, this watershed is now in transition from a rural to a suburban area. The aquifer is overexploited with more than 700 boreholes used for agriculture dominated by rice paddy fields (Dewandel *et al*. 2010). Currently, the water table is 15–25 m below ground and there is no surface water except for a few days subsequent to very heavy rain falls. Thus, no regular infiltration is observable in the watershed during most of the year.

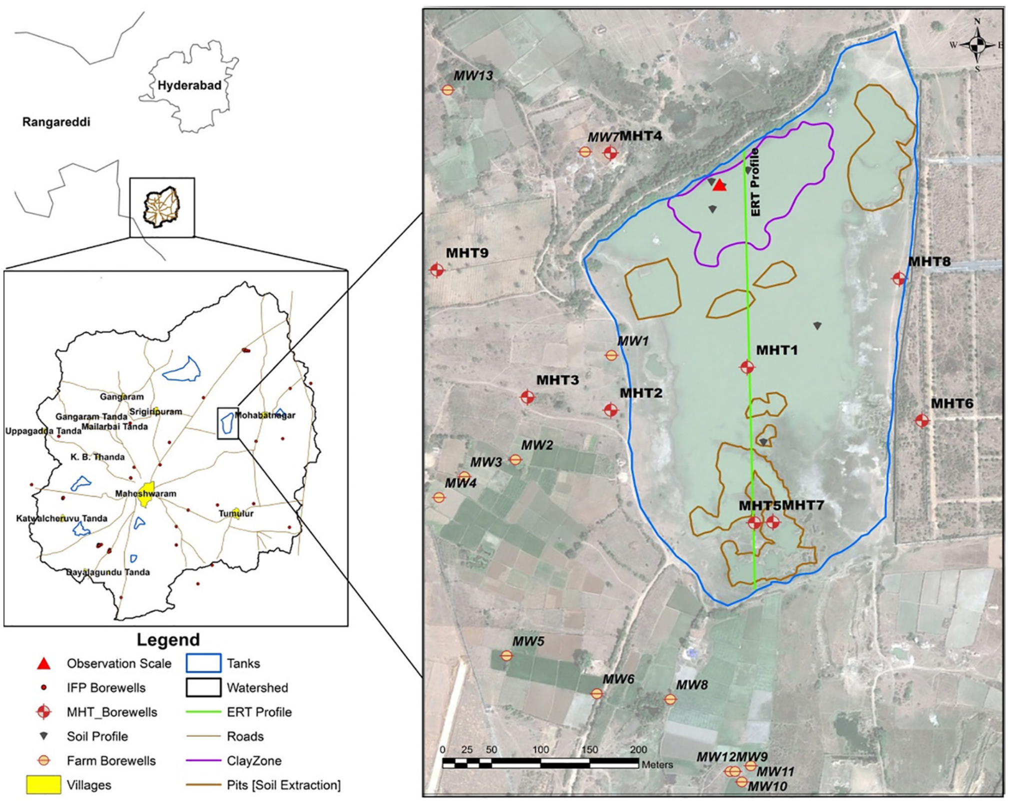

Figure 7.1 Study site map (from Boisson *et al.* 2014).

7.2.2 Main characteristics of the crystalline rock aquifer

Crystalline rock aquifers, which represent most of South India and about 66% of Andhra Pradesh state (G.S.I, 2005), present specificities which may limit the potential of MAR. The typical geological profile is described as follows (Acworth, 1987; Chilton & Foster, 1995; Dewandel *et al*. 2006; Figure 7.2): the first zone is the saprolite (or alterite or regolith) on top consisting of clay-rich material, derived from bedrock decomposition with a thickness of approximately ten meters. Because of its clayey–sandy composition, the saprolite zone has a high porosity, and a low permeability. This zone is the main storage capacity of the aquifer. The second zone is a fissured zone, generally characterized by dense horizontal fissuring in the first few meters and a depth-decreasing density of sub-horizontal and sub-vertical fissures (Maréchal *et al*. 2004). This zone mainly provides the transmissive function of the aquifer and is tapped by most of the wells drilled in hard-rock areas. The third zone is the fresh basement which is only permeable where tectonic fractures are present. Boisson *et al*. (2015) showed that the storage potential of the deepest fractures is very limited.

7.2.3 Tummulur tank monitoring program

Currently, three main percolation tanks are located within the watershed. The monitored tank is close to Tummulur village, in the downstream part of the watershed (Figure 7.1), and has been used for more than 10 years for water storage. An earth bund in its northern part dams the natural stream outlet, and consequently run-off water can be stored over an estimated maximum area of 158 000 m^2 and a maximum water depth of 3.5 m. Before the first significant rainfall events in 2012, the tank was dry for over 7 months with temperature ranging from 30 to 45°C which created shrinkage cracks at the entire tank area. This area is covered by silt loam soil on the surface underlain by sandy loam at a depth of 40–80 cm. Because of thin sedimentary deposits, there is an important clayey zone, at the foot of the bund, in the northern part of the tank. Clay pits are located on the southern part of the tank to feed the nearby brick industry. Nine monitoring boreholes (labelled MHT's) were implemented in 2012 and one staff gauge records the surface water level within the tank. Temperature and electrical conductivity logging are regularly performed in the boreholes, in addition to the long term piezometry, temperature and electrical conductivity records. Slugs tests were also performed (Boisson *et al.* 2015). The topography of the tank area was measured by DGPS (Differential Global Positioning System) and regular GPS tracking of the water contour give the tank area evolution. Within a radius of 500 m, at least 15 irrigation boreholes are in use (rice paddy and maize). Irrigation duration and times are controlled by the availability of electricity (7 h a day). The percolation tank constitutes a drinking water supply source for livestock (few goats and buffaloes) and no significant direct tank water extraction for irrigation purposes occurs. This tank system is representative of MAR practice in semi-arid southern India.

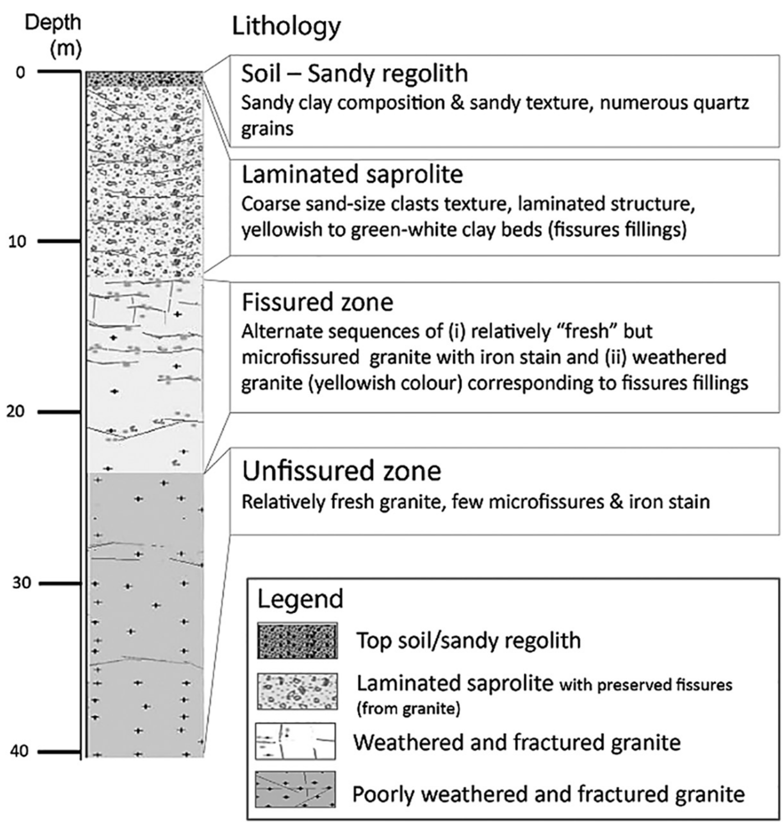

Figure 7.2 Geological log characteristic for the study area.

Eight sampling campaigns for major ions analyses and two campaigns for stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) analyses were performed in 2013 and 2014 during different hydrological conditions (Figure 7.3). Groundwater was sampled in 7 MHT boreholes and 3 farmer boreholes as well as the Tummulur tank water (when filled) (Figure 7.1). In situ electrical conductivity, temperature and pH were measured for each sample. Water samples were collected in clean, triple-rinsed polyethylene bottles. Raw water was sampled for isotopes and hydrogen carbonate analyses. Water for anion analyses was filtered (0.45 µm) in situ. Water for cation analyses was filtered (0.45 µm) and acidified (nitric acid, 1M) in situ. Bottles were completely filled, limiting air contact. Chloride, nitrate, sulphate and fluoride were analysed by ionic chromatography (Dionex) according to the NF ISO 10304 method. Hydrogen carbonate contents were determined using the NF ISO 9963–1 method based on potentiometric analysis. Calcium, potassium, sodium and magnesium were analysed by ICP-emission spectrometry according to the NF ISO 11885 method. Stable isotopes ratios ($\delta^{18}O$, $\delta^{2}H$) were measured by mass spectrometry.

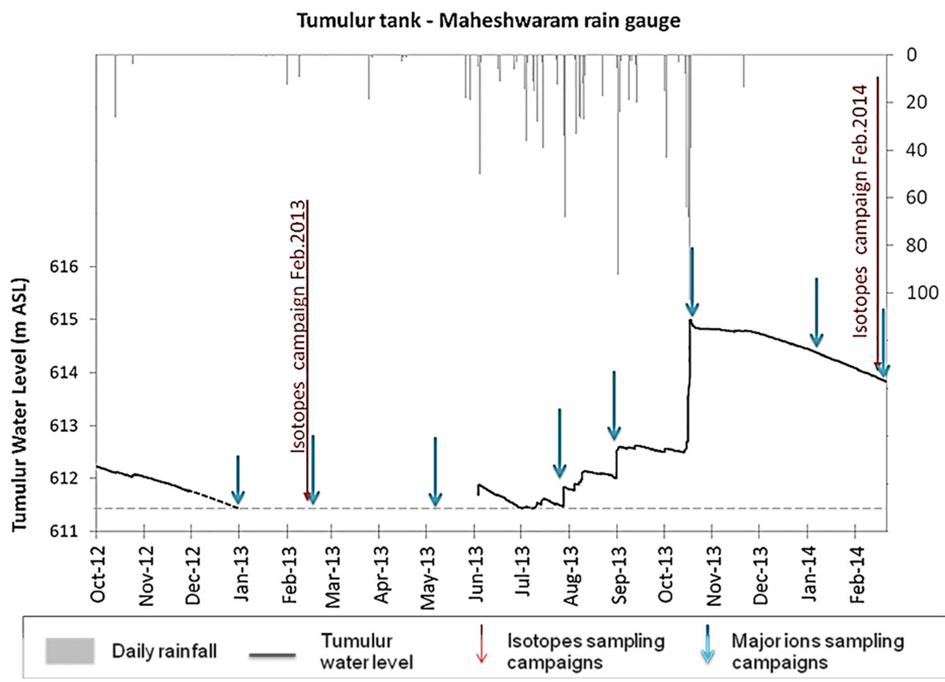

Figure 7.3 Tank water level (in m above sea level- ASL) evolution and daily rainfall with corresponding hydrological conditions on the Tummulur site for the sampling campaigns in 2013 and 2014.

7.3 RESULTS AND INTERPRETATION

7.3.1 Field results and observation

The Tummulur tank was monitored from 01/01/2012 to 11/04/2014. The variability of the monsoon (700 mm in 2012; 1 110 mm in 2013) had a large impact on water level and tank area evolution (Figure 7.4). From the water levels coupled with the DGPS topographic survey the maximum tank volume after the 2012 monsoon is estimated to be 8,100 m^3 and above 90,000 m^3 after the 2013 monsoon. During monsoon, a few extreme events appear to have a major impact on the tank's replenishment.

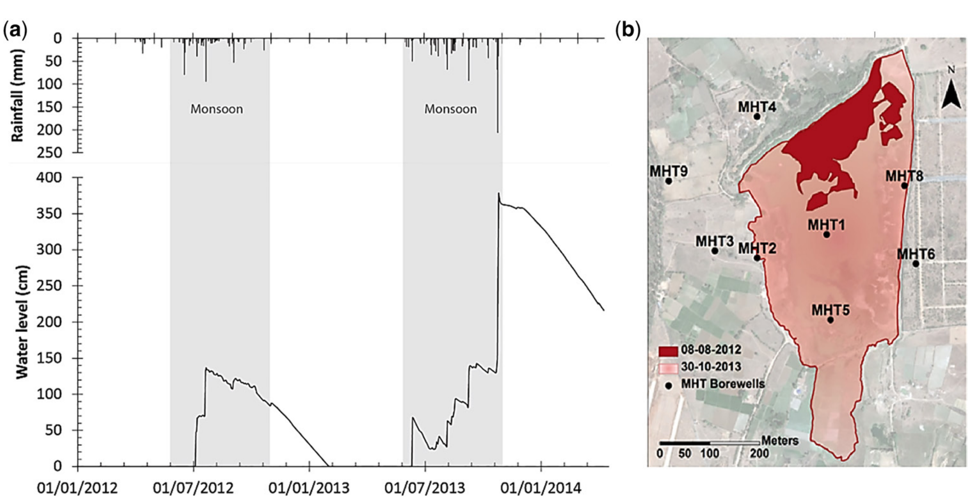

Figure 7.4 (a) Evolution of water levels in the tank versus rainfall; (b) Maximum water extent in tank are after 2012 monsoon (08/08/2012, dark grey) and 2013 monsoon (30/10/2013, light grey).

7.3.2 Tummulur tank water balance

A water balance for the Tummulur tank was established following the methodology developed in Massuel *et al.* (2014) computed on a daily basis. To sum up, the balance is based on the following equation:

$$\Delta V = F_{\text{net}} + R_{\text{rain}} - E - L_{\text{v}} - S_{\text{eep}} - P \tag{7.1}$$

where

ΔV = change in tank water storage
F_{net} = net inflow to the tank i.e. run-off
R_{rain} = direct rainfall collected on the surface of the water tank
E = evaporation from the tank surface (estimated from Class-A pan data with a pan coefficient of 0.8)
L_v = water consumption by livestock
S_{eep} = seepage across the dam
P = percolation

From the local condition, i.e. limited cattle, the term L_v can be neglected. This assumption is justified since Massuel *et al.* (2014) show that in a similar context with more goats breeding this element represents a minor part of the water budget (<5%). F_{net} represent the run-off flowing to the tank from the surrounding area during important rainfall events.

A relation between tank water level and percolation was developed for the days without rainfall, run-off or seepage through the dam when the percolation can be defined as:

$$P = \Delta V - E \tag{7.2}$$

This relation is then used to define percolation on a daily basis depending on the water level (Figure 7.5).

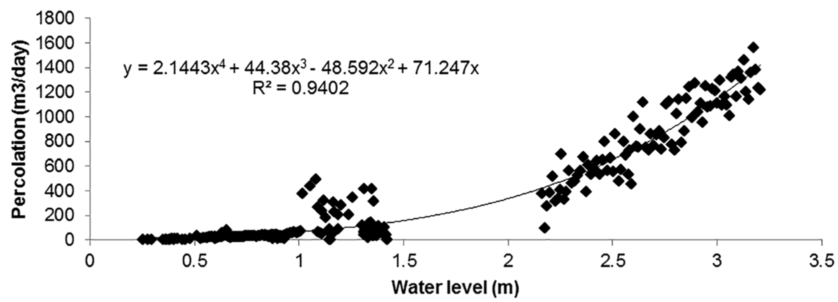

Figure 7.5 Relationship between the water level and the percolation rate in the tank.

Using this relation in eq. 7.1 a complete water balance at the tank scale can be established. The results are presented in Figure 7.6 and Table 7.1. Note that the balance for the 2013 monsoon ends on 11/04/2014 while percolation and evaporation would arise in the following months.

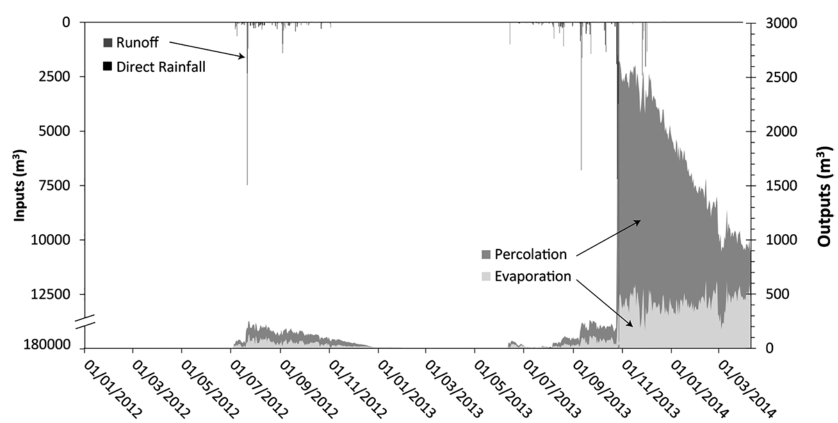

Figure 7.6 Temporal evolution of main components of a water balance at Tummulur percolation tank (Inputs on top x-axis and outputs in bottom x-axis).

Table 7.1 Main components of water balance of Tummulur percolation tank.

	2012 Monsoon	%	2013 Monsoon	%
Runoff [m^3]	10,612	58	278,442	92
Direct rainfall [m^3]	7,795	42	21,666	8
Input [m^3]	18,407	100	300,108	100
Evaporation [m^3]	7,281	38	75,970	25
Percolation [m^3]	11,730	62	229,155	75
Output [m^3]	19,010	100	305,124*	100
Balance in-out [m^3]	–603		–5016	
Error (%)	3.22		1.66	

*Budget for the 2013 monsoon ends on 11/04/2014 without considering further evaporation and percolation.

The results of the water balance show a high variability in the tank infiltrated water from 11,730 m^3 during the 2012 monsoon to 229,155 m^3 during the 2013 monsoon. The results are in agreement with the predictive water balance performed in Boisson *et al.* (2014a) through a different approach for the 2012 monsoon. As well, the estimated infiltration rates and ratio percolation over inputs are in the same range as that observed in Massuel *et al.* (2014) in a similar context. It is noteworthy that tank refilling occurs mostly during a few intense events through run-off occurring on the watershed (up to 92.8% in 2013). On the contrary, outputs are evolving slowly during the entire flooding period.

Maréchal *et al.* (2006) estimate the mean annual groundwater abstraction at the watershed scale on Maheshwaram (53 km^3) to be 8.8 million m^3/year. Therefore, the percolated volume from the Tummulur tank represents 0.13% and 2.6% in 2012 and 2013 monsoons, respectively of the groundwater abstraction. Considering the 40% of return flow in average at the watershed scale (Maréchal *et al.* 2006), the percolated water from the tank represents 0.2% and 4.2% of the net groundwater abstraction for the two monitored periods.

Those calculations show that under low rainfall conditions, the impact of a percolation tank is negligible at the watershed scale, and very limited at the local scale. On the contrary, when it is filled, the tank has a significant impact on the total water balance and can be very helpful for the surrounding farmers. However, it should be noted that following an important rainy season, farmers tend to increase the irrigated surface in the tanks surroundings and therefore increase the water abstraction at the watershed scale.

7.3.3 Flow characteristics in crystalline aquifer

In crystalline rock aquifers, flow is constrained by the fracture network (distribution of fracture length, orientation and density and connectivity) (Bour & Davy, 1998; de Dreuzy *et al.* 2001). Studies on the Maheshwaram watershed have shown that the bulk permeability is anisotropic ($K_h \gg K_v$; Maréchal *et al.* 2004) and that predominant water flow occurs in shallow fractures (Mayo *et al.* 2003) mostly at the contact between the saprolite and the top of the granite (Dewandel *et al.* 2006). Detailed investigations also show that the storage decreases drastically with depth and that the deepest fractures may have a semi-confined behaviour (Boisson *et al.* 2015). Example of a detailed log with pictures of fractures and fissures are shown in Figure 7.7. In this example, before monsoon (June) the water electrical conductivity profile is constant at a value of ~1,000 µS/cm. When the recharge starts (September–October), the borehole appears to cross two separate water bodies: the upper part of the profile appears to be diluted by rainfall and surface water (decrease of electrical conductivity); while in the deepest part, the conductivity increases. This behavior is observable in all monitored boreholes on the area (data not shown).

The crystalline rock aquifer structure implies a strong variability of the porosity with depth, ranging from 0.5 to 10% (White *et al.* 2001; Wyns *et al.* 1999) in the saprolite and from 1 to 2% in the fractured zone (Dewandel *et al.* 2012; Maréchal *et al.* 2004).

The higher storage capacity of the saprolite compared to the fractured zone can create strong discrepancies in the piezometric evolution. In MHT4 borehole, for example (Figure 7.8), two rain events of 18 and 19 mm (03 and 06/06/2013, when the water is in the fractured zone) induced water level rise of 8 m, while a rainfall event of 50 mm (12/06/2013, when the water table has reached the saprolite) induced a rise of 24 cm.

This specificity described in Boisson *et al.* (2015), should be taken into account while doing the monitoring of the boreholes, since a given rise of the water level may correspond to several water volumes depending of the local storage capacity.

Weathering profile maps made from Electrical Resistivity Tomography presented in Boisson *et al.* (2015) show that the storage potential of the tank is higher in the southern part of the tank due to a thicker weathering profile.

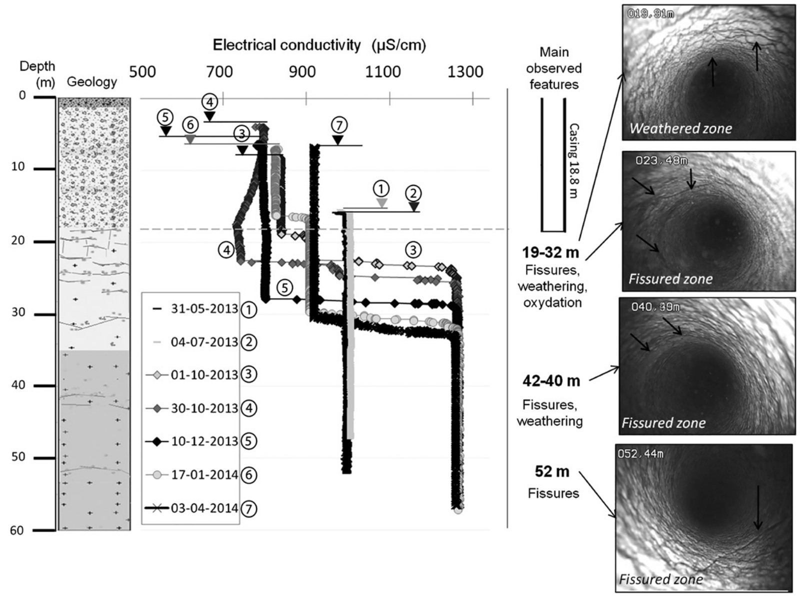

Figure 7.7 Geological log of MHT9 borehole; Electrical conductivity loggings evolution and fractures observed in borehole. (1) Pre-monsoon campaign, (2) early stage of the monson (i.e. July 2013), and (3 to 7) late stages of the monsoon and post-monsoon campaigns. Water level for each campaign are shown (triangles).

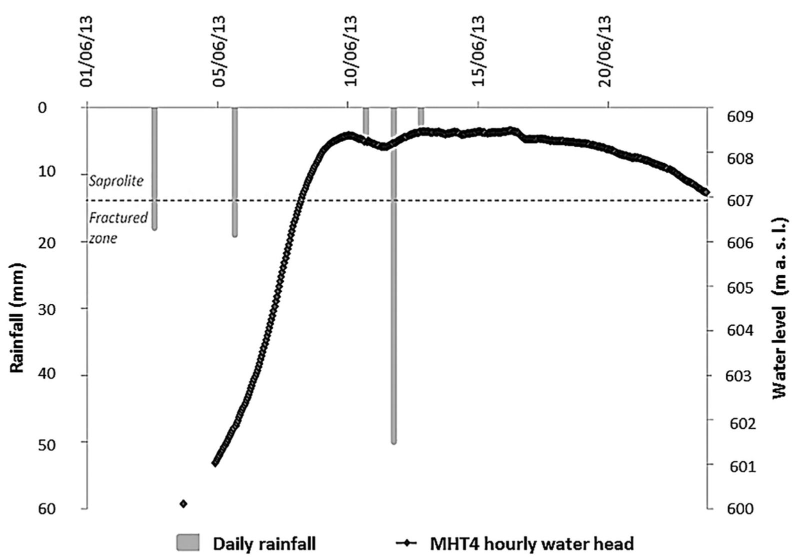

Figure 7.8 Evolution of ground water levels following rainfall event of different intensity in MHT4 borehole. The limit between the saprolite and the fractured zone (about 607 m above seal level-ASL) is shown as a dotted line.

7.3.4 Impact of Tummulur tank recharge on groundwater quality

Groundwater on the Tummulur site is characterised by high salinity (electrical conductivities between 800 and 1,700 µS/cm). Chemical groundwater facies is dominated by Na-HCO_3^- (sodium-hydrogen carbonate) water type (Figure 7.9) mainly caused by cation exchange, silicate weathering and leaching of fluid inclusions (Siva Soumya *et al.* 2013). The abundance of major anions is as hydrogen carbonate > sulphate⁻ > nitrate or chloride > fluoride and that of major cations is sodium > calcium > magnesium > potassium. The sampled ground water shows concentrations of nitrate and fluoride above permissible limits for drinking water (50 mg/L and 1.5 mg/L, respectively according to the WHO guidelines or 50 mg/L and 1.2 mg/L respectively according to the Bureau of Indian Standards (BIS, 2012)).

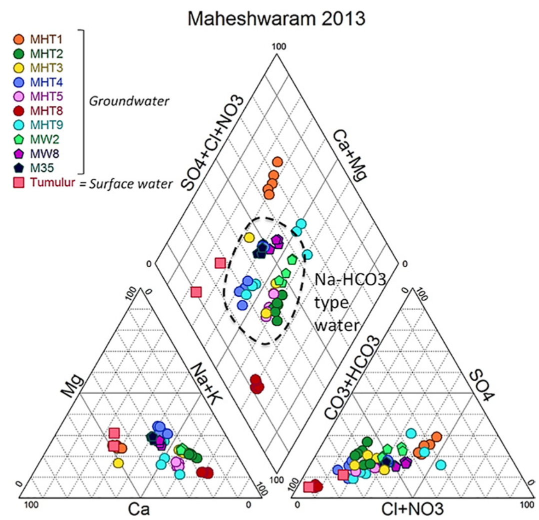

Figure 7.9 Piper diagram for groundwater (10 wells) and Tummulur tank surface water for the 2013–2014 campaign.

In the Maheshwaram context (i.e. strong evaporation rates, mineral dissolution of primary fluoride containing minerals such as fluorapatite, biotite and epidote, important irrigation return flow) fluoride is accumulated in groundwater (Pettenati *et al.* 2013). This accumulation is enhanced by the reduction of calcium activity due to calcite precipitation and by calcium/sodium exchange mechanism on clay minerals, thus impeding fluorite (CaF_2) precipitation, which is the only efficient mechanism controlling fluoride concentrations (Jacks *et al.* 2005). As a result of the strong cationic exchanges, most of the groundwater samples show a sodium excess, as seen on a scatter plot comparing the sodium + potassium (Na + K) excess vs. calcium + magnesium (Ca + Mg) excess ((Na + K)-Cl vs. (Ca + Mg)-(SO_4 + HCO_3) plot, Figure 7.10). In this geological context, hydrogen carbonate ions originate from the silicate weathering process (Rajesh *et al.* 2012), and organic matter mineralization leading to high carbon dioxide (CO_2) content in the soils can significantly increase the hydrogen carbonate content. High sulphate, nitrate and chloride contents do not come from the water-rock interaction; they mainly have anthropogenic and/or meteorological origin, enhanced by evaporation processes in soils (Rajesh *et al.* 2012; Siva Soumya *et al.* 2013).

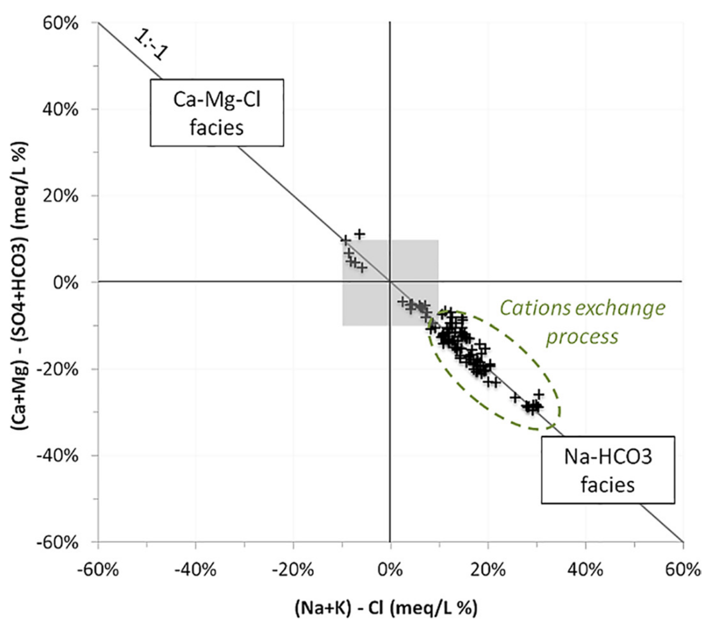

Figure 7.10 (Na + K)-Cl vs. (Ca + Mg)-(SO_4 + HCO_3) plot for Tummulur site groundwater (7 scientific boreholes and 3 farm boreholes) for the 2013–2014 sampling campaigns. NB: the ±10% area (grey area) does not allow accounting for ion exchange processes.

This incoming surface water has a wide range of effects on groundwater chemistry, depending on both time and space. Electrical conductivities between pre- and post-monsoon samples are quite constant, but have strongly varied during monsoon (Figure 7.11a).

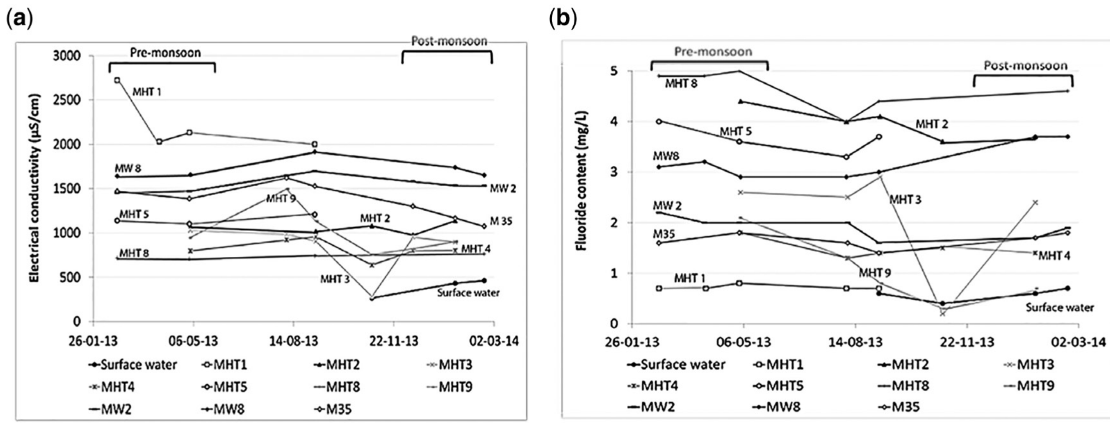

Figure 7.11 (a) Electrical conductivities in 10 boreholes and surface water on Tummulur site between February 2013 (pre-monsoon) and February 2014 (post-monsoon). (b) Fluoride content evolution in 10 boreholes and surface water on Tummulur site between February 2013 (pre-monsoon) and February 2014 (post-monsoon).

Nitrate, sulphate and chloride concentrations tend to decrease after the monsoon due to dilution, but can significantly increase due to leaching of soil processes (i.e. the chloride content increase in MHT9 during the early stage of monsoon season and the important input of nitrates at the beginning of monsoon for MHT4 and MHT9 and in the latest stage of monsoon for MHT2 and MHT3 – Figure 7.12).

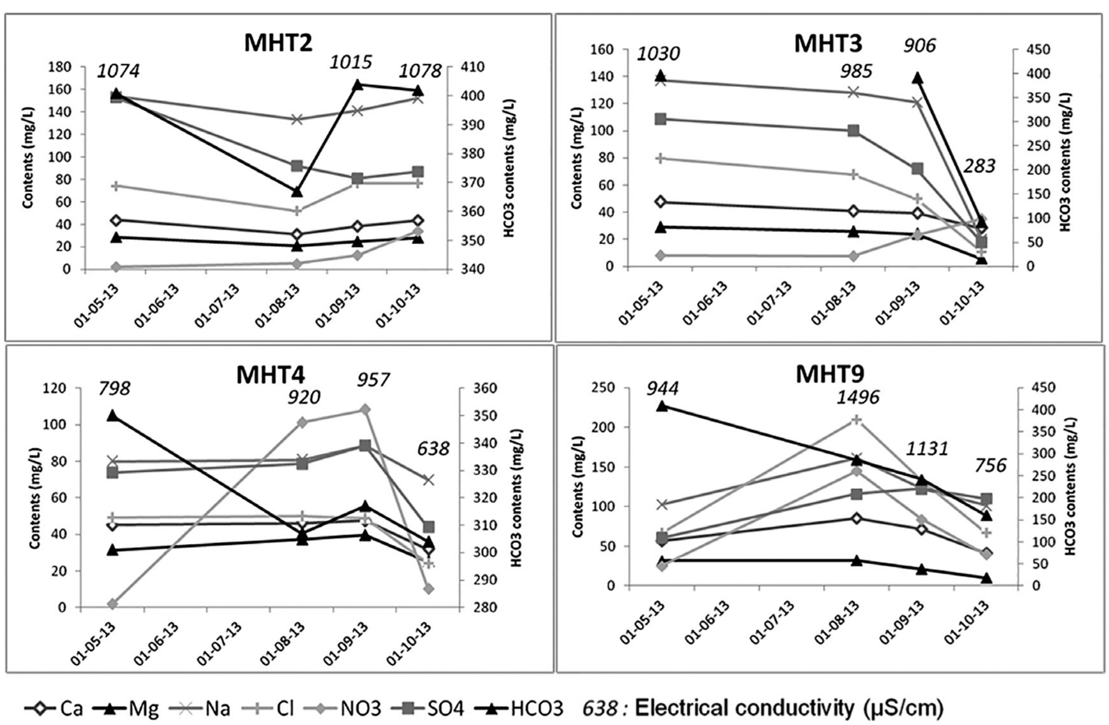

Figure 7.12 Evolution of calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), chloride (Cl^{-}), nitrate (NO_3^{-}), sulphate (SO_4^{2-}) and hydrogen carbonate (HCO_3^{-}) contents (mg/L) for the campaigns of May (i.e. before monsoon), August and September (i.e. early stages of the monsoon), and October 2013 (i.e. late stage of the monsoon) with the corresponding electrical conductivity.

Except for MHT9, fluoride concentration do not decrease after the monsoon showing the fluoride content evolution complexity, i.e. an input of fresh water does not lead to its decrease (Figure 7.10b). Quite rapid chemical weathering of fluoride bearing minerals and cationic exchanges within clay minerals can occur during the percolation time, in these highly eroded environments (Alazard *et al.* 2015).

7.3.5 Stable isotopes

The recharge from the Tummulur tank is highlighted by the change in isotopic content ($\delta^{18}O$ and $\delta^{2}H$) of surface and groundwater between pre- and post-monsoon samples (Figure 7.13). Pre-monsoon groundwater samples (i.e. 'dry conditions') form a line which deviates from the local meteoric water line (LMWL) according to an evaporation line with the same slope value (=4.2) found by Négrel *et al.* (2011). The LMWL was defined by Kumar and Pande (2010) for South India as $\delta^{2}H = 7.82 (\pm 0.17)^{*} \delta^{18}O + 10:23 (\pm 0.85)$ ‰ vs. Vienna Standard Mean Ocean Water (VSMOW).

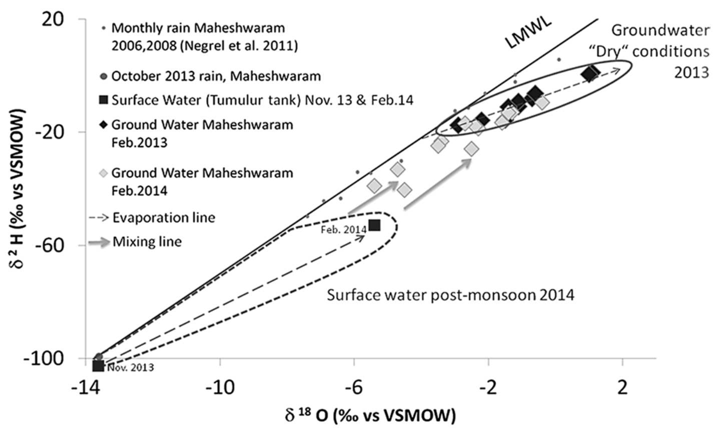

Figure 7.13 $\delta^{18}O$ vs. $\delta^{2}H$ (‰ vs. VSMOW) plot of monthly rain in Maheshwaram (Negrel *et al.* 2011), groundwater (February, 2013 and 2014) and Tummulur tank (November, 2013 and February 2014). Evaporation lines and mixing lines are shown as dashed lines and grey arrows.

The rain event of October 2013 was strongly depleted ($\delta^{18}O = -13.6$ and $\delta^{2}H = -99.3$‰ vs. VSMOW) and plot on the global meteoric water line (GMWL). As a result of this strong event, the surface water in November 2013 and February 2014 tuned out very low. Since October 2013, no significant input has occurred in the tank. As a consequence, the isotopic signature of the surface water in February 2014 results from the evaporation of the water body since October 2013 and strays from the GMWL.

Some post-monsoon groundwater samples deviate from the pre-monsoon values. Mixing lines between the surface water and the groundwater during 'dry conditions' appear. The post-monsoon groundwater samples, under the influence of surface water, move between the two poles, depending on the rate of surface water mixing (Figure 7.13).

7.4 DISCUSSION

This study is in agreement with the existing studies performed on percolation tanks in crystalline rocks aquifers performed in south India. It shows that under normal conditions the ratio percolation/stored water ranges in general between 56–63% (Massuel *et al.* 2014: 57% to 63%; Mehta *et al.* 1997: 57%; Perrin *et al.* 2012: 56%; Singh *et al.* 2004: 63%) and can be slightly higher in case of extreme monsoon and high water levels (in this study 75% for the 2013 monsoon). At the watershed scale (53 km^2) the tank impact can be negligible as for the 2012 monsoon but can reach 2.6% of the watershed abstraction in case of extreme monsoon, as in 2013. In the latter case presence of group of tanks may have a significant impact on the water balance of the watershed. Results of this study are in agreement with estimates from Perrin *et al.* (2012) on another watershed in a similar context stating that the multiple percolation tanks may contribute up to 33% of the recharge at the watershed scale (32 tanks on an 84 km^2 area near Gajwel AP). It is important to note that at a small scale the tank clearly enhances groundwater availability on the rainy years (i.e. rainfall are above average and when natural recharge is the most important) but cannot be considered as a solution to counteract directly dry years. Water stored during the rainy years should be partially kept for further possible dry years. This requires multiple-years management plans.

These management plans should include monitoring of water levels, limitations of water abstraction, maintenance of the tank to increase infiltration efficiency. From the two monitored years, the second monsoon event contributes to 95% of the percolated water of these two years. This highlights the strong variability of the monsoon and its obvious impact on the stored water volume. Often analyzed during one to three years-duration programs, tank efficiency studies do not allow assessing the variability related to the erratic monsoon behavior on a long term basis. Long term monitoring should be developed as well as methodologies to build reliable long term budgets. Those percolation tanks may also increase water abstraction at the watershed scale since the farmers adapt their crop to the water availability in crystalline rock aquifers (Fishman *et al.* 2011; Aulong *et al.* 2012).

An analysis of the flow dynamic through borehole logging highlights complex flow patterns during the recharge processes. The steep transition in electrical conductivity logs between pre and post-monsoon shows the complexity of the recharge mechanisms. It appears that the aquifer encompasses several water bodies, with distinct chemical features, which exchange evolving during the recharge processes. This latter point is further discussed in Alazard *et al.* (2015). This also highlights the existence of different flow paths and that recharge occurs not only vertically but that a strong horizontal flow has an impact on the change in water level.

Geological information coupled with hydraulic tests point out the contrast between storage capacities in the different layers of the aquifer. The deepest fractures may rapidly respond but do not represent a large water volume even with an important rise in water level. This specificity can lead to confusion since, most of the time, as observed by Batchelor *et al.* (2003), the monitoring of percolation tank efficiency is based on the rise of water level in nearby boreholes, without taking into account the properties of the local media. In hard rock aquifers it should also be noted that the geological structure may create inequity between farmers in the recovery of water since accessibility is constrained by the connectivity of the fractures which decreases with depth, leading in case of low-water levels to compartmentalisation of the aquifer (Guihéneuf *et al.* 2014). For example, Boisson *et al.* (2014b) show that in the Tummulur case in 2012, only 2 farmers appear to pump 53% to 88% of the stored water during years of low rainfall while the impact for the farmers at the south side of the tank is negligible. For large scale planning it is also important to take into account the externalities for the downstream users since the water collected in a given watershed will not flow downstream (Calder *et al.* 2008). The water balance presented here is based on observation and cannot be used for prediction. Simple predictive modelling based on water budget as the one developed from the same site presented in Boisson *et al.* (2014a) are efficient, easy to perform and require limited monitoring. However, as observed by Boisson *et al.* (2014b), the contribution of surface water to the real effective recharge of the aquifer tends to be overestimated due to possible storage in the unsaturated zone, especially in cases of a weak monsoon. More investigation should be carried out at this point to develop guidelines and management policies.

A tank's impact on water quality is usually considered as positive since it appears to dilute contaminants. However, in the case of geogenic contaminants such as fluoride, the infiltration of water with a different chemistry may change equilibriums and may tend to release fluoride in the aquifer (Pettenati *et al.* 2014). Also, in case of polluted water or leaching soils, infiltration of surface water may decrease water quality (bacteria or solute).

This percolation tank assessment shows that those structures may, under certain conditions (i.e. heavy monsoon) be a possible solution to enhance ground water availability but is of limited impact during average monsoon conditions. However, these percolation tanks need to be carefully considered and guidelines should be defined for assessment and management.

7.5 CONCLUSION

This book chapter synthesizes the investigations performed on the Tummulur tank through Saph Pani. Details may be found in related publications. The main conclusions of these investigations are:

1) Percolation tanks can be efficient to recharge water in case of high rainfall but have negligible impact on groundwater replenishment in case of low to average monsoon years (i.e. below ~750 mm/year).
2) Tank replenishment occurs during a few limited rainfall events (2–3) per year through run-off and is therefore sensitive to surrounding changes in land use.
3) Water recovery in a hard rock aquifer may create inequity between farmers depending on the borehole's location and connectivity to conductive fractures due to the geological media heterogeneity (details in Boisson *et al.* 2014b; Alazard *et al.* 2015).
4) Percolation tanks may locally and temporarily enhance water extraction due to an increase of paddy field cultivated areas and, hence, can have a limited impact on the watershed water balance.
5) Hydrogeological studies and dense piezometric networks should be performed to ensure accurate monitoring, taking geological heterogeneity (both horizontal and vertical) into account.

6) Simple guidelines for MAR implementation and monitoring should be developed taking in account the conceptual models presented here.
7) Infiltration does not systematically improve water quality by dilution (e.g. fluoride) (See details in Pettenati *et al.* 2014). Therefore careful monitoring of water quality with regard to fluoride should be performed regularly to ensure adequate water quality.

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