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Long term monitoring of rainwater harvesting tanks: Is multi-years management possible in crystalline South Indian aquifers?

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Abstract
In semi-arid regions as in India, where agriculture relies on groundwater abstraction, increase of water resources availability through managed aquifer recharge (MAR) or rainwater harvesting (RWH) is often perceived as a major solution. Studies on these structures' efficiency exists but despite the interest, limited information is available on the temporal variation of their replenishment. In a monsoon driven climate, the inter-annual variations are crucial to assess the potential of water storage and multi-year management especially for these structures. Here, we aim at developing a methodology to reconstruct water storage of RWH tanks to further improve our understanding on long term efficiency and multi-years drought management. To tackle this issue, long-term monitoring of a RWH tank located in Telangana in South-ern India is achieved by a combination of field monitoring over 2 years (tanks surface and water levels) and a daily water balance compared to LANDSAT measurements of the tank area. The procedure allows reconstructing the tank filling dynamic over a 14-years period at a daily time step and show the extreme variability of the tank filling level. During this period, the yearly maximum tank volume ranges from 8650 to ~200 000 m^3. On the 14-years period, the tank reach its maximum capacity only once and, for 1/3 of the time, yearly maximum replenishment is below 15% of its capacity. The surface water availability remains limited in time since the tank dries-up annually, except for 2 years. However, water percolation to the aquifer is slightly enhanced for some years. During this monitoring period, very few extreme raining events (6) contribute for more than 50% of the collected volume. This observation highlights (1) the dependency of the structure to extreme storm events, (2) the limited capacity for a multi-year's management and (3) the farmers vulnerability to successive droughts.

KEYWORDS
crystalline rocks, India; managed aquifer recharge, percolation tank, rainwater harvesting, remote sensing, water budget

1 | INTRODUCTION

With the development of mechanized irrigation pumps since the green revolution in the 1970 s, India becomes the country with the highest annual groundwater abstraction (Doll et al., 2012; Shah, 2005). Such groundwater exploitation through 26–28 million structures (Mukherji & Shah, 2005; Shah, 2008) represents 85% of the domestic water and 50% of irrigation water. Due to this increasing intensive extraction (Kumar et al., 2005; Smith & Urpelainen, 2016), water scarcity is a major issue in numerous areas of the country (CGWB, 2009) and solutions for a better management at global and local scale are considered. Comprehensive management of water resources may promote global water, food security and reduce human vulnerability to climate change. Conjunctive uses of groundwater and surface water that use surface water for irrigation and water supply during wet periods, and groundwater during drought, are likely to prove essential (Taylor et al., 2013; Zaveri et al., 2016). To tackle the problem of water scarcity, India invests in numerous programs both at federal and local scale. The "Master plan for artificial recharge" (CGWB, 2013) recommends building 11 million artificial recharge and rainwater harvesting (RWH) structures at the national level. It is estimated that about 36 km^3 of water (1% of the rainfall) could be stored annually (CGWB, 2007). Managed aquifer recharge (MAR) and RWH are common practices in India with a sound historical experience. Sakthivadivel (2007) estimates the number of MAR and RWH structures to be 0.5 million of which 0.25 million are located above crystalline aquifers. Renovation of such existing structures is also part of the recharge master plans.

MAR solutions are increasing over the world, with successful results worldwide (Dillon et al., 2019) including in India (Dashora et al., 2018; Stiefel et al., 2009). However, water management is complex with both long term and short-term issues (Batchelor et al., 2003; Bitterman et al., 2016; Gleeson et al., 2012) and impact of large MAR programs remain unclear in semi-arid regions. Despite the common view and some studies supporting the belief that MAR is a possible solution to the actual water scarcity problems on those area, various authors such as Dillon et al. (2009), Kumar et al. (2006), Oblinger et al. (2010) Glendenning et al. (2012) point out the lack of available data for an accurate assessment and the scarce evidence of a positive impact of such recharge structures both at local scale and watershed scale in semi-arid regions. A modelling approach at small watershed scale showed that percolation tanks can on average contribute to significant local aquifer recharge (up to 33% of total recharge), although this managed recharge is highly variable spatially (Perrin et al., 2012). Some authors (Calder et al., 2008; Glendenning et al., 2012; Sakthivadivel, 2007; Meter et al., 2016) point out a possible negative impact due to downstream effects of upstream harvesting and recharge. This thought is shared by other authors who assessed large watershed programs on both hydrological and socio-economic aspects and show unevenly benefits to populations (Batchelor et al., 2003; Bouma et al., 2011; Kerr et al., 2002; Kumar et al., 2008). They argue that the limited or negative impact of the water harvesting structures is partly due to a lack of knowledge on the structure functioning or unproper dimentioning of the structures due to strong interannual rainfall and runoff variability (Kumar et al., 2008). In addition, the existence of these recharge structures may tend to increase local water abstraction due to a larger local water availability created by new water distribution (Adhikari et al., 2013; Batchelor et al., 2003; Machiwal et al., 2004). A limited but growing number of studies on percolation and storage tanks exist (e.g., Boisson et al., 2014; Dashora et al., 2018; Gale et al., 2006; Massuel et al., 2014; Mehta & Jain, 1997; Nicolas et al., 2019; Perrin et al., 2009; Sukhija et al., 1997; Meter et al., 2014, 2016). However, the efficiency of these structures is still a matter of debate due to a mitigated ratio of storage/infiltration. Comparison between tanks can be difficult and even tanks in cascade in the same area may show different efficiency (Meter et al., 2016). In most of the studies, impact assessment is only performed over one or 2 year (e.g. Boisson et al., 2014; Dashora et al., 2018; Nicolas et al., 2019; Oblinger et al., 2010; Meter et al., 2016; Vanthof & Kelly, 2019). Tank filling variability is usually expected, but not quantified with enough data to draw clear water budgets. In a context of variable monsoon and projected climate changes, this monitoring duration may be insufficient for a proper long-term assessment, especially regarding the tank filling mechanisms that are expected to be highly variable from 1 year to another.

Asian monsoon is a highly variable phenomenon on large time scale (Prell & Kutzbach, 1987) and on a year-to-year basis as well as spatially, with a contrasted behaviour between Southern and northern Indian monsoon (Wang et al., 2001). Temporal and spatial variability in these atmospheric circulations can result in severe droughts or floods with historical socioeconomic impact on populations (Cook et al., 2010; Gupta et al., 2006; Pandey et al., 2003). Due to this importance, monsoon prediction models have a high priority in many Asian countries with the question: will the Asian monsoon strengthen or weaken in the future? Impact of climate change on South Indian rainfall remain not fully understood with in some cases a low impact on rainfall expected for South India (Reuter et al., 2013) or an increase of rainfall, mostly during the monsoon season, while winter precipitation is reduced, and suggest a widespread warming especially in the winter and post-monsoon season (Vigaud et al., 2013). Others even indicate an overall suppression of the South Asian summer monsoon precipitation (Ashfaq et al., 2009). However, a general trend goes toward an increase of the inter-annual variability due to climate change (Menon et al., 2013). Locally, it is even considered that intensive irrigation may also have an impact on regional climate (Douglas et al., 2009). In a general way, monsoon irregularity is expected to increase but impact of climate change on groundwater resources remains poorly known due to the lack of observations (Taylor et al., 2013). Nevertheless, impact of climate on water abstractions is becoming more documented at global scale (Asoka et al., 2017; Gurdak, 2017; Russo & Lall, 2017; Zaveri et al., 2016) and local scale (Ferrant et al., 2014). These include emerging knowledge of the direct and indirect (through groundwater use) effects of climate forcing, including climate extremes on groundwater resources (Asoka et al., 2017; Taylor et al., 2013). The risk is particularly acute in semi-arid regions where projected increases in the frequency and intensity of droughts is combined with rising populations and standards of living increase. Moreover, the projected expansion of irrigated land, will intensify groundwater demand in a country where large decrease of ground water levels is already observed (Asoka et al., 2017; Ferrant et al., 2014; Fishman et al., 2011; Rodell et al., 2009).

Whatever its evolution, the irregularity of the monsoon is well known and succession of drought years is common in South India with an impact on populations, groundwater levels, and agricultural practices. As example, Ferrant et al. (2017, 2019) have quantified how groundwater and surface water abundance impacts rice cultivated area extent using high spatial and temporal satellite data in Telangana state. Impact of monsoon variability on RWH structure filling is obvious but not quantified yet.

The objective of this study is to quantify the volume variation in water storage structures (for MAR or direct uptake) by recreating, at a daily time step, the long-term storage dynamic to assess their potential for a multi-year management and drought mitigation. While, most studies focus on water budgeting and structure efficiency for improvement of local condition, in this study, we focus on the inter-annual variability of the water budget which is usually not considered for such structures. We based the analysis on a RWH tank located in a crystalline and semi-arid context. RWH tanks are artificially made reservoirs of varied sizes, which are commonly built across a hill to collect and store water by utilizing natural mounds and depressions. Tanks are an important source of irrigation in South India because there are no perennial rivers.

We aim at developing an efficient methodology easily applicable to assess tank capacity evolution on long term. In the following we use a water balance approach to reconstruct the 14 years dynamic of the tank filling and storage based on a tank monitored over two contrasted years (Alazard, Leduc et al. 2015b; Boisson et al., 2014). The computation of the water balance over 14 years allows reconstructing the tank filling dynamics at a daily time step during this period. Validity of the reconstruction is compared to remote sensing estimates (LANDSAT data) of the flooded area and demonstrate the good quality of the results.

2 | MATERIAL AND METHODS

2.1 | Site presentation

The method is tested on a RWH tank in the Maheshwaram watershed, located 35 km South of Hyderabad (Telangana, India) which covers an area of 53 km^2 (Figure 1). Detailed studies of this watershed for more than a decade (Alazard, Boisson et al., 2015a; Boisson et al., 2014; Dewandel et al., 2006; Marechal et al., 2004; Maréchal et al., 2006; Perrin et al., 2011) provide a solid baseline for investigating the functioning and impact of MAR systems.

The region has a semiarid climate with annual monsoon rains (June–October). Mean annual precipitation (P) is about 750 mm, of which the monsoon accounts for more than 90%. The mean annual temperature is about 26°C although during summertime (October–May) maximum temperatures can reach 45°C. The watershed is over-exploited with more than 700 boreholes used for agriculture dominated by rice fields. Currently, the water table is 15–25 m deep and is disconnected from surface water. Maheshwaram watershed is underlain by weathered Archean biotite granite. Its weathering profile leads to a stratified aquifer with two distinct layers (Dewandel et al., 2006, 2011). The saprolite (10–15 m thick layer from the surface) is characterized by a sandy-clay composition. Its total porosity is relatively high, up to 10%, but due to the clay content the effective porosity is low and ranges from 0.5% to 2% (Dewandel et al., 2012; Wyns et al., 2004). Its hydraulic conductivity is low (1.10^{-7} – 3.10^{-5} ms^{-1} [Dewandel et al., 2006]) but may contain locally preserved fissures. Below, the fissured layer (10–30 m thick) constitutes the transmissive part of the aquifer (hydraulic conductivity between 10^{-6} and 10^{-4} ms^{-1}) with a low effective porosity 1%–2% (Dewandel et al., 2012; Marechal et al., 2004). The monitored tank is close to Tumulur village and has been used for more than 15 years for water storage. No direct tank water extraction for irrigation occurs. The current tank system can be considered as a representative example of MAR in semi-arid Southern India. Dry season piezometric map shows a dominant groundwater flow NE to SW. An earth bund dams the natural stream outlet and consequently runoff water is stored over a maximum area of ~150 000 m^2 and a maximum water depth of 3.8 m. Clay soil characterizes the lower northern part of the tank (~ 30 000 m^2). Most of the remaining tank area is covered by silt loam soils underlain by sandy loam at a depth of 40–80 cm. The agricultural land use next to the restricted study area is mainly composed of rice, maize and various vegetables. Within a radius of 500 m from the tank, at least 15 irrigation wells are in use. Irrigation duration and times are controlled by the availability of electricity (6 h per day) provided by the state of Telangana.

2.2 | Tank water level and water table evolution

Tank monitoring was performed for two climatically contrasted years (2012–2013). During the driest one (2012), bathymetric measurements were made using a Trimble DGPS inside the tank (Figure 1). Surrounding topography was defined using MNT 50 m around it. Water level measurements were made using a CTD Diver pressure sensor with continuous record (15 min time step) fixed to a scale (accuracy 1 cm) implanted in a concrete block. Validity of the measurements was verified by direct scale reading once a week. Area of the tank was measured regularly by GPS tracking using a GARMIN 60Cx. Daily rainfall was recorded from the rainfall station of the MRO (Mandal Revenue Office) of Maheshwaram and evaporation data from the ICRISAT meteorological station. The evaporation is measured by an evaporation pan and is corrected by a correction coefficient of 0.8 as recommended by Alazard, Leduc et al. (2015b) for estimates of

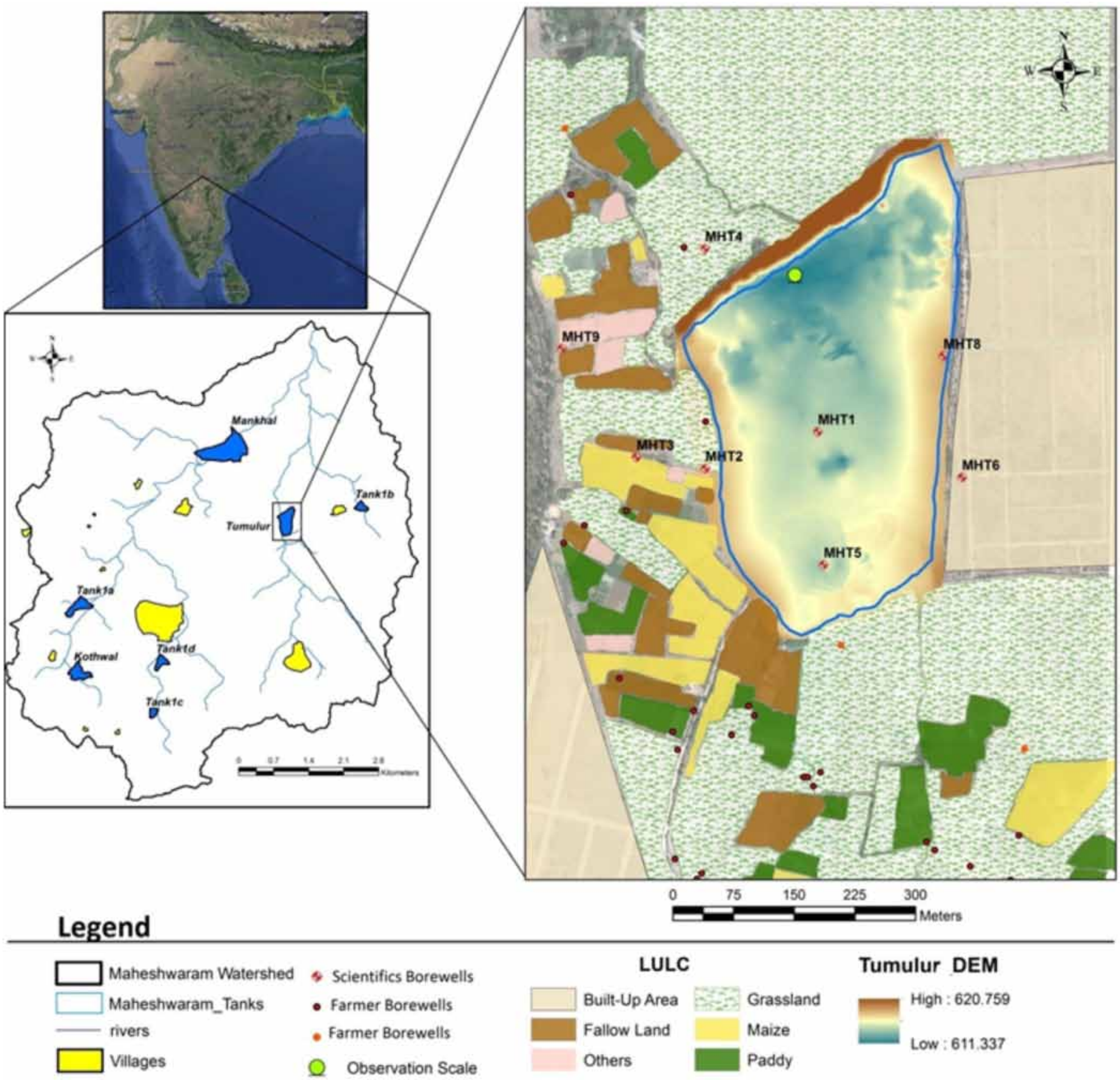

FIGURE 1 Location and study site presentation

water bodies in semi-arid environments. Surrounding boreholes, drilled in 2012 were also monitored for water levels and chemistry (labelled "MHT's" in Figure 1). More details on borehole monitoring and tank relationship with the groundwater can be found in Boisson et al. (2014) and Alazard, Boisson et al. (2015a).

3 | WATER BALANCE

3.1 | Computation

The water balance quantifies the tank volume variation on a daily basis ΔV, $[L^3.T^{-1}]$ calculated using the Equation 1:

$$\Delta V = A_{Tank} \,.\, P + R \,.\, a - A_{Tank} \,.\, E - A_{Tank} \,.\, q - U \tag{1}$$

with A_{Tank} the tank flooded area that evolves with time $[L^2]$ and q the infiltration rate $[L.T^{-1}]$, P is the precipitations $[L.T^{-1}]$, R the runoff $[L.T^{-1}]$, a the "effective" drainage area of runoff $[L^2]$, E the evaporation $[L.T^{-1}]$, and U the uptake by direct irrigation or livestock consumption $[L^3.T^{-1}]$. It is hypothesized that q is a constant infiltration rate $[L.T^{-1}]$. These elements are presented for two water level conditions (Figure 2). Runoff R $[L.T^{-1}]$ is estimated using the Curve Number Method known as SCS-CN method (United States Department of Agriculture USDA, 2004). The SCS-CN method is a commonly used empirical relationship to estimate runoff based on an estimated initial

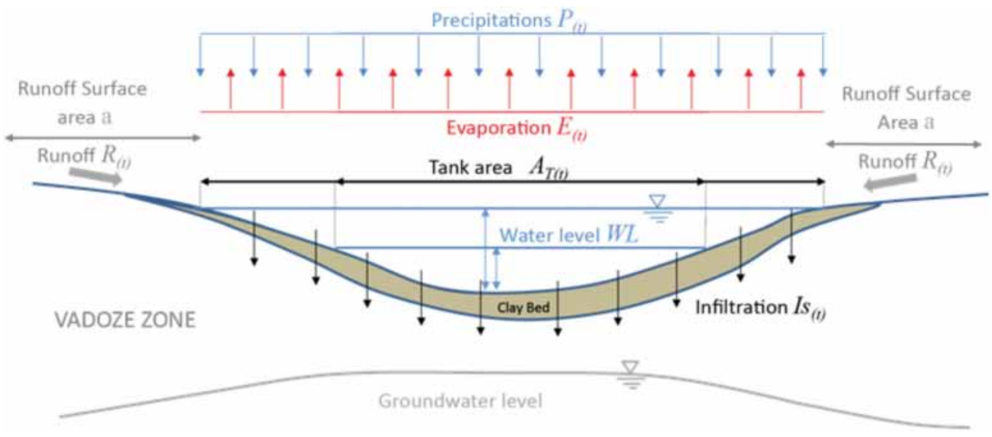

FIGURE 2 Water balance components. The figure represent two water levels conditions: (1) continuous line is low water level; (2) dashed line is the high water level. The water level has a strong influence on the water balance computation due to its dependence to Atank. Continuous and dashed lines on each component highlight the impact of the change of Atank.

abstraction, soil type and land use adapted for semi-arid climates. The runoff (R, [L.T^{-1}]) is active when P > I_a and is expressed as:

$$R = \frac{(P - 0.2S)^2}{P + 0.8S} \quad (2)$$

Where

$$S = \frac{25\,000}{CN} - 254 \quad (3)$$

where S is the potential maximum retention after runoff begins [L], I_a is the initial abstraction defined as $I_a = 0.2$ S. CN is the empirical curve number, depending on the hydrologic soil groups and the hydrologic conditions. R is then calculated using CN (Equation [3] and "a" [-Equation 1]) as fitting parameters. Calculations are run at daily time step. The parameter "a" should be in agreement with the size of the tank catchment area and CN in agreement with the soil type (value of 79–86 in the present case - United States Department of Agriculture USDA, 2004).

3.2 | Validation

The tank volume (V) is obtained by computing the bathymetry of the tank measured during the dry period using differential global positioning system (DGPS) for different water levels through SIG computation (Figure 1). The relationship between water levels and area is estimated from field measurement (GPS tracking [23 measurements] and automatic water level measurements [continuous measurement over 2 years]). An empirical relationship between water level and both volume and surface area is thus established. Estimated volumes from water balance computation and measurements are compared for parameter adjustment.

Quality of the calibration are assessed by Nash-Sutcliffe efficiency (NSE; Nash & Sutcliffe, 1970). The reference case is based on the best fit. Impact of each fitting parameter is estimated by water balance computation on a large range of values. Sets of parameters with NSE above 0.9 on the period 2012–2014 are kept and used for the simulation over the complete period (2000–2014). Extremes values of the fitting parameters for the different models are presented and discussed along with the reference case for the complete period in the results section.

3.3 | Remote sensing data analysis methodology

Remote sensing is a common tool to quantify surface water extension (e.g. Feyisa et al.,2014; Ji et al., 2009; Klein et al., 2014; Peña-Luque et al., 2021; Vanthof & Kelly, 2019). Tank area evaluation from past years is performed using LANDSAT data. The LANDSAT satellite has a periodicity of 16 days, and the images are built with a 30 m spatial resolution in the visible bands (i.e. blue, green, red, near-infrared, and mid-infrared). From the 31 May 2003, the scan line corrector (SLC) in the ETM+ instrument failed and images have come with "no data" strips. Therefore, a part of the data is not always available. Moreover, LANDSAT data are sensitive to cloud cover hence limiting the data availability in such cases. Images, both thematic mapper (TM) & enhanced thematic mapper plus (ETM+) were downloaded from the USGS online database (http://glovis.usgs.gov/) with two criteria: cloud free (0%) images and gap free (over the studied zone). A total of 26 images were gathered with almost 2 images per year covering the pre-monsoon period (March–May) and the post-monsoon period (November–January).

Flooded areas are computed from the commonly used modified normalized difference water index (MNDWI) from Xu (2006). The MNDWI is an improvement of the normalized difference water index NDWI developed by McFeeters (1996) for the extraction of water bodies. The MNDWI uses the middle infrared band instead of the near infrared band. The MNDWI is computed from the at-sensor reflectance following the methodology presented in Chander et al. (2009). The pre-processing has been made using the raster calculator module of the spatial analyst tools of ArcGIS 10.

The estimated tank area is further compared to the area measured using GPS tracking as explained in the section ("tank monitoring").

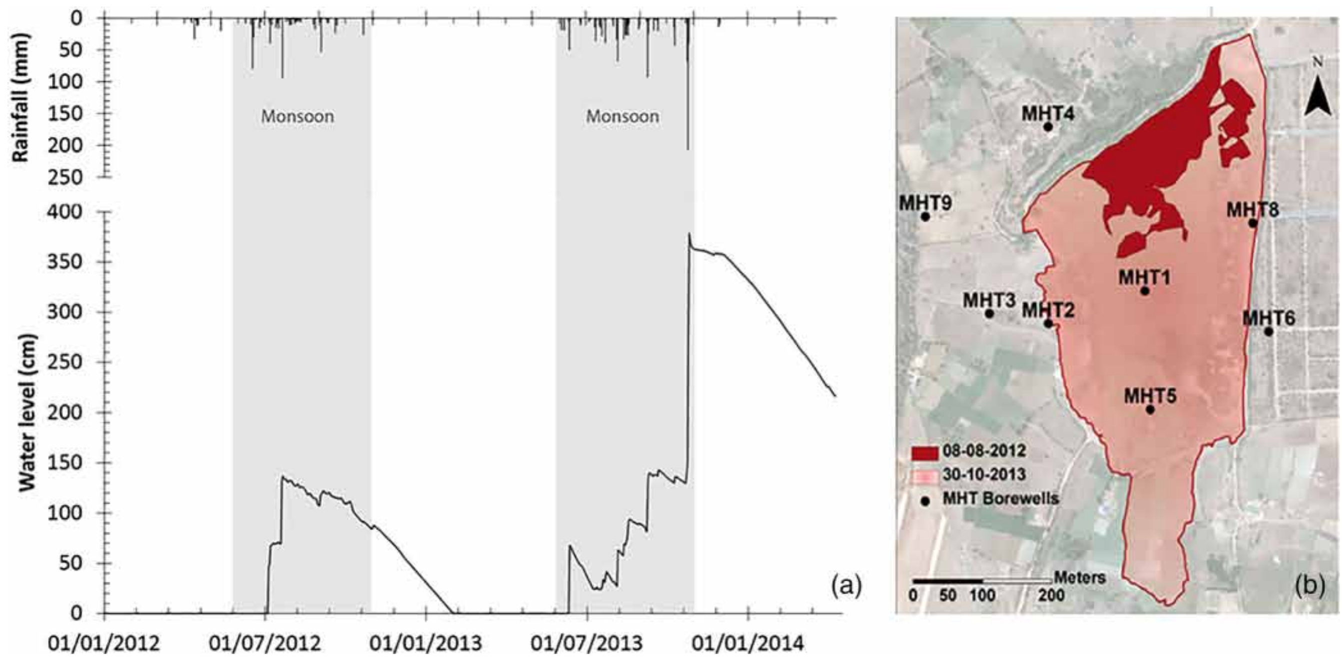

FIGURE 3 Measurements: (a) evolution of water levels in the tank versus rainfall; (b) maximum water extent in tank are after the 2012 monsoon and 08/08/2012, dark red and 2013 monsoon (30/10/2013, light red)

4 | RESULTS

4.1 | Tank water levels and volumes

The tank water level and precipitations monitored for 2 years are presented in Figure 3a along with the maximum tank area in 2012 and 2013 (Figure 3b).

Relation between the surface area of the tank measured by GPS tracking and the tank volume estimated from the bathymetry ground measurements is defined by an empirical power law relationship (Equation 4) as shown in Figure 4.

$$V = 4072 \, x \, WL^{2.9} \tag{4}$$

With V = Tank volume (m^3)

WL = Water level (m).

The water level and tank area monitored for 2 years (Figure 3) shows a strong variability of the tank filling. The maximum volumes present in the tank in 2012 and 2013 are respectively 12 000 and 195 000 m^3 for areas of 23 700 and 152 100 m^2. In 2013 one raining event is responsible for almost all the tank filling. During this extreme event (from 23 to 26/10/2013) a total rainfall of 274 mm fell in only 4 days with a daily maximum of 103 mm on 25/10/2013 producing important runoff. Before this event, the flooded area of the tank was smaller than the one observed the 08/08/2012 (Figure 3).

Based on the abstraction of 8.8 Mm^3/year at the watershed scale estimated by Maréchal et al., 2006, the stored volume in the tank represents 0.1% and 2% of the total abstraction at the watershed scale (in 2012 and 2013, respectively). This high variability highlights the dependence of the tank efficiency to the extreme meteorological conditions. Hence it shows that long term monitoring is needed for a proper assessment of the storage capacity dynamics of such tank in order to capture this variability.

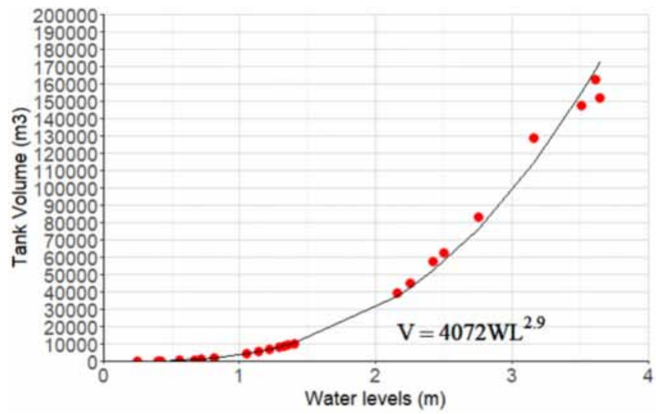

FIGURE 4 Water levels (based on direct measurements) versus estimated volume (based on bathymetry and tank area computation) relationship

4.2 | Water balance calibration

The water balance was first computed for the 2012–2013 monsoon using GPS data tracking for calibration, then was further extended on the 2000–2012 period and compared to the remote sensing estimates. The water balance is computed as volumes which are further transformed as water levels and surface following empirical relationships (Equation 5 and 6).

$$WL = 0.0569 \times Volume^{0.3448} \quad (5)$$

$$Surface = 17095 \times WL^{1.7809} \quad (6)$$

Input data are precipitations and PET. Fitting parameters are then the percolation rate (q;[L]); the CN number (S and I_a being dependant of it) and the runoff surface (a; $[L^2]$). Two sets of water balances were needed to achieve a correct data fitting on the 2012–2014 period, i.e. for both small and large tank size conditions. The selection between the two sets of parameters was based on the watered area. The first set of parameters is used for a tank area below 32 500 m^2 which corresponds to the clay area on the northern part of the tank and another set of parameters was used for tank an areas above this value. The threshold of 32 500 m^2 makes sence since it corresponds to the clay area filled almost annually. Outside this area the soils are more sandy and different percolation and runoff parameters can be expected. To limit the number of fitting parameters, the runoff area for the small tank size (<32 500 m^2), corresponding to low flow periods, was limited to the physical tank area (150 000 m^2) which correspond to the direct catchment. Hence, for the computation, only four fitting parameters are used. Fifing parameters are the CN number, the percolation rate and the effective runoff area for small and large tank conditions. The comparison between the computed water levels measured and computed from the water balance are given in Figure 5a. As well the tanks surface measured by GPS tracking is compared to the surface estimated from the water balance computation Figure 5b. Best data fitting for the period 2012–2014 is obtained using the parameters reported in Table 1 with the reference case and the range of parameters for which the correlation of observed area and modelled area is above an NSE of 0.9.

The CN number obtained is 79 for both small and large tank areas. This parameter is within the range of 79–86 expected for such soil types. Percolation coefficient was also identical for both periods at 3.7 mm/days. Hence CN and percolation coefficient are constant in time or space showing no important changes between the two configurations of the water balance. These coefficients are also within the expected range with a low infiltration due to clayed minerals filling of the porosity in small tank conditions or in case of large tank conditions a low infiltration due to the limited underground storage availability. Runoff area was fixed at the size of the tank for small areas. During these periods, runoff is limited to the runoff within the direct

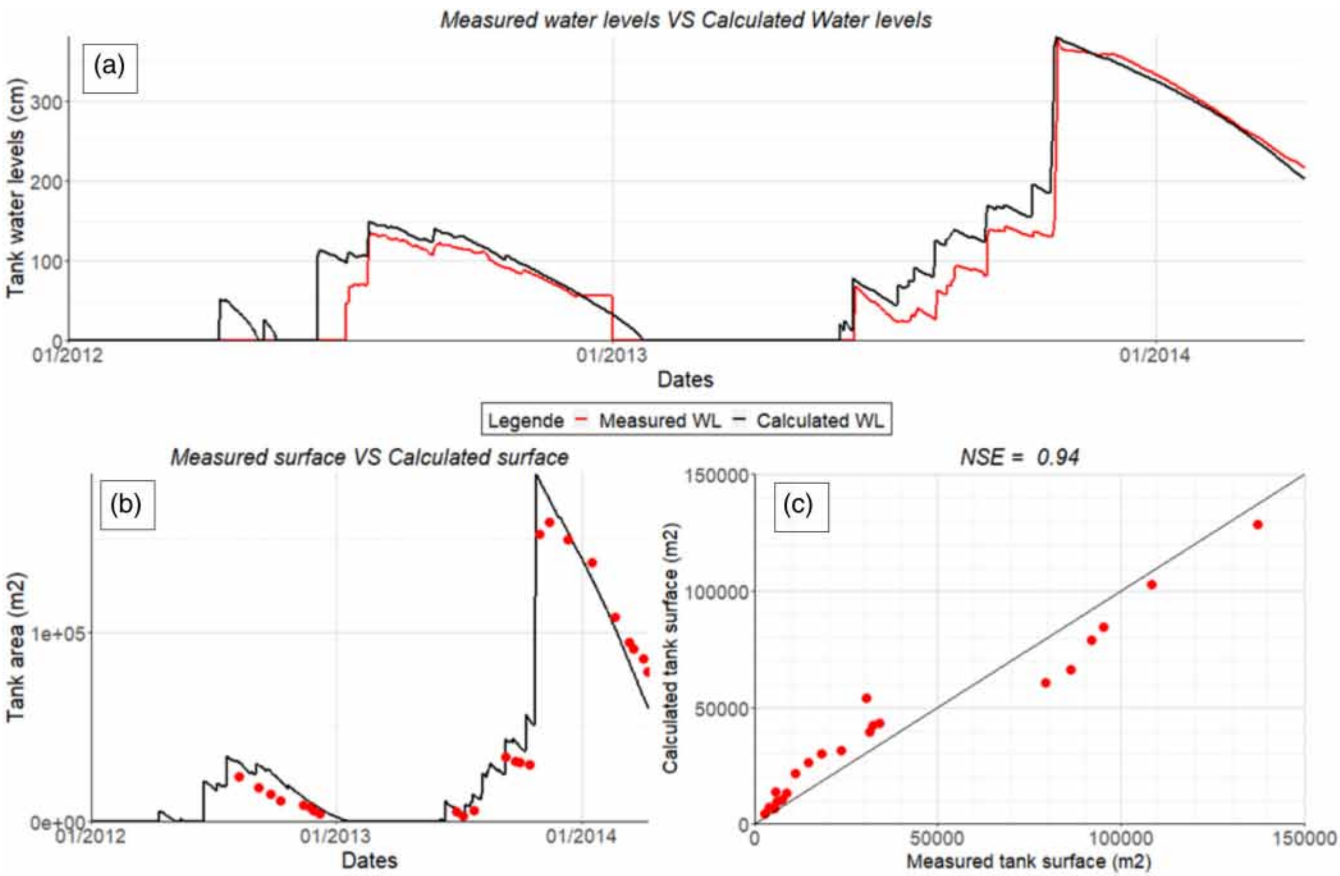

FIGURE 5 (a) Comparison of measured water level and simulated from water balance computation; (b) comparison of measured and simulated surface from water balance computation; (c) measured and simulated surface

catchment while for larger flooded areas, which correspond to high flow periods, the runoff area is larger due to the formation of overland flow and the setting of ephemeral streams reaching the tank. This is in agreement with field observations following the major raining event of 2013 during which some runoff was coming from outside the area though small ephemeral streams. Moreover, when a large area of the tank is flooded, the other surrounding pounds are also flooded, overflow and runoff is hence expected to be larger than during dryer conditions.

Three major discrepancies are observable between the measured water levels and the computed water levels (Figure 5a). The computed water levels start rising before the observed water levels for both periods. This difference may be due to the clayed nature of the soil and climate. Indeed, following the dry period, the soil presents large desiccation slots, which allow temporarily rapid infiltration. Following this infiltration swelling of the clay seal the slot and the infiltration rate drastically decrease. This element is not taken in account in the model. However, this phenomenon represents a limited volume and hence is not significant regarding the global water balance computation. Secondly, the step by the end of the year 2013 is due to a misfunction of the sensor. Thirdly, the plateau observed on the highest water levels is explained by the fact that the water level had reached the top of the embankment and induced overflow, which limits the maximum water level. This feature is not represented in the model. Hence, water levels are allowed to rise above this limit and do not show a plateau.

4.3 | Water balance simulation

Since the fitting on the period 2012–2014 is considered acceptable on both tank areas and water levels, the water balance was computed for the period 2000–2014. Obtained volumes are provided in Figure 6. The computation underlines a large variability in storage capacity over this period with maximum tank volume ranging from 0 to 200 000 m^3. To assess the relevance of this water budget the volumes were transformed into areas and compared with LANDSAT measurements (Figure 7) using the Equation 5 and 6 relationship. Correlations between the computed surfaces and the LANDSAT estimates are provided in Figure 8. The comparison between computed surfaces and LANDSAT estimates are rather good with a NSE of 0.9 for the reference case (black line on Figure 7) without further parameter adjustments. Minimum and maximum results of the computations within the range of parameters given in Table 1 are presented in shaded grey for uncertainty evaluation. Despite uncertainties on the parameters the produced water balance shows limited variability except for three periods (2003; 2006; 2010). The relatively strong variations during theses periods comes from a threshold effect related to the change of the effective drainage area changing from local runoff to large runoff. However, the LANDSAT data (58 500 m^2 in 2003 and two points at 0 m^2 in 2007) helps selecting the best solution since only few parameters allow fitting these events. This selection was not possible using only the 2012–2013 data. Using this LANDSAT information, the range of acceptable parameters can be reduced to (CN:

TABLE 1 : Fitting parameters for the mass balance. Column 1: Parameter selected for the reference case; column 2: Range of fitting parameters from the period 2012–2014; column 3: Range of fitting parameter allowing the reproduction of the observation on years 2003 2007 (Figure 7)

Parameter	Reference case	Range from calibration on the 2012–2014 period	Range from calibration on the 2000–2014 period using LANDSAT data
CN (CN number [−])	79	77–80	78–79
Q (percolation coefficient [mm])	3.7	3–5	3.7–5
a (effective runoff area for small tank condition [m^2])	150 000	120 000–180 000	140 000–150 000
a (effective runoff area for small tank condition [m^2])	1 400 000	1 200 000–1 800 000	1 200 000–1 500 000

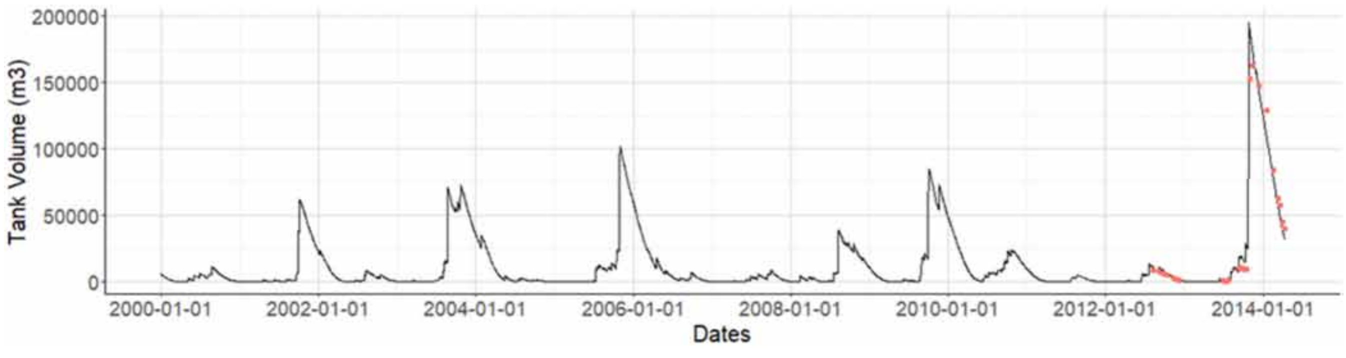

FIGURE 6 Volume stored in the tank from the computed water balance. Coloured dots are the estimates from GIS computation

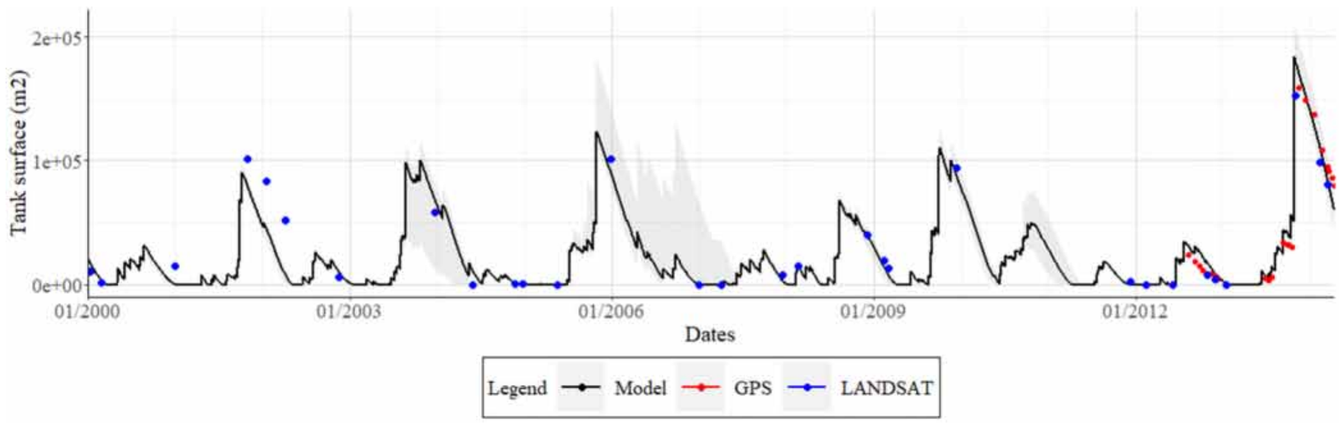

FIGURE 7 Tank area evolution estimated through computed water balance, remote sensing data and GPS tracking. Shaded grey represent the uncertainty related to the parameters of the Table 1.

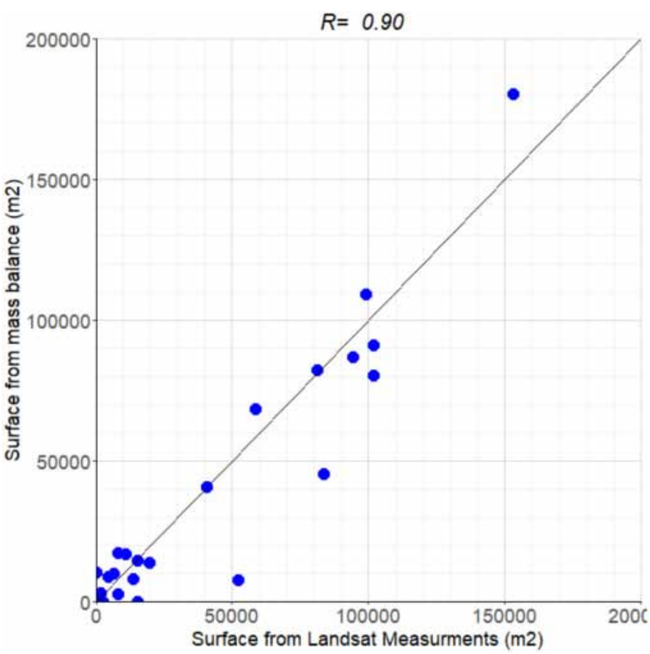

FIGURE 8 Comparison of tank surface obtained from LANDSAT measurements and from the computed mass balance.

78–79; q: 3.7 mm to 5 mm; $a_{small\ tank}$: 140 000–150 000 m^2; $a_{large\ tank}$: 1 200 000 to 1 500 000 m₂; Table 1 -Last column). The main tank dynamics seems well captured by the water balance computation.

Fluctuations of stored volume are large from 1 year to the next. Due to the specific shape of the tank, temporal variations of volumes are larger than the area variations, hence very high differentiation can be done between rainy and dry years. Maximum stored volume for each hydrological year is reported in Table 2. The estimated maximum volume after monsoon (August–November) shows a very high variability ranging from 8600 m^3 to 200 000 m^3. Expressed against the maximum volume estimated it represent a variation of the tank filing from 4.2% to 100%, illustrating the variability of precipitation amounts from year to year. During the 6 years of large volume stored (>50 000 m^3) the water level rise is occurring each time within a few days (1–3) showing dependence to extreme events of the tank filling in comparison to continuous refilling all along the monsoon period.

Yearly budgets are dressed in Figure 9 and Table 2 with estimated percolated volumes. Evaluation of the percentage of evaporation and infiltration cannot be accurately calculated at a daily time step with such a model due to the assumption of a constant percolation rate and a rough evaluation of the PET. However, calculated on a yearly basis when the tank is flooded the percentage of infiltration volume range from 43% to 59% with a median of 52%. This is in agreement with other studies as (Mehta & Jain, 1997: 57%; Perrin et al., 2009: 56%; Singh et al., 2004: 63%) and gives confidence on the general results of the water balance.

This yearly budgets shows that direct rainfall in the tank remains limited and is consistently lower than the evaporation. The main control of the tanks filling is the runoff. Over the studied period, six extreme raining events (>50 000 m^3) contribute to most of the tank filling. The last documented event in the time series (2013) caused large floods in the nearby Hyderabad city.

Runoff days and dry days are presented Figure 10. On average, 18.5 days of runoff per year occurs, with a maximum of 29 days in 2010 and a minimum of 10 days in 2011 (2014 was not taken in account as the year was not complete in the dataset). However, the runoff intensity can vary significantly. Number of days per year where the tank is dry can also vary significantly (from 0 to 173 days). Despite some important water collection on the period 2000–2014 period, only 2 years saw the tank filled continuously during the whole year (only 2 day dry in 2006). On 7 years over the time series (50% of the time), the tank was dry for more than 3 months (Figure 10 and Table 2). This highlights the limitation of the use of the tank for a multi-year management.

5 | DISCUSSION

5.1 | Long-term management of RWH tanks

The developed methodology of reconstructing detailed tank filling history from water balance proves to be reliable thanks to the validation

TABLE 2 Yearly cumulative rainfall, maximum tank volume in m^3 of the maximum filling during monsoon (August–November). Percentage is expressed against the volume observed the 30/10/2013

Year	Direct rainfall (m^3)	Runoff (m^3)	Evaporation (m^3)	Infiltration (m^3)	Volume maximum (m^3)	Replenishment (%)	Runoff days (days)	Dry days (days)
2000	8633	15 053	14 240	15 246	10 876	5.2	11	46
2001	15 101	58 233	23 165	26 918	62 988	30.4	15	143
2002	7422	12 316	23 059	19 879	24 160	11.6	13	44
2003	30 976	92 888	38 409	46 881	77 672	37.4	22	123
2004	7427	13 227	33 405	25 873	38 209	18.4	14	32
2005	32 406	100 084	28 831	39 254	107 332	51.7	28	173
2006	13 942	15 372	54 157	39 561	63 761	30.7	18	2
2007	8634	13 821	12 426	10 019	8643	4.2	22	96
2008	20 028	53 239	29 305	32 688	40 041	19.3	22	68
2009	27 717	99 586	41 558	44 804	89 541	43.2	17	61
2010	25 405	26 921	47 481	46 950	51 725	24.9	29	0
2011	4282	4529	9288	9642	9932	4.8	10	127
2012	11 721	16 641	13 480	14 701	13 037	6.3	13	134
2013	46 878	189 846	46 812	55 380	207 497	100	26	132
2014	0	0	58 997	40 180	133 750	64.5	0	0

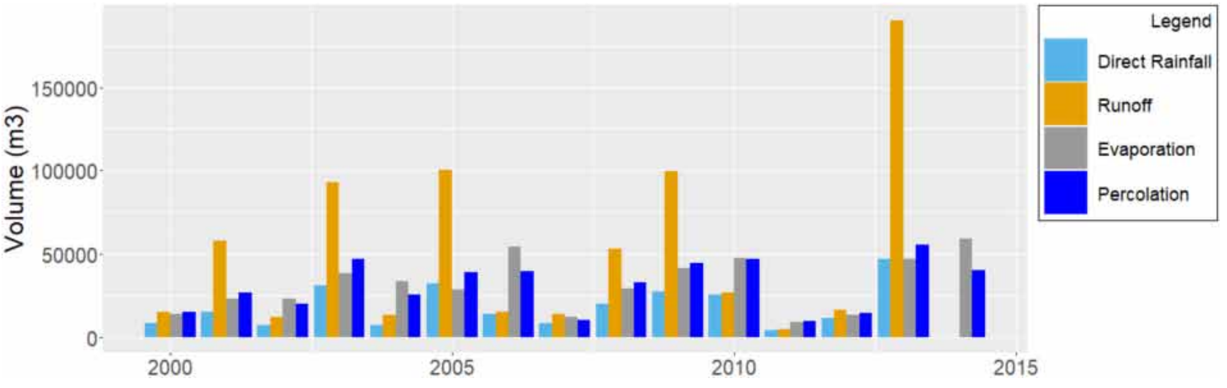

FIGURE 9 Yearly evaluation of the different components of the water balance.

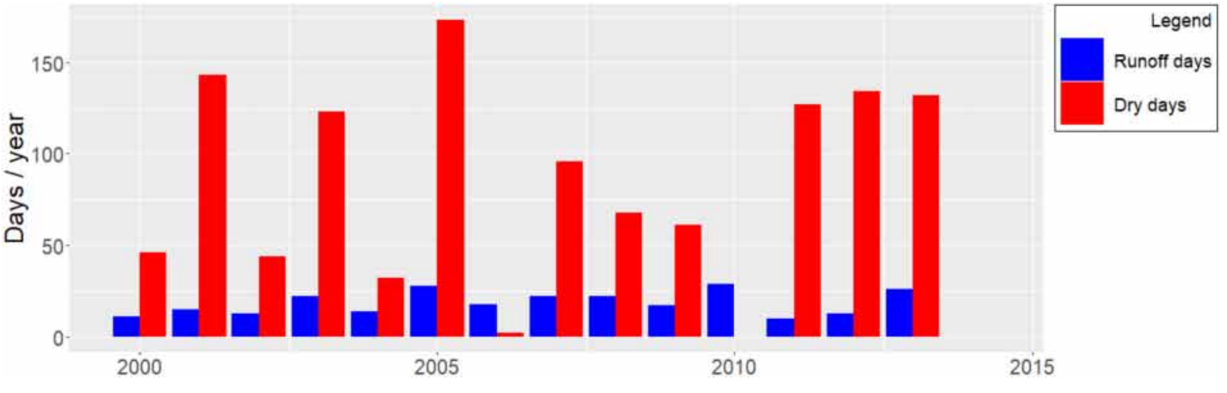

FIGURE 10 Number of runoff days and dry days per year estimated from the computation

of the results through remote sensing information. The detailed water budgeting at a daily time step on a 14 years period is unique and is a new valuable information for the understanding of the RWH tanks hydrology. This detailed water budget allows discussing the interest and limits of such tanks on a long period. Despite the fact that stored volumes vary widely from year to year, an important result is that the tank becomes fully depleted by the end of almost each hydrological year with, for 7 years over 13, complete drying other 3 months. The limited replenishment of the Tumulur tank over the period agree with the water occurrence maps of Pekel et al. (2016) for this tank on the period 1984–2020 (https://global-surface-water.appspot.com/map). This point is obviously dependent of the tank size. However, this tank size is very common in South India. This highlights that such a tank can hardly be used for multi-year management and counteracts consecutive drought years. Similar droughts are observed on the nearby tanks in the watershed (Figure 1).

Even if impact of climate change is locally uncertain, the population growth in Southern India makes the water demand and the groundwater dependence increasing. The long time series produced in this study, which can qualitatively be transposed to numerous tanks in South India, shows that RWH tanks can locally improve water supply situation on a yearly basis (2 years max) but not on the long term. It should be kept in mind that this runoff collection may also have impact for downstream users. RWH tanks increase locally and temporarily water availability enhancing irrigation solution for nearby users. However these tanks should not be perceived as a standalone solution and must be completed with water demand management to reduce farmer and population vulnerability to droughts. This is especially true in crystalline aquifers where limited underground storage (Boisson et al., 2015; Chilton & Foster., 1995; Dewandel et al., 2006; Fishman et al., 2011; Guihéneuf et al., 2014) do not allow storage of large volumes on long term. Comparison of the tank dynamics with continuous piezometric water levels, not connected to the tank, on the same period shows that aquifer is as well almost yearly depleted and yearly recharged (Figure 11). The regular drying of the tank and groundwater level depletion for consecutive years, as shown Figure 11, place farmers in a risky situation forcing them to a perpetual adaptation to climate variability (Aulong et al., 2012; Ferrant et al., 2014; Shah, 2012) with dramatic consequences in case of important droughts (Maréchal, 2010; Merriott, 2016). Under those conditions, the use of this tank may enhance crop production for some years but cannot counteract consecutive drought years.

Hence, current massive and expensive projects like Kakatiya mission (rejuvenating more than 45 000 tanks over the Telangana state) may have limited impact in the local context. While renovation of the tanks and other RWH structures can improve efficiency for underground storage, they will not, in most of the cases, modify the filling processes and hence the strong dependency of the system to extreme or consecutive drought events. The large programs of percolation on numerous structures and the cost of them at the scale of India make the present study socially and economically sound.

5.2 | Methodological improvement

The methods and concepts developed in this paper are relatively simple. However it provides, by the conjoint use of direct and precise field data with remote sensing over a long period of time, a clear enhancement of understanding the impact of RWH and MAR structures. Indeed, although various studies address this issue through remote sensing and GIS (Arshad et al., 2020; Pekel et al, 2016; Rahman et al., 2012; Sallwey et al., 2018; Senthilkumar et al., 2019; Yeh et al., 2016) a clear lack of field data exists for an accurate assessment, as deplored by numerous authors. To our knowledge, no studies use both methods for assessment on such time-scale.

The present approach is developed on a single tank, however the methodology can be applicable to other tanks as soon as bathymetry and meteorological data are available. The recent improvements on waterbodies detection (Peña-Luque et al., 2021) and tank volume estimation (Pascal et al., 2021; Vanthof & Kelly, 2019) from remote sensing using Sentinel 1&2 and TanDEM-EX DEM provides larges opportunities to obtain the needed data. However, the satellites measurements still lack temporal resolution for complete assessment of water resources that can be obtained using the proposed water balance approach. Such coupling of methodologies gives great opportunities for regional scale estimates of water availability related to these structures. This methodological coupling can provide effective information to feed models for an integrated water resource management.

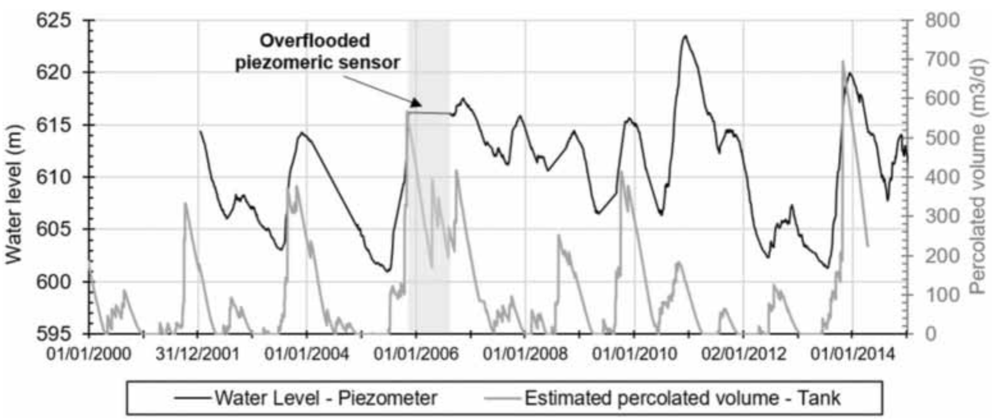

FIGURE 11 Long-term water level in the IFP9 borehole in the Maheshwaram watershed, near the Tumlur rainwater harvesting (RWH) tank and estimated percolated volume from the tank. Grey area represent piezometric sensor misfunction due to flooding

As shown by the sensitivity analysis, the use of such methodology, on long term time series instead of 2 years monitoring can be efficient to precise the range of calibration parameters. From the 2012–2013 data, the range was rather large and may produce variable results for the 2000–2012 periods as seen on Figure 7. LANDSAT data provide additional calibration points, reducing the range of calibration parameters and enhancing the results accuracy. This upgrade allows better reproduction the tank hydrodynamic. This is a direct improvement for further detailed modelling or prediction.

6 | RESULTS ACCURACY

With only four fitting parameters (CN, percolation rate, runoff effective area for a small and large tank) the model provide a good fit of the available data over a period of 14 years. The simplicity of the model and its consistency over a 14-years period, give confidence in the model and limit uncertainties about accuracy of the fitting parameters and their constancy in time.

Since each parameters are not directly measured, uncertainties remain. However, CN and runoff surface counteract each other's, meaning that different sets of parameters may lead to the same data fitting. Since no measurements allow constraint on those elements, absolute values are not certain. However, whatever the set of parameters chosen, if the data are well fitted the volume of runoff remains almost constant. The range of acceptable parameter estimated from the sensitivity test shows to be limited. Hence, the confidence on the runoff calculation, which is the main objective, seems sufficient to further discuss the differences between years.

The percolation rate and the PET also counteract each other's. Both being a length in the formulation used, those values are constrained by the decay rate of the water level measured during dry period. However, no independent direct measurements are available. PET is very complex to accurately measure in semi-arid climates due to strong spatial and temporal variability, numerous influencing factors (e.g.: wind, thermal inertia, temperature at the air-water interface…) and discrepancies between estimation methods (Alazard, Leduc et al., 2015b; Meter et al., 2016). Since the data availability is scarce, the PET estimate is here limited to the classical evaporation pan measurement and coefficient. Uncertainty on this parameter is hence reported on the percolation rate (q). The comparisons between the measured and estimated water levels from the water balance provide good confidence on the estimate despite the fact that relative influence is prone to some uncertainties. The area allowing the shift between one water balance to the other is fixed by the tanks size. Its use would have been critical aiming at understanding tank filling functioning. However, since the main point of interest in this case is the tank relative dynamic, which is compared and fitted to field data of different types (water level and flooded area from local and satellite measurement) this parameter formulation, nor value, has consequences.

The temporal constancy for the parameters such as surface runoff, percolation coefficient and CN number can also be questioned. On a 14 year's duration scale those parameters are unlikely constant. Runoff area and CN are affected for example by infrastructures construction, variation of land use, soil moisture, previous raining events. However the data fitting quality with only two parameters on this time scale assumed that changes in land use are relatively minimal. This agree with field observation since the watershed is monitored since 2000 (Maréchal et al., 2004). However, LANDSAT data on the period 2000–2001 seems less well reproduced than the later years. This may come from an unidentified modification in the area of interest. Percolation coefficient, which may vary depending on the soil type, soil moisture, depth of the saturated zone, clogging at the tanks bed is likely to vary in time and space. However the good 14 years fitting of the flooded area variation as well as the water levels makes this assumption acceptable.

Hence, despite the uncertainty on individual parameters, if we consider the data fitting (Figure 7) acceptable, the relative variations of the tank filling can be discussed. The objective of this study being assessing the long-term general variation of such tanks in crystalline aquifers rather than the definition of an accurate water balance for the Tumulur tank itself the methodology and results are appropriate.

This approach captures the main trend of the stored water volume fluctuation. This approximation is acceptable since the aim was to evaluate the long-term dynamics. Moreover, detailed tank water volume fluctuation as already been performed previously (Alazard, Boisson et al., 2015a; Boisson et al., 2014). Finally, the tank area varies sharply to large extend (from 0 to 184 000 m^2) as well as the tank volume (from 0 to 195 000 m^3). Hence, differentiation between important and poor storage years becomes straightforward. The sensitivity analysis on the 2012–2013 period shows that the range of parameters fitting the data is limited. Remote sensing data allow further reducing the range of these parameters. Estimates of dry days range from 84 to 107 d/y within the selected parameters (85 for the reference case). Runoff days range from 17 to 18.5 days per year (18.5 for the reference case); mean replenishment percentage of the tank from 26% to 28.5% (28% for the reference case); the ratio of infiltration range from 50% to 59% (50% in the reference case). Those small ranges show limited uncertainties on the presented results. Such dynamics is comparable to other tanks in the country or elsewhere. The strong variations in levels and volumes observed between the years 2012 and 2013 are similar to the variations observed in other studies for the country (e.g. Massuel et al., 2014) or other tanks in the watershed (Figure 1). These comparisons give confidence on the representativeness of the Tumulur tank to provide general trend.

This methodology also presents the advantage of being cheap, since the LANDSAT data are free, the GPS tracking can nowadays be made through a smartphone and the pressure sensor can be replaced by a direct reading on a scale.

7 | CONCLUSIONS

This study documents the replenishment and drying dynamics of a typical South Indian RWH tank over a period of 14 years. The detailed water budgeting at a daily time scale on such long period is unique and is a new valuable information for the understanding of the RWH tanks hydrology. This provides information on the long-term temporal dynamics of this type of structure which is usually poorly documented in the literature. This long-term assessment of a representative water storage tank (or percolation tank) shows a strong dependence to extreme raining events and an extreme variability of its storage capacity due to a strong variability of the monsoon and major storm occurrence. The tank can be largely filled during rainy years while it is able to store only a limited water volume during monsoons with low rainfall or if no extreme event occurs. This long-term monitoring also highlights that, whatever the yearly monsoon intensity, the tank is depleted by the end of the hydrological year except after two extreme events over a period of 14 years and is dry 3 months a year half of the years. Hence, while the tank can be used to store large volume of water on rainy years, it remains a very short-term option with no or limited multi-years management and hence have limited impact on poor monsoon years. This apparent efficiency should also be confronted to its impact for downstream users under a global assessment. Finally, the very low infiltration rate estimated thanks to this analysis questions the efficiency of such a scheme for managed aquifer recharge, a large volume of water being loss by evaporation.

Such analysis can be performed everywhere to assess the long-term impact of such tanks and requests a limited financial investment, since LANDSAT data surface water are freely available. In addition, most recent missions Sentinel offers improved spatial resolution (10 m rather than 30) and revisit frequency: 5 to 12 days for respectively optical multispectral data Sentinel-2 and radar data Sentinel-1. True bathymetries from very high-resolution digital elevation model are also a way to generalize this modelling approach at regional scale (Pascal et al., 2021). Comparison with other similar schemes show the representativeness of the approach and may help in the assessment of larger programs of MAR around the country and abroad.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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