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The socio-ecohydrology of rainwater harvesting in India: understanding water storage and release dynamics at tank and catchment scales

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Abstract

Rainwater harvesting (RWH), the small-scale collection and storage of runoff for irrigated agriculture, is recognized as a sustainable strategy for ensuring food security, especially in monsoonal landscapes in the developing world. In south India, these strategies have been used for millennia to mitigate problems of water scarcity. However, in the past 100 years many traditional RWH systems have fallen into disrepair due to increasing dependence on groundwater. This dependence has contributed to an accelerated decline in groundwater resources, which has in turn led to increased efforts at the state and national levels to revive older RWH systems. Critical to the success of such efforts is an improved understanding of how these ancient systems function in contemporary landscapes with extensive groundwater pumping and shifted climatic regimes. Knowledge is especially lacking regarding the water-exchange dynamics of these RWH “tanks” at tank and catchment scales, and how these exchanges regulate tank performance and catchment water balances. Here, we use fine-scale water-level variation to quantify daily fluxes of groundwater, evapotranspiration (ET), and sluice outflows in four tanks over the 2013 northeast monsoon season in a tank cascade that covers a catchment area of 28 km². At the tank scale, our results indicate that groundwater recharge and irrigation outflows comprise the largest fractions of the tank water budget, with ET accounting for only 13–22 % of the outflows. At the scale of the cascade, we observe a distinct spatial pattern in groundwater-exchange dynamics, with the frequency and magnitude of groundwater inflows increasing down the cascade of tanks. The significant magnitude of return flows along the tank cascade leads to the most downgradient tank in the cascade having an outflow-to capacity ratio greater than 2. The presence of tanks in the landscape dramatically alters the catchment water balance, with runoff decreasing by nearly 75 %, and recharge increasing by more than 40 %. Finally, while water from the tanks directly satisfies ~40 % of the crop water requirement across the northeast monsoon season via surface water irrigation,

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of large dams and canal systems (Cullet and Gupta, 2009; Mehta, 2001). For millennia, however, India has met the demand for seasonal water storage and increased water availability at the local level via the building of village-scale rainwater harvesting (RWH) structures, often referred to as tanks (Van Meter et al., 2014).

It is estimated that more than 39 000 of these RWH tanks are present in the southern Indian state of Tamil Nadu, which is the focus of the present study (Van Meter et al., 2014). These RWH tanks, which commonly take the form of earthen impoundments, 20–40 ha in size (Gunnell and Krishnamurthy, 2003), are built up from natural depressions in the landscape and have historically been designed to meet the water needs of subsistence-level farmers for rice production via managed sluice channels for irrigation (Farmer, 1977). Tanks are often linked in a cascade, with overflow from the upstream tanks spilling into surplus channels that lead to downstream tanks. The tank systems have fallen into decline in recent decades, primarily as a result of increasing reliance on groundwater pumping, and cheap access to electricity. This changed has led to declining groundwater levels, which coupled with a growing demand for increased agricultural production, have led to renewed interest in these traditional systems (Kumar et al., 2008; Shah, 2004). Although the majority of existing RWH tanks remain in a state of disrepair (Anbumozhi et al., 2001), it is estimated that reviving RWH systems at an all-India scale could potentially add as much as $125 \text{ km}^3 \text{ year}^{-1}$ to the country's current water supply, making them critical in meeting the projected water shortfall of $300 \text{ km}^3 \text{ year}^{-1}$ by 2050 (Gupta and Deshpande, 2004). Consequently, in India's Groundwater Recharge Master Plan (2005), the need for renovation or new construction of RWH structures was highlighted at a cost of approximately \$6 billion, leading to high rates of revival of RWH structures across India (Agarwal and Narain, 1997; Shah et al., 2009)

With the renewed and large-scale interest in the use of RWH structures, it is critically important to ask whether these ancient structures perform their intended purpose of significantly improving water availability in a basin. To do so requires quantifying the dominant tank inflows and outflows, specifically evapotranspiration (ET), groundwater

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recharge, and sluice outflows to irrigated fields. These water fluxes determine relative water allocation to aquifer supplies, irrigation needs, and atmospheric losses, and are influenced by a wide range of both natural and management controls, from climate and geology to the more direct anthropogenic controls (e.g., sluice outflow regulation).

5 As such, a better understanding of tank fluxes and drivers of these fluxes is necessary when managing individual and cascades of tanks to meet both societal (irrigation demand) and environmental (increasing rates of groundwater recharge) needs (Glendenning et al., 2012; Neumann et al., 2004; Ngigi, 2003).

10 Unfortunately, there is a lack of empirical studies that quantify tank hydrologic fluxes, especially at the scale of watersheds comprising multiple tanks (Glendenning et al., 2012). One reason for the lack of information is that both groundwater recharge and ET are highly spatially variables, and thus difficult to accurately measure at the field scale (Glendenning et al., 2012). Most previous studies of RWH tanks estimate recharge as a residual term in the water-balance method (Glendenning et al., 2012); in arid environments, however, recharge magnitude is small compared to other fluxes (Bond, 1998), making estimates from water balance residuals vulnerable to errors in other measured components. Furthermore, water-balance methods used in RWH tanks estimate recharge using modeled values of tank evapotranspiration, another rarely measured but critically important water flux in these arid environments (Sharda et al., 2006).

20 While there is consensus regarding the value of direct measurements of temporal variations in recharge and evapotranspiration fluxes from RWH structures, such data are difficult to obtain due to the inherent complexities in making these measurements, especially under resource constraints (Glendenning et al., 2012).

25 Here, we propose an innovative use of the White (1932) method as a cost-effective means of obtaining spatially integrated, direct measurements of both ET and groundwater exchange in flooded RWH tanks. The White Method, which was originally developed to estimate the magnitude of groundwater consumption by phreatophytes (Loheide, 2008; Loheide et al., 2005), has since been used to estimate ET and groundwater exchange in small, surface water systems (Carlson Mazur et al., 2014; Hill and

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Meter et al., 2014) (Fig. 2). During times of elevated water levels, flooding extends beyond the main depressional area and into flatter, often farmed areas (i.e., tank water spread area). The bunds are constructed using locally available materials, usually a combination of amassed earth and stones, supported by the roots of trees and bushes growing along the bunds (Weiz, 2005). Sluices (typically sliding gates) are constructed within the tank bund and are used to control the release of water into irrigation channels, which then transport the stored water to agricultural fields in the tank command area (i.e., tank-supported irrigated fields). During heavy monsoon rains, water may spill over the tank's overflow weir into surplus channels leading to downstream tanks or to nearby waterways (Van Meter et al., 2014). Tanks are often linked through these surplus channels in chains, or cascades, that can range in size from several to more than a hundred tanks, forming a dense hydrological network across this intensively managed agricultural landscape.

Tank storage capacities vary across sites and time, with the latter due to siltation and desiltation cycles (Weiz, 2005). Historical data regarding maximum tank area and storage volumes for the four study tanks, obtained by the Public Works Department in India in approximately 1900, are summarized in Table 2 (DHAN, 2010). Information regarding the tank irrigated area, also known as the command area or "ayacut" (Weiz, 2005), is also provided. Although the maximum water depths of the four tanks are similar, ranging from 3–4 m at maximum fill, the historical data show that the tank areas vary significantly, ranging from 19.3 ha (Tank 3) to 58.7 ha (Tank 2). The ratio of command area to tank area historically ranged between 0.77–1.25 (Table 2), which is characteristic of tank systems found in this area (von Oppen and Subba Rao, 1987; Weiz, 2005). Table 2 also includes measurements made in the present study for comparison (discussed later).

to the tank base (lowest point), which was defined as zero. The bathymetric data were used to create stage-volume and area-volume relationships for each tank, and estimate current tank capacities. The capacities estimated by this method led to reasonable values, with current capacities ranging between 62–92 % of the historical capacities (Table 2).

3.2 Sluice and overflow weir outflow estimates

There are six sluices in the study area, two in Tank 1, two in Tank 2 and one each in Tanks 3 and 4. Water releases from the sluices are controlled by sluice gates that can be opened to different degrees by a sluice rod. For our study tanks, the degree of sluice openness remained primarily unchanged during the period of study, and thus the major factor that controlled sluice discharge was found to be the tank water level. To understand this relationship, sluice discharge was estimated at different tank water levels. Discharge was estimated by measuring the velocity and cross-sectional area over a chosen section of each outflow channel just downstream from the sluice outlet. This section was selected based on width uniformity and channel straightness. Approximately 20–40 measurements were made during each discharge measurement to obtain a reliable velocity estimate. Stage-discharge relationships developed for each sluice were used to estimate volumetric daily sluice outflow rates; these rates were then converted to area-normalized rates (S_o , cm day^{-1}) based on tank stage-area relationships (Sect. 3.1).

As described in Sect. 2.2, in addition to water loss via sluice outflow, water may also flow out of the tank by spillage through the overflow weir into surplus channels during large storm events. Overflow was observed during the study period only in the case of Tank 4 on 10/20, during the first major rains of the monsoon season. For this event, the surplus flow volume was estimated based on the observed drop in water levels between 10/20 and 10/21.

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S_o , ET, and GE. For non-rainfall days, ET and GE values were calculated using the White method. For rainfall days, however, ET and GE could not be calculated directly via the White Method, as the method necessarily assumes a constant groundwater flow and therefore cannot account for rainfall-related inputs (McLaughlin and Cohen, 2013).

This disruption in the continuity of the data set, without correction, would lead to gaps in the daily water balance and an underestimation of both ET and groundwater exchange across the monsoon season. To eliminate these gaps, we estimated ET values on rainfall days via interpolation between White Method-estimated ET rates on days without rain. GE on rainfall days was estimated based on the residuals of the daily water balance, using the measured 24h change in tank water levels, estimated ET rates, measured precipitation, and estimated runoff (McLaughlin and Cohen, 2013). Runoff was estimated using the Strange method (Shanmugham and Kanagavalli, 2013), an empirical method that was developed to predict runoff from catchments with irrigation tanks and small reservoirs and that is widely used throughout India by government departments dealing with irrigation (Latha et al., 2012). Stage-to-area relationships (Sect. 3.1) were used to convert daily stage change and estimated fluxes (ET, GE, and S_o) into volumes, which were calculated for each tank. Note that the water balances for all tanks are calculated for the period from 17 October 2013–13 January 2014, a period that spans the entire monsoon season and for which water-level data is available for all four tanks.

Water balances were also calculated at the catchment scale using a nested catchment design for four catchments: (1) Catchment 1 (C1): Tank 1 (T1), and its contributing catchment; (2) Catchment 2 (C2): Tank 2 (T2) and its contributing catchment which includes Tank 1 and its catchment area and command area; (3) Catchment 3 (C3): Tank 3 (T3) and its contributing catchment which includes tanks 1 and 2, and their catchment and command areas; and (4) Catchment 4 (C4): Tank 4 (T4) and its contributing catchment which includes tanks 1, 2 and 3, and their catchment and command areas. This nested catchment design enabled us to explore the effect of varying catchment sizes and tank to catchment ratios on the water partitioning.

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Further, in order to understand the impact of the tanks at the catchment-scale, we explored two scenarios for each of the four catchments scales (i.e., C1–C4): (1) a with-tank (WT) scenario to represent current conditions within the catchment (i.e., four existing tanks); and (2) a no-tank (NT) scenario, with all other conditions (e.g., rainfall, ET on the catchment area) being the same. For the NT case, catchment-scale runoff was calculated using the Strange method (Shanmugham and Kanagavalli, 2013) and daily rainfall over the monsoon season. Remaining rainfall was assumed to exit the system through ET and groundwater recharge. For the WT case, we assumed the sluice outflow from the most downstream tank in the catchment (T1 for C1, T2 for C2, T3 for C3 and T4 for C4) to represent the Q value for the catchment. For T4 a surplus overflow event occurred at the start of the season, the volume of which was estimated based on stage-volume relationships; this volume was added to the sluice outflow to estimate the Q for C4. The Q values for the NT and WT scenarios were compared for all four catchments to understand the effect of tanks on the catchment runoff.

To understand the effect of tanks on groundwater recharge, we assumed the mean recharge to be 17% of the mean annual rainfall for the NT case following Anurag et al. (2006). For the WT case, the landscape was assumed to include three different domains, with separate recharge fractions being assumed for each domain: (1) tank bed area: GE (Sect. 3.2) was used, (2) tank command area: 50% of the sum of rainfall and sluice outflow (based on typical values for paddy fields; Hundertmark and Facon, 2003), and (3) the rest of the watershed: 17% of rainfall (Anurag et al., 2006). The command area and the tank bed area estimates for the four tanks are provided in Table 2.

4 Results and discussion

The current section is divided into two broad subsections. In the first, we report measurements of tank water levels, and fluxes (ET and GE), and use these data as a basis for discussing tank water level dynamics across the monsoon season. In the second,

we provide analysis of these and complementary data to answer questions regarding controls on the tank and catchment water balances and the ability of tank rainwater harvesting systems to meet irrigation water demand.

4.1 Tank water–exchange dynamics

4.1.1 Tank water levels over the Northeast Monsoon season

Water levels in the tanks rose sharply in mid-October following the start of the monsoon rains, and then dropped over the next 3 months as water left the tanks through ET, sluice outflow, and groundwater recharge (Fig. 4). Note that although the Northeast Monsoon rains began in early September, the tanks started filling only in mid-October.

This time lag is likely due to a threshold effect, where runoff to the tanks occurs after cumulative rain volumes begin to exceed catchment infiltration capacity. Two distinct fill events can be observed, one on 16 October and the second on 17 November for all tanks except Tank 1, for which the second fill event is not as apparent. Between 16 October and 17 November, the trajectories of tanks 1 and 3, and of tanks 2 and 4, parallel each other. Towards the later part of the season, the water level trajectories of all four tanks approximately parallel each other. Tank 1 loses its water the earliest and is mostly dry by January, while the other three tanks retain some water until February. In the following sections, we explore how the outflow fluxes in the four tanks vary over the course of the monsoon season.

4.1.2 Estimation of evapotranspiration

Evapotranspiration (ET) fluxes estimated with Eq. (1) for the four tanks are shown in Fig. 5. ET rates derived by the White Method are reasonable for the region and season (potential ET (PET) ca. 3–12 mm day⁻¹ for Madurai; Rao et al., 2012), ranging from 5.5 ± 1.0 for Tank 1 to 10.1 ± 0.8 mm day⁻¹ for Tank 3 during periods when the tank inundated area is greater than 25 % of maximum area. Below this 25 % threshold (shown

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contrast, immediately following a rain event, the system becomes more dynamic, and recharge is a function of not only tank water levels but also the short-term response of the local surrounding aquifer. When plotted for all tanks, GE was also found to respond linearly to tank water levels for most days throughout the monsoon season, except in the hydrologically dynamic periods after rain events, when the behavior was more erratic (Fig. 7b).

In addition to these patterns of groundwater exchange across the monsoon season, differences can also be seen along the tank cascade, from top (Tank 1) to bottom (Tank 4). First, while recharge, as represented by the positive GE values in Fig. 6, can be seen to dominate the exchange dynamics of Tanks 1–3, Tank 4 is more discharge-driven. As shown in Fig. 8a, close to 90 % of all days throughout the monsoon show net recharge behavior for Tanks 1–3, while Tank 4 is split almost equally between net recharge and net discharge days. From a volume perspective, the discharge-to-recharge ratio for the tanks shows a general trend from smaller (0.3 in Tank 1) to larger (1.2 in Tank 4) across the tank cascade (Fig. 8b), with Tank 4 demonstrating net discharge behavior. Tank 4 is the most down-gradient tank, suggesting the possibility that aquifer levels adjacent to Tank 4 are higher (possibly due to upstream tanks' recharge) for a longer period of time than the other three tanks, leading to more frequent groundwater inflow.

Our finding of a distinct spatial pattern in groundwater exchange and sluice outflow dynamics across the tank cascade is a novel contribution of the present study. Most studies that have explored the recharge/discharge functions of tanks (Glendenning et al., 2012) have focused on individual tanks, with no consideration of the position of the tank in a cascade as an important control on its functioning. Our results indicate that in order to upscale tank-scale information to understand catchment and regional scale impact of tanks, more studies should focus on exploring the spatial arrangement of tanks in the landscape.

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4.2 Exploring biophysical vs. management controls on tank water balance at the tank and catchment scales

Three questions were posed in the introduction regarding the partitioning of water within a tank cascade, the ways in which tanks alter the catchment water balance, and the ability of tanks to meet irrigation requirements in the semi-arid landscapes of South India. Below, we use our measured data to provide answers to these questions in the context of a discussion of physical vs. management controls on tank functionality.

4.2.1 Water balance at the tank scale

The first question we asked was how tanks partition incoming water (direct rainfall on tank and surface runoff from tank catchment) into various outflow components, namely evapotranspiration, groundwater outflow/inflow, and sluice outflow to the fields in the tank command area. The flow volumes corresponding to these components for each tank over the duration of the Northeast monsoon season are plotted by week in Fig. 9a and are summarized in Table 3. Notably, recharge to groundwater is a significant component of tank outflows. Although the primary function of tanks in South India has historically been to provide surface water for irrigation, and despite the high clay content of soils in the area, groundwater recharge is the primary outflow mechanism in Tanks 1–3 (from 46–59% of total outflows). For Tank 4, however, which is dominated by discharge behavior, the primary outflow mechanism is sluice outflow, which directly provides irrigation water to the tank command area. As seen in Fig. 9a, sluice outflows and recharge are the greatest early in the season, when tank levels are at their highest, and then decrease over time, ceasing entirely by mid-December for all four tanks.

Although the volume of water lost to ET is substantial (0.48–1.64 million cubic meters over the 83 day study period), it is a relatively small fraction of the overall water budget. On a cumulative scale (Table 3), ET values range from 13% of total outflows for Tank 1 to 22% for Tanks 2 and 3. These relatively small percentages contradict the established view of tanks losing a significant fraction of their water through ET (Kumar et al., 2006).

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In addition, although the tanks have been constructed in soils with a high clay content, all but Tank 4, which has a high discharge-recharge ratio, have high relative rates of groundwater recharge. For Tanks 2 and 3, recharge is the largest outflow component (57–59 %) and is more than double the values for sluice outflow and evapotranspiration.

For Tank 1, recharge is also the largest outflow component (47 %), although it is similar in magnitude to sluice outflows (41 %). The differences in flow partitioning between the four tanks can be attributed to differences in both natural (e.g., topographical position of the tank along the cascade) and human (e.g., sluice management) factors.

Interestingly, a trend can be seen in the relationship between total tank outflows over the monsoon season and the maximum tank capacity (Fig. 9b). As we move down the cascade of tanks, the outflow-to-capacity ratio increases, from 1.06 for Tank 1 to as high as 2.25 for Tank 4. The outflow-to-capacity ratio is an indication of how many times a tank fills up during the season, and the increase in values along the cascade of tanks is a function of increasing return flows from upstream command areas entering the downstream tanks. For Tank 4 in particular, groundwater discharge provides a significant input of water into the tank (Fig. 8). Accordingly, Tank 4 has relatively greater amounts of water available for surface water irrigation throughout the season, with sluice outflow alone accounting for 1.2 times the total tank capacity. This increase in the outflow-to capacity ratio along the cascade of tanks is an important feature of the tank cascade system, and highlights the need to study the tanks not in isolation, but in relation to their position along the cascade. Biophysical controls (for example weeds or sediments in tank beds of upgradient tanks) or management choices (for example, planting crops with lower or high water requirement in upgradient tanks) can completely alter the water availability in a downstream tank. Thus, rehabilitation efforts and tank management should focus on maximizing benefits at the cascade scale instead of only at the individual tank scale.

4.2.2 Water balance at the catchment scale

The second question we asked was how tanks alter the partitioning of rainfall into runoff at the catchment outlet (Q) and recharge within the catchment. Water balance calculations were performed at the tank and catchment scales for the four nested catchment scenarios described in Sect. 3.4. Further, we simulated scenarios both with and without tanks to understand the contribution of tanks towards altering catchment scale water partitioning.

Our results show a dramatic difference between the with-tank and no-tank scenarios, and a distinct spatial pattern of response in the four nested catchments. We found a significant decrease in Q at the four nested scales, from 22 % of rainfall in the no-tank scenario to 5–9 % of rainfall with tanks (Table 4). At the largest catchment scale (C4), the runoff decreased from approximately 2.29 million cubic meter (MCM) in the NT scenario to only 0.69 MCM in the presence of tanks (Table 4). This approximately 70 % decrease is consistent with other work showing large decreases in runoff due to the presence of tanks (Kumar et al., 2008). Conversely, catchment-scale net recharge was observed to increase from 17 % of rainfall without tanks to 24–27 % with tanks (Table 4), which corresponds to an overall increase in net groundwater recharge of 40 %, highlighting the potential beneficial role tanks may play in augmenting groundwater resources.

Despite this strong link between the presence of tanks and groundwater recharge, tank maintenance has declined across South India as farmers have become increasingly reliant on groundwater irrigation sources (Balasubramanian and Selvaraj, 2003). With tank-irrigated area across Tamil Nadu having decreased from 940 000 ha in 1960 to approximately 503 000 ha in 2010, some suggest that current tanks are operating at only 30 % of their potential capacity (Amarasinghe et al., 2009; Government of Tamil Nadu, 2011; Palanisami and Meinzen-Dick, 2001). This degradation of tank functionality is eliminating or significantly degrading the primary mechanism for aquifer recharge in an area where, without rainwater harvesting, the majority of monsoon rainfall will

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most down-gradient tank has a much greater outflow-to-capacity ratio, and is able to provide a much larger volume of sluice outflow compared to its capacity. The ability of the most downgradient tank to provide more irrigation water is a function of the return flow from the command areas of the upstream tanks, and highlights the need to study tanks, not in isolation, but as a part of a cascade. There is also a distinct pattern in the crop planting dates in the four tanks, with the more down-gradient tanks having earlier planting dates that eventually lead to a more efficient use of the tank water. Interactions with the villagers revealed that the earlier planting dates in the downgradient tanks could be attributed to the greater availability of groundwater in that area of the cascade, which enables the farmers to plant before the monsoons have arrived. This dynamic highlights the feedbacks between the natural and human systems, where a greater availability of water at the catchment outlet leads to farmers deciding on earlier planting dates, which in turn leads to a more efficient use of the available water.

In conclusion, our results demonstrate the significant role that tanks can play in addressing challenges of limited water availability, by both increasing groundwater recharge as well as the water available for irrigation. However, they also draw attention to the detrimental environmental impacts of tanks with respect to reducing downstream flows. These findings highlight the need to understand the spatio-temporal patterns in tank water dynamics at the basin scale, especially within the framework of a coupled natural and human systems approach that allow us a more complete understanding of how tanks alter the sociohydrological dynamics of water stressed landscapes. Thus, ongoing rehabilitation efforts of tanks need to be complemented with more studies that quantify the functioning of these rehabilitated tanks and their impacts in altering basin scale water dynamics, with the overall goal of appropriately managing the tradeoffs between socioeconomic benefits and environmental costs.

Author contributions. The field study was carried out by M. Steiff under the guidance of D. L. McLaughlin Data analysis was carried out by K. J. Van Meter and M. Steiff Drafting of the manuscript was led by K. J. Van Meter and N. B. Basu with contributions by D. L. McLaughlin, N. B. Basu conceived of the project and was instrumental to the basic experimental design.

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[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)**Table 1.** Population and land-use data for the study cascade.

Tank #	Village Revenue District	Population			Land Use				
		Total Pop-ulation	Workforce	Farmers and Agricultural Laborers	% of Total	Agriculture	Forest	Settlements	Other
Tank 1	Pappinaickenpatti	3313	1986	1724	87%	73%	16%	2%	9%
Tank 2	Kudipatti	2122	1300	1172	87%	74%	13%	3%	11%
Tank 3						91%	–	5%	4%
Tank 4	Ketuvarpatti	622	356	316	89%	99%	–	1%	–
Cascade		6057	3642	3212	88%	81%	9%	3%	7%

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Table 2. Summary of tank attributes based on historical tank data (made available by DHAN Foundation) and the current study.

Tank #	Soil Type	Maximum Depth (m)	Maximum Tank Surface Area (ha)	Tank Command Area (ha)	Command Area/Surface Area Ratio	Tank Capacity (m ³)		Current Capacity/Historical Capacity
						Historical	Current	
Tank 1	Alfisol	3.2	15	27	0.96	357 700	276 405	0.77
Tank 2	Vertisol	3.4	51	45	0.77	656 500	407 513	0.62
Tank 3	Vertisol	4.0	14	19	0.93	237 000	217 633	0.92
Tank 4	Vertisol	3.3	21	24	1.25	168 000	139 270	0.83

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Table 3. Partitioning of tank outflows across the Northeast Monsoon season.

	Tank 1	Tank 2	Tank 3	Tank 4
Total Outflows (m ³)	376 794	762 483	352 934	377 257 ^a
Evapotranspiration				
Total (m ³)	48 291	164 423	78 745	64 358
Percent of Total Outflows	13 %	22 %	22 %	17 %
Sluice Outflow				
Total (m ³)	153 038	146 612	72 279	207 636
Percent of Total Outflows	41 %	19 %	20 %	55 %
Recharge				
Total (m ³)	175 465	451 448	201 910	105 263
Percent of Total Outflows	47 %	59 %	57 %	28 %

^a Note that the total outflow volume given here for Tank 4 does not include the 10/20 overflow event at the start of the monsoon season. As water exiting the tank via the overflow weir passes directly out of the tank catchment, bypassing the tank command area and thus not remaining as a source for irrigation or groundwater exchange within the tank cascade, we considered it separately from other flows.

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Table 4. Water balance summary at the tank catchment scale.

	Catchment 1	Catchment 2	Catchment 3	Catchment 4
Area (km ²)	5.0	16.2	22.5	28.4
Precipitation <i>P</i> (MCM)	1.8	5.8	8.1	10.2
Runoff, <i>Q</i> (MCM)				
with tanks	0.15	0.30	0.37	0.69
without tanks	0.40	1.31	1.81	2.29
Recharge, <i>R</i> (MCM)				
with tanks	0.48	1.44	1.97	2.42
without tanks	0.31	0.99	1.37	1.73
<i>Q/P</i>				
with tanks	0.09	0.05	0.05	0.07
without tanks	0.22	0.22	0.22	0.22
<i>R/P</i>				
with tanks	0.27	0.25	0.24	0.24
without tanks	0.17	0.17	0.17	0.17

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Table 5. Sluice outflows and irrigation water demand (IWD).

	Tank 1	Tank 2	Tank 3	Tank 4
Planting Date	10/17	10/17	9/25	9/13
Sluice Water				
Total (mm)	570	326	391	861
Utilized (mm)	283	210	333	516
Surplus (mm)	287	116	58	345
Percent Surplus	50 %	36 %	15 %	40 %
Irrigation Water Demand				
Total (mm)	996	996	872	752
Unmet Demand (mm)	713	786	540	235
Percent Unmet	72 %	79 %	62 %	31 %

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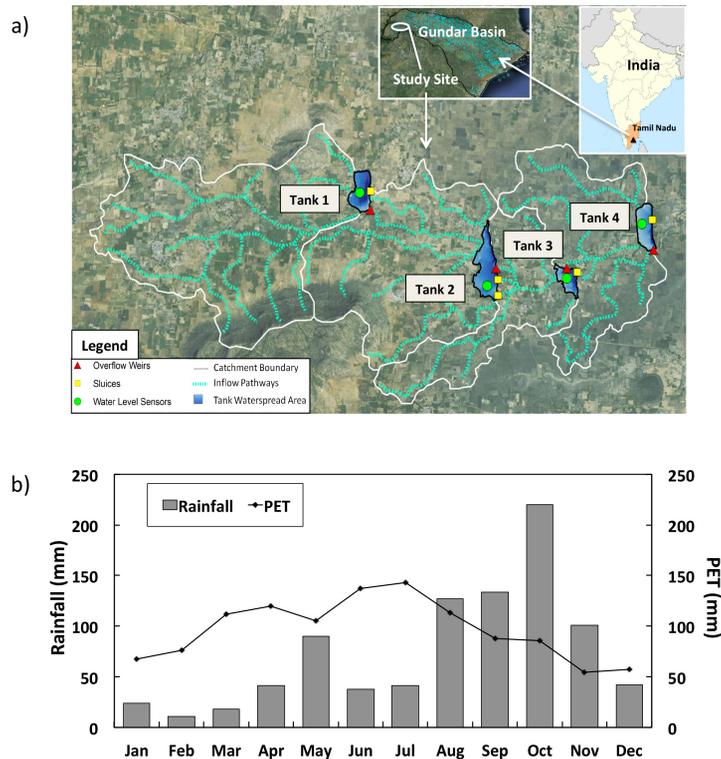


Figure 1. (a) Location of the Thirumal Samudram cascade within Tamil Nadu. The dotted lines indicate flowpaths calculated based on a digital elevation map (DEM) for the area; (b) average rainfall and potential evapotranspiration (PET) (1900–1970) measured at Peraiyur weather station, 10 km from the study cascade.

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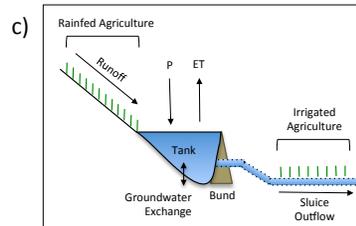
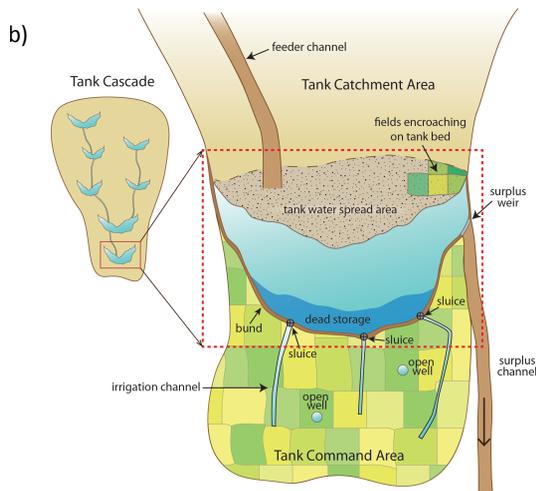
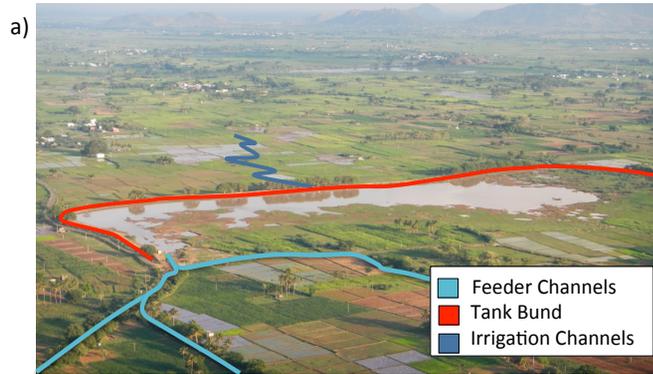


Figure 2. (a) Aerial view of a Tank 4 in the TS cascade; (b) plan view of typical tank along with catchment and command area; (c) cross section of tank water budget components.

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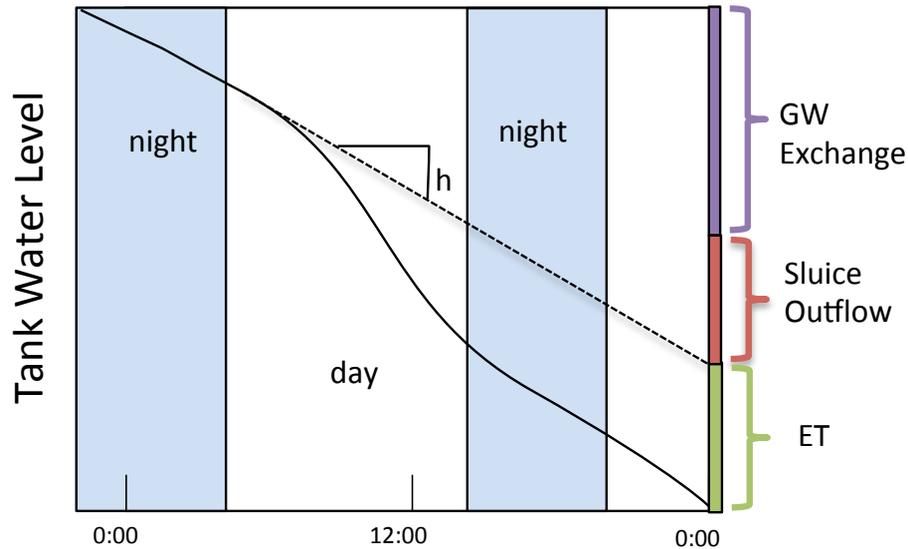
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$$ET = S_y \cdot (s - 24h)$$

$$GE = S_y \cdot 24h - S_o$$

Figure 3. The White Method for estimating ET and groundwater exchange using diurnal water level fluctuations. Gray bars denote nighttime.

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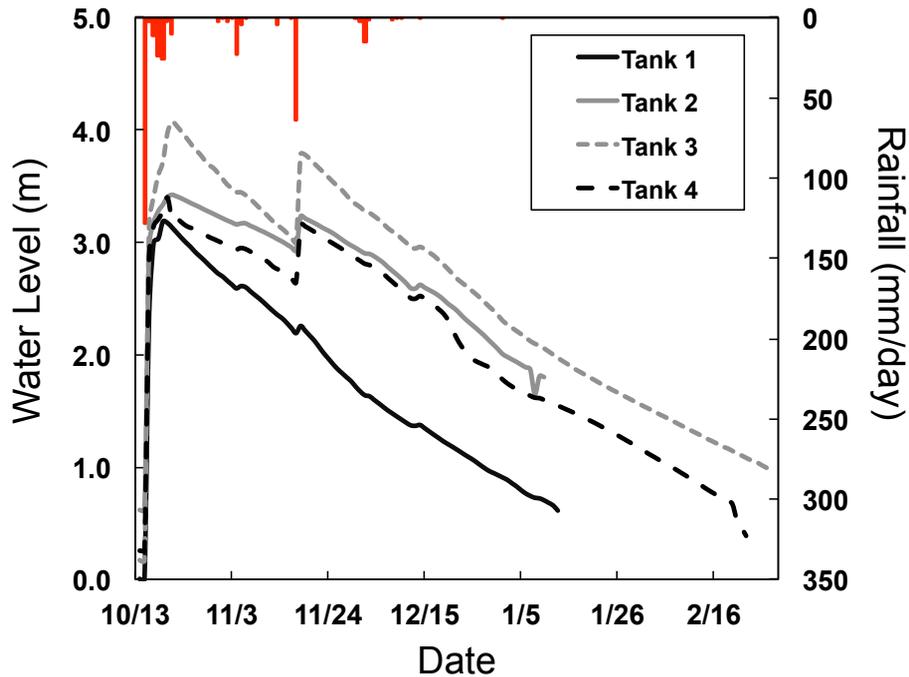


Figure 4. Tank water level and daily rainfall for the four tanks over the North East monsoon season. Tank water level is measured from the deepest point of the tank.

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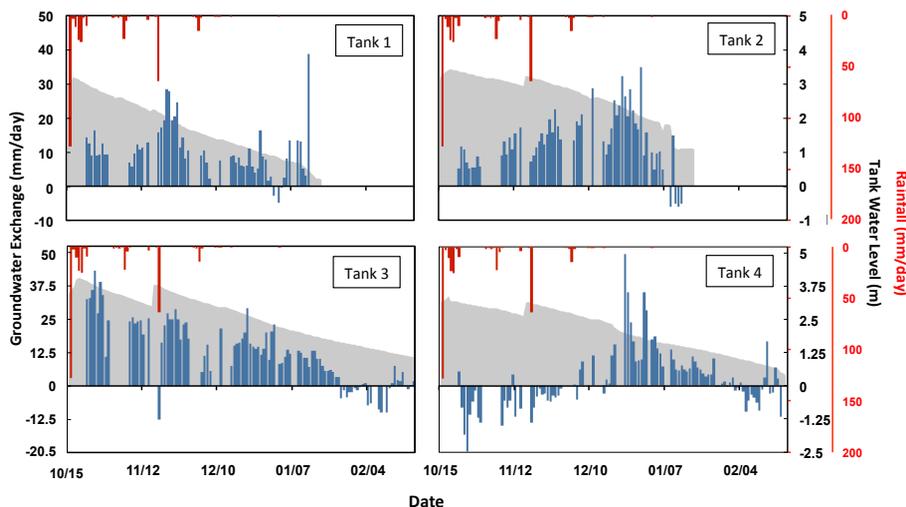


Figure 6. Daily groundwater exchange (mm/d) over the course of the Northeast Monsoon season (blue bars). Positive values indicate groundwater outflow (recharge) from the tank, while negative values indicate inflow (discharge) into the tank. Groundwater exchange magnitudes generally decrease and even switch from outflow to inflow towards the latter part of the season, when tank water levels (shown in grey and plotted on the secondary y-axes) are low. There are in some cases some very high groundwater outflow events near the end of the season corresponding to pumping in the vicinity. Rainfall is shown as red bars.

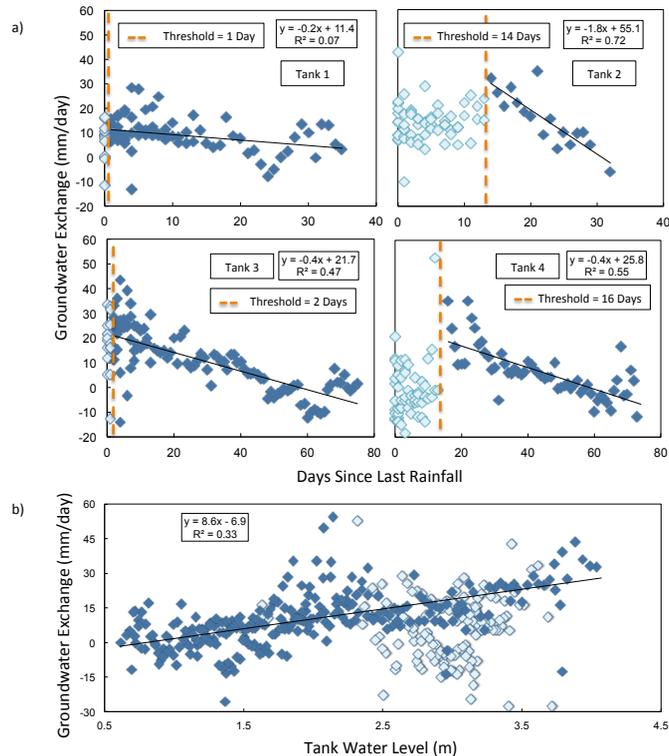


Figure 7. (a) Relationship between groundwater exchange and days since last rainfall, shown separately for the four tanks. The threshold line (dashed orange) separates the more erratic rainfall-driven groundwater exchange behavior following rain events (shown as light-blue diamonds) from the more predictable behavior typical of drier periods (shown as dark blue diamonds), when GE is driven primarily by hydraulic head values determined by tank water levels. (b) Relationship between tank water levels and groundwater exchange shown for all four tanks combined. Lighter blue diamonds correspond to the rainfall values below the threshold shown (a).

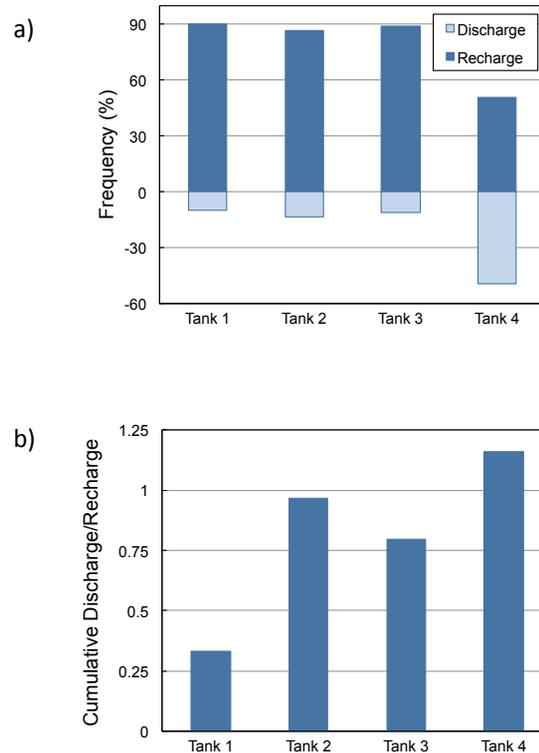


Figure 8. (a) The frequency of daily recharge (outflow) and discharge (inflow) events over the Northeast Monsoon season, and (b) the ratios of cumulative discharge to cumulative recharge magnitudes. The results for the four tanks indicate that all tanks function as both recharge and discharge systems, but that Tank 4 is much more dominated by discharge behavior based on both frequency and overall magnitudes.

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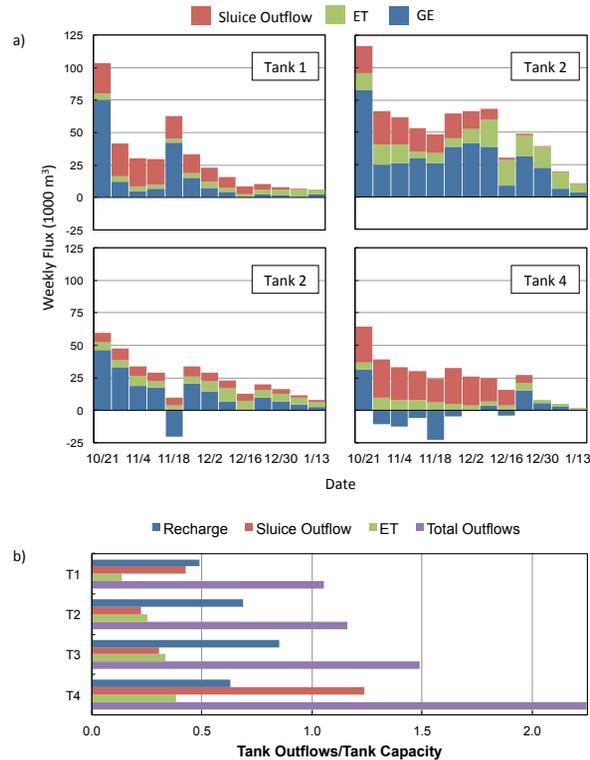


Figure 9. (a) Tank outflow dynamics (ET in green, sluice outflow in red and GE in blue) shown as weekly integrated volumes for all four tanks. These are stacked bar graphs with the areas shown in the different colors representing the subcomponents of the outflow. (b) Tank water outflows as a fraction of the tank capacity, with total outflows calculated as the sum of ET, S_0 and groundwater recharge. The outflow-to-capacity ratios increase down the cascade, such that total outflows for Tank 4 over the study period are more than double the total tank capacity.

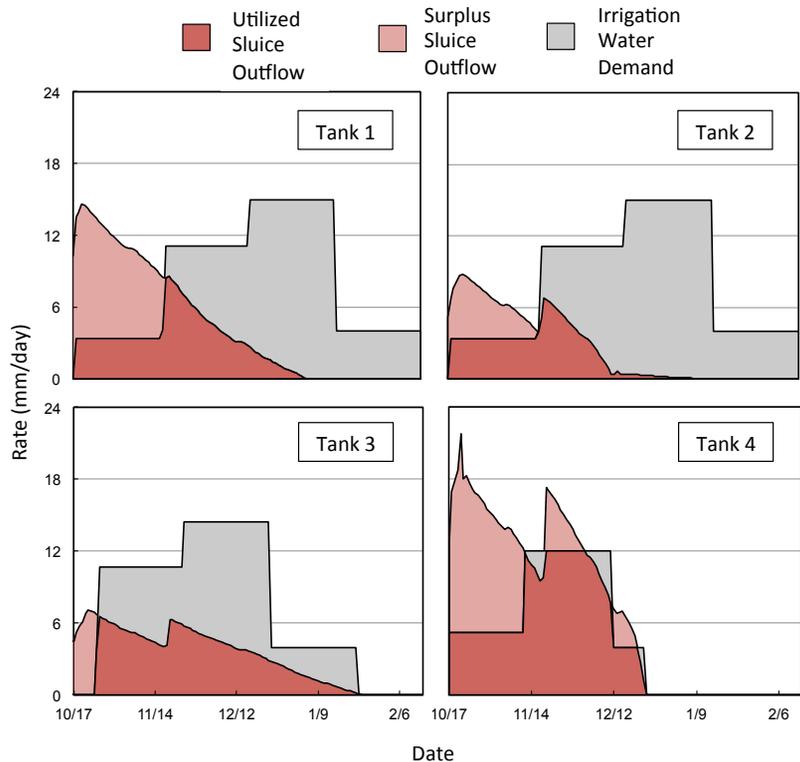


Figure 10. Water supply-and-demand portraits in our tank cascade. The grey area represents the Irrigation Water Demand (IWD), which is calculated as the difference between crop water requirements and rainfall (Brouwer et al., 1989). Planting dates were 10/17, 10/17, 9/25, and 9/13 for Tanks 1, 2, 3, and 4, respectively. The darker red area corresponds to the portion of sluice outflow that is utilized to meet the irrigation water demand, while the light red area corresponds to the portion of sluice outflow that is “wasted”.

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