The Socio-ecohydrology of Rainwater Harvesting in India: Understanding Water Storage and Release Dynamics at Tank and Catchment Scales

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science

in

Civil and Environmental Engineering

Waterloo, Ontario, Canada, 2016

Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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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 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. Further, the effects of imposing management controls on improving tank system sustainability and the ability to meet crop water requirements are not well understood.

In this thesis, I have attempted to quantify the water exchange dynamics in a cascade of four RWH tanks, using a conjunction of field data and modeling, in the Gundar Basin watershed in Southern Tamil Nadu. Water level sensors were installed in the tanks over the NE monsoon season. Using fine-scale water-level variations, the White method was used to estimate daily fluxes of groundwater exchange (GE), and evapotranspiration (ET) in the four tanks over the 2013 northeast monsoon season. Groundwater recharge and irrigation outflows comprised the largest fractions of the tank water budget, with ET accounting for only 13-22% of the outflows. While water from the tanks directly satisfied ~ 40% of the crop water requirement across the northeast monsoon season via surface water irrigation, a large fraction of the tank water was not available for direct use in the tank's irrigated area. This is because the sluices were not managed properly, and discharged continuously, instead of only supplying water when it was required for irrigation. For the cascade, a distinct spatial pattern in groundwater-exchange dynamics was observed, 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 altered the catchment water balance, with runoff decreasing by nearly 75%, and recharge increasing by more than 40%.

The second major output is a tank water balance model to evaluate the effect of climate versus management controls on tank water dynamics. The model was run with a 65-year long (1906- 1969) rainfall dataset to evaluate climatic controls, while the two primary management controls imposed were those of an alternate planting date, and the management of sluice outflows to discharge only the amount of water needed for the crops in the irrigated area. Following the imposition of management controls, these previously unutilized outflows were converted more effectively into groundwater recharge (24-54%) and sluice outflow to meet crop water requirements (9-54%) than ET (5-21%). For the long-term (65 year) simulation, catchment scale reductions in runoff (60-80%) and increases in recharge (17-53%) were largely dependent on variations in seasonal rainfall, with proportionally larger decreases in catchment runoff for years of higher seasonal rainfall. Additionally, three sustainability metrics were defined, namely reliability (probability of successfully meeting crop water requirements), resilience (likelihood of meeting crop requirements after a year of crop failure), and vulnerability (severity of crop water requirement shortfall during failure years) to explore the effects of management controls on tank system performance. Evaluation of the sustainability metrics revealed sluice management driven increases in reliability and resilience for tanks 1 and 4. In tanks 2 and 3, increased reliability and resilience was found as a result of changes in the planting date. Vulnerability remained largely unchanged except for tank 2 which became less vulnerable following the imposition of management controls.

Acknowledgements

This research is financially supported by the U.S. National Science Foundation (1211968), Dynamics of Coupled Natural-Human Systems and by University of Waterloo start-up funds. The assistance of Dr. K. Palanisami was crucial in establishing connections in India and with his guidance regarding field site selection. I thank the DHAN Foundation for generously sharing their experiences, data, and hospitality during the two field visits that allowed for this project to be carried out. They were the grand facilitator for much of my time in India. Everything from food and lodging to field assistance and use of technical equipment I owe to their careful coordination. In particular, I thank Mr. A Gurunathan for his close attention to my needs and his gracious hospitality. Help from DHAN foundation field personnel was also most appreciated. Unparalleled support (logistically, technically, and culturally) was given by Mr. Rajsekaran; through his intimate knowledge of the local people and environment, blending into village life was made easier and all scientific tasks more achievable.

The hospitality of T. Ramanathapuram was essential; especially Ramar, Jaylakshmi, and their children Keerthana, Nanthini, and Sambat. Through their kindness, my wife Nicole and I were taken care of and immersed within rural south Indian culture. Language lessons from the children and many others gave me the ability to converse with farmers albeit rudimentarily. Of these farmers, the closest bond was struck in Pappanaickenpatti. I thank them for accepting us into their lives, for their patience, and humor.

Through the course of this work I have been fortunate to have the support and guidance of many. As an advisor, Dr. Nandita Basu surpassed all expectation of what a student could hope for. A careful understanding of how and when to give the appropriate guidance gave me the academic freedom to explore while not straying too far from the main course. The fieldwork portion of my study was a critical representation of this freedom. Words cannot express my appreciation for the literal day-and-night assistance via rooftop skype conferences despite a multitude of external variables.

Dr. Daniel Mclaughlin instilled the momentum necessary for carrying out the practical aspects of conducting field work. His expertise both in the field and afterwards in the interpretation of data was invaluable for moving the study forward. I thank Terry Ridgeway for trusting a long-haired graduate student with an expensive datalogger for four months in rural India. Likewise, I am indebted to the geospatial expertise of Eric Tate and Joe Wykoff. Without the GPS equipment provided by Eric, surveying would have been orders of magnitude more difficult.

To Kim, Xiaoyi, Tejasvi, Idhaya, and Fred I am grateful for your patience and thought provoking conversation through many long days and nights in the office. Your input no doubt shaped my study for the better.

Finally, I thank my family for their support through what has been, no doubt, an eventful process. My wife Nicole, quite literally drove this study forward. In the field her assistance resulted in more coordinated data collection, sensor installation, and all other tasks. For her constant help and support, I am fortunate, grateful, and humbled.

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Chapter 1

Introduction

"All over the world people are saying, "We have not got enough water and thus we have a water crisis." However, the main problem is not physical scarcity of water, but its continued mismanagement! Unless water management can be improved significantly, the world's water problem cannot be solved. "

—*Asit Biswas*

1.1 Background and Motivation

Humankind has been shaped by a relationship with water, both prosperous and destructive (Grey & Sadoff, 2007a). Livelihood and life itself exist in a delicate balance with this essential resource, the nature of which is perhaps understood most clearly during extremes. Extremes of drought and flood, of disease and poverty all certainly keep our knowledge of water and its importance in check. "When the well is dry, we know the worth of water" (Franklin, 1746). Scarcely has this notion been more evident than now. Issues of water stress are now estimated to impact more than one-third of the global population, and it is predicted that this fraction will nearly double as the world reaches peak population (Wada, Gleeson, & Esnault, 2014). Such increases in water stress are driven not only by a growing population, changing patterns of food consumption, and climate-driven changes in water availability (Wiltshire et al., 2013), but also by spatial and temporal mismatches between water availability and water demand (Oki, 2006). From a spatial perspective, regional per capita water availability can vary drastically from more than 50,000 m^3/year to less than 500 m^3/year (Parish, Kodra, Steinhaeuser, & Ganguly, 2012; Wada et al., 2014), with levels of water stress in one basin having little impact on that in another. Similarly, temporal mismatches, particularly in areas with high seasonal rainfall variability, can create high rates of runoff leading to flood events and high short-term availability during wet seasons, followed by severe water stress during dry periods (Haile, 2005). For these reasons, the capture and storage of rainfall and or runoff during the wet season is particularly important (Myers, 1967). Commonly achieved using surface water structures, this storage is essential since temporal mismatches, paired with a shortage of surface-water storage, has been linked to both reduced incomes and a lack of food security (Gohar, Ward, & Amer, 2013; Grey & Sadoff, 2007b).

As a result of such circumstances, techniques of rainwater harvesting (RWH) are used in many parts of the world to generate, collect, and store rainfall and runoff for later productive use (Glendenning et al., 2012; Siegert, 1994). In general, RWH involves linking areas where runoff is generated with areas where runoff is collected and stored (Boers and Ben-Asher, 1982). Such harvesting ranges in scale from an individual roof or field, in which rain is collected and used where it falls, to the micro and macro watershed scale where runoff generating areas are distinct from areas of runoff storage (Rockstrom, 2000; Mbilinyi et al., 2005). Rainwater harvesting has been applied extensively for meeting domestic needs (Handia et al., 2003; Kahinda et al., 2007), providing supplemental irrigation (Jayatilaka et al., 2003; Ngigi et al., 2007), and recharging groundwater aquifers, (Kumar, Ghosh, Patel, Singh, Ravindranath, et al., 2006) among many other uses (Ganesan, 2008).

In recent years, interest in the application of RWH for augmenting groundwater supplies has increased (Shah, 2008; Vohland & Barry, 2009). This attention has been largely in response to alarming levels of groundwater depletion afflicting regions of both the developed (United States and Europe) and developing (China, India, Middle East) world (Döll et al., 2014; Wada et al., 2010). Groundwater depletion in India, for example, has been particularly severe due to population growth and increased agricultural demand (Rodell et al., 2009).

Characterized by both spatial and temporal mismatches in water stress and availability, the climatic regime of India is favorably suited to RWH. The monsoon-driven climate common to semi-arid areas of India results in remarkable temporal variation where it is common for half of the year's total rainfall to fall over a period of only twenty hours (Keller, Sakthivadivel, & Seckler, 2000). With such extreme intra-annual rainfall variability, there have been ongoing efforts in India to increase storage capacity and additional water supplies for agricultural production and economic development (Grey & Sadoff, 2007b). Over the last century, such efforts have focused primarily on large-scale projects designed to ensure higher levels of water storage and availability such as the building of large dams and canal systems (Cullet & 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, Basu, Tate, & Wyckoff, 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 & Krishnamurthy, 2003), are built along natural depressions in the landscape. Historically, tanks have been designed to meet the water needs of subsistence-level farmers for rice production via managed sluice channels for irrigation (Farmer, 1977). Furthermore, tanks are often linked in a cascade with overflow from the upstream tanks spilling into surplus channels that lead to downstream tanks. While these systems have traditionally been very important to communities, many have over time been degraded, primarily as a result of increased reliance on groundwater pumping (Mosse, 1999), and cheap access to electricity. This 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, Patel, Ravindranath, & Singh, 2008a; T. Shah, 2004a). In response, efforts have been undertaken to restore tanks to facilitate more groundwater recharge and reduce groundwater depletion (Shah, 2008). However, the hydrologic impact of tanks and their restoration, specifically for augmenting groundwater storage, is still not well understood (Glendenning et al., 2012).

1.2 Structure and Function of Rainwater Harvesting Tanks

Tanks in South India are created through the construction of an earthen dam (bund) across depressional areas in the landscape as a means of storing surface runoff (Van Meter et al., 2014) (**Figure 1.1-a,c**). At the peak of the monsoon season, flooding often 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) constructed within the tank bund 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) (**Figure 1.1b**). Groundwater wells typically exist in this command area and are recharged annually by water from the tank (Glendenning & Vervoort, 2010a). In addition, when tank water levels decrease to below the sluice invert elevation, the water remaining is referred to as the dead storage (**Figure 1.1b**), which leaves the tank primarily by groundwater recharge and evapotranspiration.

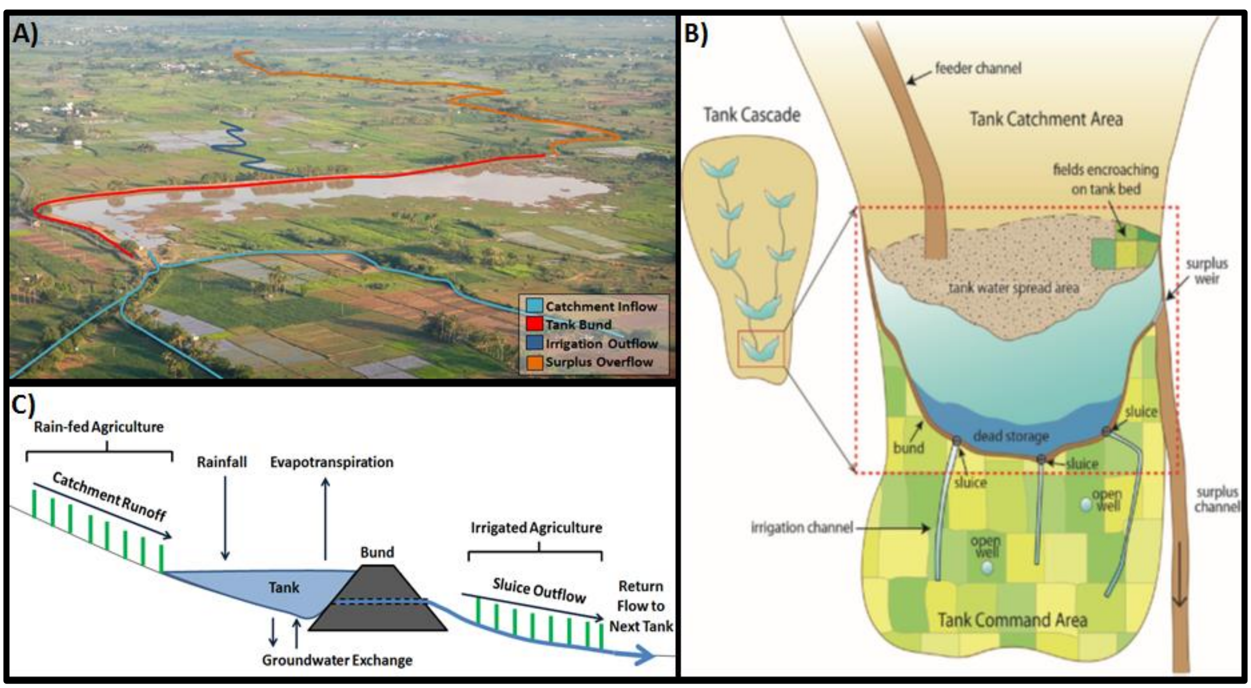

Figure 1.1: Components of a Tank system (A) Aerial view of Tank 1 in the TS cascade; (B) plan view of typical tank along with catchment and command area; (C) cross section of tank water budget components.

Arrival of the southwest (June) and northeast (October) monsoon rains generate runoff in the tank catchment area (**Figure 1.1b**) that are collected by feeder channels that convey water to the tank. Here, arrival of the northeast monsoon and filling of the tank in October allows for the cultivation of paddy, the staple crop of the area. After the October filling, water remains in the tank for four to six months, leaving the tank by sluice outflow, evapotranspiration, and groundwater recharge, (Matsuno et al., 2003) (**Figure 1.1-a,c**). Any excess storage spills over the tank's overflow weir into surplus channels leading to downstream tanks or to nearby waterways (Van Meter et al., 2014). In this way, tanks are often linked in chains, or cascades, (**Figure 1.1b**) creating a vast hydrologic network of tanks and water courses. With some cascades comprising of as many as 100 tanks, these systems truly define this intensively managed agricultural landscape (**Figure 1.2**).

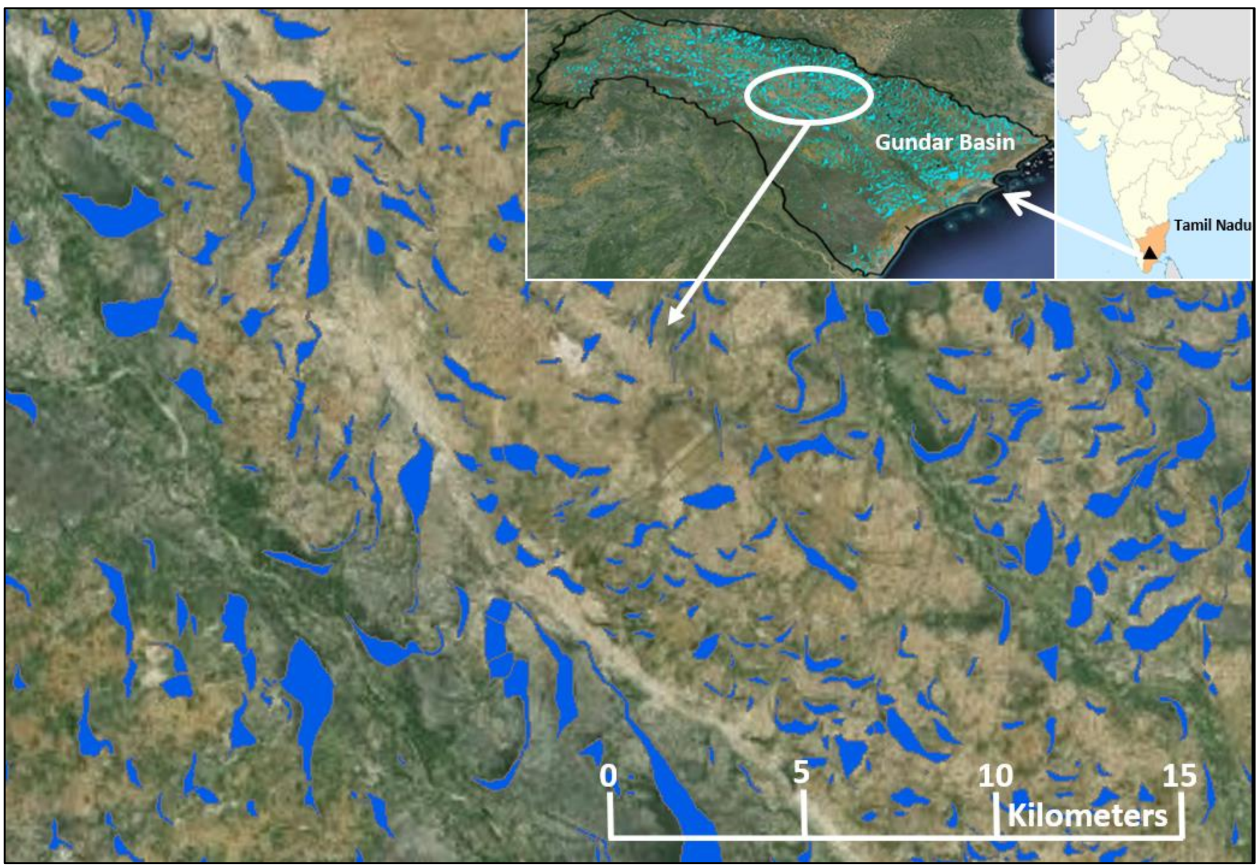

Figure 1.2: Tank systems, as seen through a remote sensing image, are ubiquitous throughout South India.

Tanks have not only been a source of water to these communities for millennia, but provide many economic, cultural, and ecological functions (**Figure 1.3**). Economically, the tanks allow for subsistence as well as market agriculture to be sustained across 61% of Tamil Nadu's land area (Season and Crop Reports, 2004). Tanks also add substantially to the wetland and aquatic richness of India (Prasad et al., 2002), and are the nucleus of human-made ecosystems traditionally managed by an association of community members (Sakthivadivel et al., 2004). Moreover, tanks play vital social and cultural roles in communities, especially in rural areas (Ganesan, 2008;Oppen,and Rao, 1987).

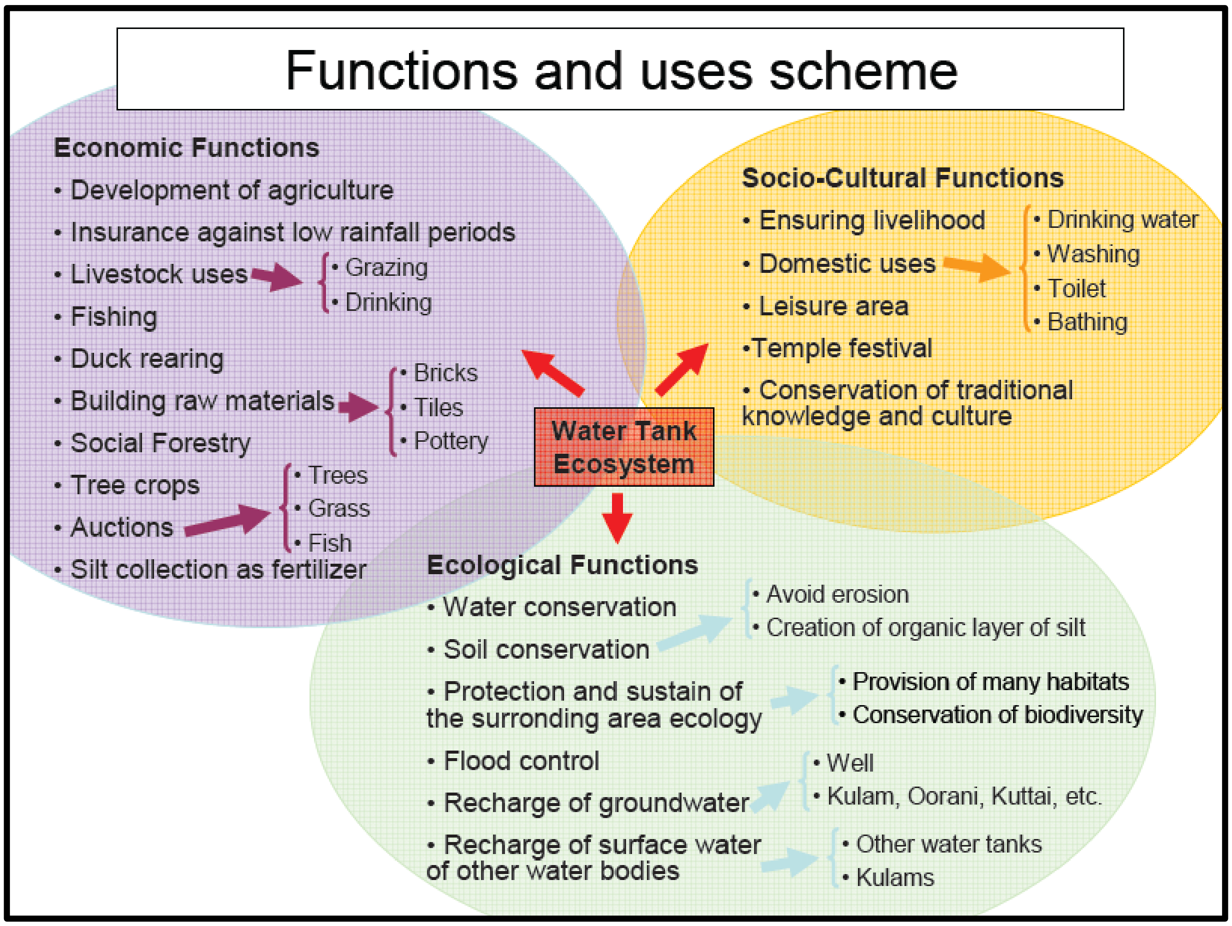

Figure 1.3: Functions and Uses of Tank Systems: Economic, Socio-cultural, and Ecological (Ariza et al., 2007).

At the local scale, it is evident tanks are the central hub of village activity. Festivals held after tank filling often celebrate opening of the tank sluice, showing a close connection between tanks and local communities (Ariza et al., 2007). Use of tanks for domestic purposes (**Figure 1.4b**), leisure activities and generally as a gathering place, demonstrate their social importance (Ariza et al., 2007).This socio-cultural role extends further with the acknowledgement of tanks as sacred places where Hindu rituals and celebrations take place (Shah, 2012). Temples constructed within the embankment are believed to protect the bund from breaching (**Figure 1.4d**). As a result of this cultural connection, tanks and temples have become nearly inseparable (Ganesan, 2008).

Figure 1.4: Multiple Tank Uses. A) Irrigation of paddy fields B) Domestic water use, C) Goats grazing in tank waterspread area, D) Temple in tank bund, E) Tree production in tank waterspread area, F) Silt removal for bund rehabilitation, G) Migratory Avian Habitat, H) Fishing from the tank.

From an economic perspective, tanks are most commonly recognized as structures to provide agricultural irrigation water. However, tanks provide a myriad of other economic benefits (**Figures 1.3, 1.4**) (Palanisami & Meinzen-Dick, 2001a). Among these uses is the extraction of silt from the tank bed for use as fertilizer, brick making, and bund strengthening (Palanisami et al., 1997; Reddy, 1991). While this extraction is beneficial, it is also necessary since annual deposition of silt in the tank bed reduces tank capacity over time if left unaddressed (Bandyopadhyay, 1987). Additionally, the planting of trees in the bund provide benefits including wood for fuel, bund stability, and income from fruit production (Pandey, 2000). Use of the tank area for livestock watering and grazing land similarly extends the economic function of tanks (Anuradha et al., 2009).

Further, tanks provide important socioeconomic and cultural benefits in addition to sustaining the local ecology through provision of habitat (Palanisami & Meinzen-Dick, 2001a). During the four to six month period following the monsoon season, tanks in South India are essentially seasonal wetlands and maintain a rich palette of biodiversity including both aquatic and terrestrial species (Prasad et al., 2002). Benefits of soil and water conservation are also made possible by tanks. The conservation of water in particular helps to buffer between drought and flood in addition to recharging groundwater (Pandey et al., 2003; Shankari, 1991). As will be discussed in the next section, many of the aforementioned relationships no longer exist in tanks and have been eroded over time through various processes (Agarwal & Narain, 1997).

1.3 History of Rainwater Harvesting in India

In India, tanks have evolved substantially in both extent and sophistication since earliest documented use around 4500 B.C. by people of the Thar Desert region, Rajasthan (Pandey et al., 2003). In Tamil Nadu, Pandey et al. 2003 notes literature from the Sangam period (150 B.C – 200 A.D.) as the first mention of tank irrigation. Historical records suggest developments in RWH practices accelerated during extended periods of drought (Pandey et. al. 2003). As an example, a text known as the Brihat Samhita was written around 575 AD following a period of severe monsoon failures, and includes details for the construction of rainwater harvesting tanks. Expansion of tanks continued through the medieval period (750 -1300 A.D.), during which general methods of tank operation such as collective management and desiltation practices were formalized (Pandey et. al. 2003).

By the mid-17th century however, colonial rule began to modify the existing social and physical landscape; notably through the construction of perennial irrigation structures like canals and assertion of proprietary rights over common resources (D'Souza, 2006; Mosse, 2003). Elizabeth Whitecombe suggested these perennial irrigation schemes led to the destruction of traditional water sources in Northern India, resulting in large social and economic equity gaps (Whitcombe, 1972). Similarly, tank systems in Bihar have been shown by numerous sources to have broken down following assertion of colonial revenue policies (Sengupta, 1980). It follows that the complex pre-colonial relationships between water and society were greatly influenced by the institution of colonial rule (D'Souza, 2006).

The decline of tank irrigation in south India has been hypothesized to be caused by an amalgamation of factors including increased soil erosion from deforestation, tank bed encroachment, intensified crop regimes, siltation, and an increase in the use of private groundwater wells (Mosse, 1999). Of these factors, expanding groundwater use has perhaps had the most drastic effect on the state of the tank systems. In fact, well expansion has mushroomed since 1960 with the number of wells in India increasing approximately two hundred fold (Shah, 2004). Increased access to diesel and electric pumpsets as well as cheap electricity has been a driving factor in the expansion of groundwater irrigation. (Barnes and Binswanger, 1986; Palanisami & Meinzen-Dick, 2001). Economic development and agricultural productivity in particular have benefited as a result of this groundwater irrigation, with yields increasing 1.2-3 times (Mukherji & Shah, 2005). While the expansion of groundwater use has improved livelihoods and offered more precise control over irrigation, groundwater depletion has been the result throughout much of India (Janakarajan & Moench, 2006). In many districts of Tamil Nadu, groundwater extraction now exceeds 100% of the natural groundwater recharge (**Figure 1.5b**). As such, approximately one third of Tamil Nadu's groundwater resources are identified as over exploited (Central Ground Water Board, 2012). Furthermore, roughly 12% of the 1.8 million wells across Tamil Nadu are dry, with much higher percentages occurring locally (Calder et al., 2008; Palanisami et al., 2008).

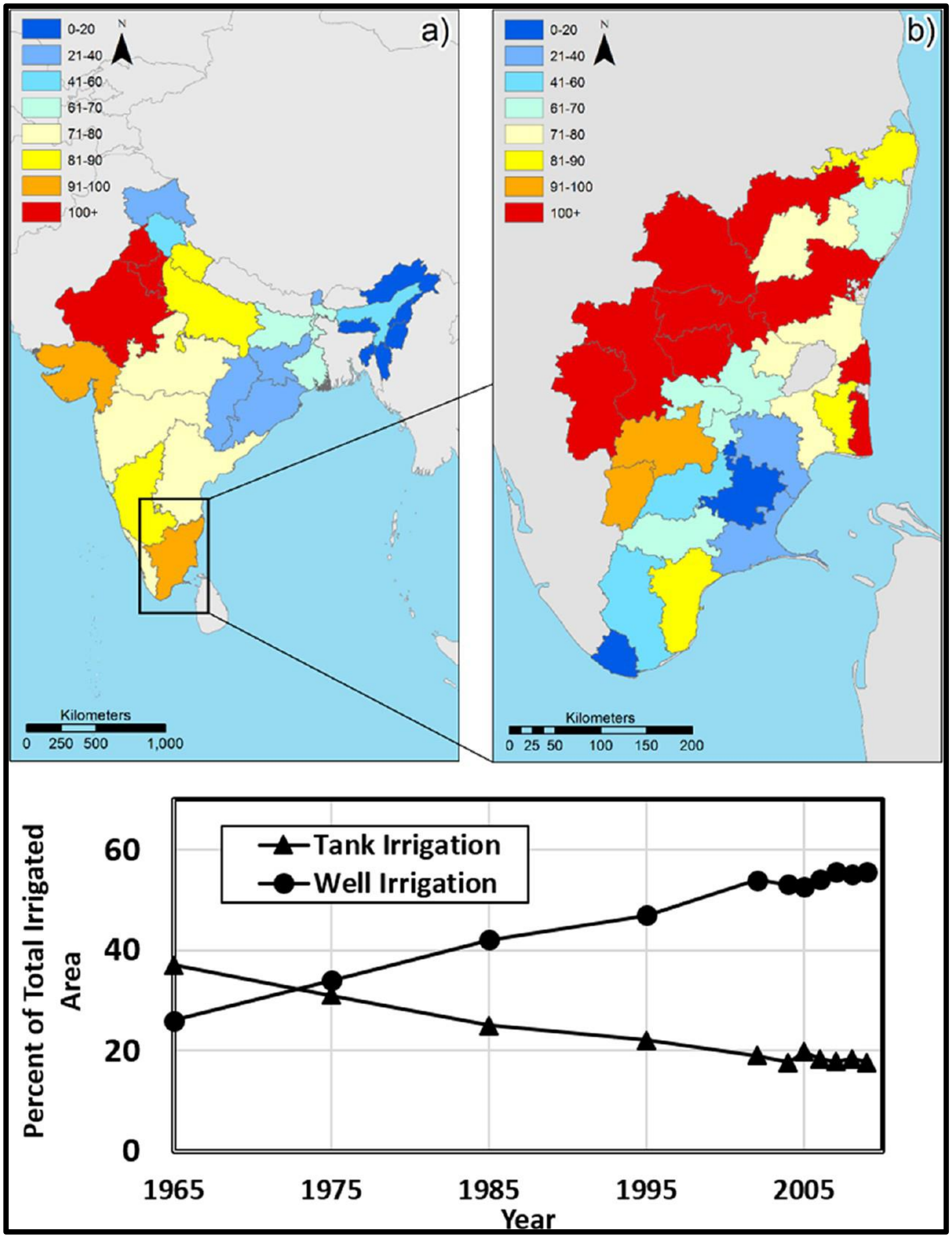

Figure 1.5: Groundwater Withdrawals and Tank Irrigation Decline (Van Meter et. al. 2014). Groundwater withdrawals as a percent of recharge across A) India and. B) the Indian state of Tamil Nadu. C) The percentages of land irrigated by tanks and wells in relation to the total irrigated area with canals and rivers accounting as additional irrigation sources. Note that the high levels of depletion within the state are a result of the expansion of well irrigation, at the expense of traditional tank systems over the last 50 years.

Rapidly expanding use and depletion of groundwater has occurred in tandem with the decline of tank systems. It has been estimated that the area under tank irrigation has decreased from 900,000 to 500,000 ha over the last 40 years (Amarasinghe et al., 2009), being essentially replaced by well irrigation (**Figure 1.5**) (Van Meter et al. 2014). Increased dependence on groundwater extraction has led to the erosion of traditional water management institutions, decline in tank maintenance, and the siltation and encroachment of tanks (Reddy & Behera, 2009). The combination of tank decline and rampant groundwater depletion has created negative environmental and socio-economic feedbacks that acutely affect poor and marginal farmers dependent on groundwater irrigation for maintaining food security (Anantha, 2013; Janakarajan & Moench, 2006).This dual degradation of both groundwater and tanks systems has drawn attention to the need for rehabilitation and a better understanding of the system as a whole (Sakthivadivel et al., 2004).

In recent years, numerous organizations have been involved in the rehabilitation of tanks. One such organization is the non-governmental organization (NGO) called the DHAN Foundation. The DHAN Foundation was the partner institution for this study and is involved extensively in the rehabilitation of tanks. In general, rehabilitation has been done most successfully by addressing degradation of the physical tank components as well as the traditional management institution (Sakthivadivel et al., 2004). Restoration of tank systems have been documented to have significant impacts, including increases in food security and social equity (Deivalatha & Ambujam, 2011; Ngigi, 2003a). Environmental benefits such as augmentation of groundwater levels and stream base flow have also been observed in response to tank restoration (Palanisami et al., 2010). Conversely, negative impacts such as reduced farmer income and increased social inequality have been associated with tank decline (Kajisa et al., 2007). Although rejuvenation efforts have increased, evaluation of the hydrologic impacts of tank rehabilitation on groundwater recharge is lacking (Hope, 2007; Sakthivadivel, 2008).

1.4 Need for the Study

Tank systems have fallen into decline in recent decades, primarily as a result of increasing reliance on groundwater pumping, and cheap access to electricity. However, dropping groundwater levels and a growing demand for increased agricultural production have led to a revival of interest in these traditional systems (Kumar et al., 2008). Although the majority of existing RWH tanks remain in a state of disrepair (Anbumozhi et al., 2001), at an all-India scale it is estimated that RWH systems could add as much as 125 km^3 per year to the country's current water supply, making them critical in meeting the projected water shortfall of 300 km^3 per year in 2050 (Gupta & 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.

While recent efforts have contributed to a revival of RWH structures in India (Agarwal and Narain, 1997; Shah et al 2009), there still exists a significant knowledge gap regarding the socioeconomic and environmental sustainability of these structures (Bouma et al., 2011; Bouma et al., 2007). It is also not well understood whether these ancient structures would 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, groundwater 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). 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, van Ogtrop, Mishra, & Vervoort, 2012b; Neumann, MacDonald, & Gale, 2004; Ngigi, 2003b).

Among these water fluxes, groundwater recharge is of particular importance. Unfortunately, there is a lack of field studies that quantify the recharge potential of these systems, especially at the scale of watershed comprising of multiple tanks (Glendenning et al., 2012b). One reason for the lack of information is that recharge is highly spatially variable, and thus difficult to adequately measure at the field scale (Glendenning et al., 2012b). Most previous studies estimate recharge using the water-balance method (Badiger et al., 2002; Glendenning & Vervoort, 2010; Massuel et al., 2014; Perrin et al., 2010; Raju, 1998; Sharda et al., 2006; Sukhija et al., 1997). However, recharge is one of the most difficult components of the water balance to measure, especially in arid environments, where recharge magnitude is small compared to other fluxes (Bond, 1998). As a result, estimates made using water balance residuals are vulnerable to errors in other measured components. Furthermore, the water-balance methods used in RWH tanks estimate recharge using modeled values of evapotranspiration, another rarely measured but critically important water flux in these arid environments. While there is a 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., 2012a).

1.5 Study Objectives and Chapter Organization

The overall intent of this study is to provide a better understanding about how tanks function in the landscape both locally in partitioning stored water to groundwater recharge (GE), evapo-transpiration (ET), and sluice outflow (S_o) as well as for altering basin scale water availability. This study focuses on a tank cascade comprising of four connected tanks in the Gundar basin watershed in the south Indian state of Tamil Nadu. The study has three closely related sub-objectives: (1) evaluate the potential of a novel approach (the White Method) to estimate temporal patterns in groundwater exchange and evapotranspiration over the Northeast monsoon season; (2) describe spatial patterns of groundwater exchange and evapo-transpiration fluxes from upstream to downstream tanks in a cascade, and (3) adapt a tank water balance modelling approach to simulate changes in the ability to manage tank sluice outflow under changing climatic conditions.

In Chapter 2, a literature review of the available field techniques for measuring recharge from rainwater harvesting structures is provided, as well as the modeling studies that describe these systems. In Chapter 3, the focus is primarily on the field methods and data analysis using the White method to quantify temporal patterns in water fluxes from tank systems. The data is analyzed to explore the following questions:

- At the local scale, how do tanks partition water, and what is the spatial variability in this partitioning behavior along a tank cascade?
- At the catchment scale, how do tanks alter the water balance in a basin?
- What percentage of the irrigation requirements do tanks meet, and can they be managed more efficiently to increase this fraction?

In Chapter 4, a tank water balance model is developed that can capture the temporal dynamics observed in the four tanks in the cascade. The model is used to answer the following questions:

- For the 2013 NE monsoon season, can changes in management affect the ability to meet irrigation requirements for individual tanks and along a tank cascade?
- For a 65 year simulation, how do changes in management effect tank system sustainability, and the water balance in a basin?
- Considering a long time series of rainfall inputs, can changes in management significantly affect the sustainability of the tank ecosystem?

Conclusions and Recommendations are provided in Chapter 5.

Chapter 2

Literature Review

"The basis of discovery is imagination, careful reasoning and experimentation, where the use of knowledge created by those who came before is an important component."

—Bengt Ingemar Samuelsson, Swedish Biochemist

2.1 Introduction

In this chapter existing literature is synthesized which examines the hydrological impacts of RWH systems on groundwater and surface water systems to identify knowledge gaps. A description of the modeling studies that have estimated local and watershed scale impact of RWH structures on groundwater and surface water systems is also presented. Finally, recognizing that field data availability is a primary limitation of previous studies and the reason modelled ET values are commonly used, the White Method is described as an innovative approach to estimate the daily evapotranspiration and recharge fluxes from RWH tanks.

2.2 Field Methods to Estimate Groundwater Recharge

Three methods have generally been used to estimate recharge in the field; the water balance method, the water table fluctuation method, and geochemical analysis. In general, these methods rely on measurement of changes in either the geochemistry or water level of ground or surface (tank) water to assess the impact of tanks on groundwater. A combination of methods has also been used.

2.2.1 Water Balance Method

The water balance method is the most commonly applied way of estimating groundwater recharge by RWH structures (Glendenning & Vervoort, 2010; Massuel et al., 2014; Perrin et al., 2010; Raju, 1998; Sharda et al., 2006; Sukhija et al., 1997). In this method, all the different tank water fluxes are measured or estimated except groundwater recharge, allowing for recharge to be calculated as a residual component of the water balance. The CGWB (Central Ground Water Board) quantified the recharge from nine RWH structures in Tamil Nadu, and found the proportion of recharge to be 67-94% of total outflow (Raju, 1998). However, in that study, outflow for supplemental irrigation was noted to occur but not measured, likely contributing to higher values of recharge as a percent of total outflow. Perrin 2010 followed a similar procedure and found the recharge from two RWH structures to be 40-65% of tank capacity. The accuracy of the water balance method is dependent on the accuracy of estimating the other fluxes. Evapotranspiration is perhaps the most important and difficult to estimate of these fluxes (Sukhija et al., 1997), and therefore modeled evapotranspiration values are often used rather than direct measurement. This use is driven largely by the difficulties and expense associated with traditional methods of estimating ET in the field (Pan Evaporation and eddy covariance), especially in remote areas. Pan evaporation data has been used by a number of the reviewed studies and most commonly obtained from a nearby meteorological station (Perrin et al., 2010a; Sharda et al., 2006a; Sukhija, Reddy, Nandakumar, et al., 1997). Application of pan evaporation data in this manner has been shown by (Lowe et al., 2009) to have large uncertainties of up to ±40% of best estimates. However, a significant reduction in uncertainty can be achieved by installing the evaporimeter at the water body itself. In line with this methodology, estimation of evaporation by (Massuel et al., 2014a) was done using a Class A evaporation pan installed at the study tank.

2.2.2 Water Table Fluctuation Method

In this method, measurement of changes in well water levels downstream of the tanks is used in conjunction with a groundwater balance to infer the relative contribution of tanks to groundwater. This method requires an estimate of the natural recharge rate when tanks are not present, and also data on aquifer specific yield that can be either assumed (Glendenning & Vervoort, 2010a) or calculated (Sharda et al., 2006a). Badiger et al., 2002 measured well water level changes for a watershed in Rajasthan, concluding recharge from the nearby RWH structures was roughly 3-8% of annual rainfall. In a similar manner, Gontia and Sikarwar 2005 estimated an 8m rise in groundwater for a region of Gujarat, assuming the rise was caused by RWH structures. One drawback of this method is that measurements are not always taken in the actual tanks, which makes the source of water unclear (Badiger et al., 2002). A combination of the water balance and the well water fluctuation method has been used in many studies (Glendenning & Vervoort, 2010a; Massuel et al., 2014a; Sharda et al., 2006a). Using this approach, Sharda et al. 2006 estimated the potential recharge for a number of RWH structures in Gujarat to be around 11% of annual rainfall. Glendenning and Vervoort 2010 followed a similar approach for four RWH structures in Rajasthan, estimating recharge from the structures to be 1.3-16.4% of total rainfall. Further, Massuel et al. 2014 found 61% of total outflow to be recharge for a RWH structure in Andhra Pradesh.

2.2.3 Geochemical Analysis

The contribution of tanks to groundwater has also been evaluated by tracking changes in the chlorine concentration of tank water(Sukhija et al., 1997). Here, tank water is assumed to leave through evapotranspiration and groundwater exchange while chlorine exits the tank system by only groundwater exchange. Similarly, measurement of geochemical signatures (Chloride (Cl^-) and stable isotope ratios of oxygen $\delta^{18}O$, which are common environmental tracers) in water from wells downstream of tanks have been used to estimate the proportion of groundwater contributed by tanks (Stiefel et al., 2009). For these measurements the signature of tank recharge must be distinguished from that of natural recharge. By analyzing threse hydrogeochemical signatures for well water downstream of tanks, Stiefel 2009 found that up to 75% of groundwater could be contributed by tank recharge. However, the contribution was variable and locally dependent on differences in hydraulic conductivity (Stiefel et al., 2009). Geochemical tracers like chloride was used by Sukhija 1997 to directly measure groundwater recharge and evapotranspiration from a RWH structure in Andhra Pradesh. Recharge by the RWH structure ranged from 22-35% of the tank volume based on geochemical analysis while parallel use of the water balance approach, resulted in a recharge estimate of 49% across the 2 year study period. In addition, Sharda et al. 2006 used a geochemical approach combined with a groundwater balance and found the recharge by RWH structures to be about 7.5% of rainfall.

Results of the reviewed field studies demonstrate the complexities and high variability associated with estimating the impact of tanks on groundwater recharge. The water balance method, applied most commonly, is dependent on modeled evapotranspiration values where accurate representation of site conditions can be an issue. Similarly, geochemical methods can allow for distinguishing between different groundwater sources but the results obtained are temporally limited and location dependent. Further, the use of a modeling approach can be advantageous, particularly in remote and data sparse regions, but results are limited by data underlying the model. Therefore, an alternative approach was used in the present study to mitigate the inherent limitations of existing methods and provide a novel method for assessing tank hydrologic impact.

2.3 The White Method: Innovative Approach for Simultaneous Estimation of ET and Recharge

The White (1932) method, which was originally developed to estimate the magnitude of groundwater consumption by phreatophytes (Loheide et al. 2005), has more recently been utilized as a cost-effective means of obtaining spatially integrated, direct measurements of both ET and groundwater exchange in surface waters (McLaughlin & Cohen 2013; Loheide & Steven 2008; Loheide et al. 2005; McLaughlin & Cohen 2014). Rushton 1996 applied the White method to estimate net groundwater exchange and ET for a 3 acre marsh in central Florida, concluding estimation errors were minimal when checked against mass balance calculations. Similarly, Hill and Neary 2007 studied an isolated seasonally inundated wetland, and it was concluded that high ET rates can occur in response to contrasting roughness and moisture conditions (oasis and clothesline effects). Most recently, McLaughlin and Cohen 2014 used the White method to understand the groundwater exchange dynamics of several isolated wetlands in northern Florida. Here, it was demonstrated that infiltration dominated the overall groundwater exchange. However, frequent switching between infiltration and exfiltration was also observed with exfiltration occurring for several days after large rain events.

The White method is based on two central assumptions: (1) that ET (cm/d) fluxes are negligible at night, enabling groundwater flows to be estimated from nighttime stage changes, and (2) there is no diurnal variation in the groundwater exchange; (cm/d). Based on these assumptions, ET and groundwater exchange can be determined based on the difference in the rates of water level change between the nighttime and daytime periods, according to the following equations:

$$ET = S_y * (24h \pm s) \qquad \text{Equation 2.1}$$

$$Groundwater\ Exchange = S_y * (24h) \qquad \text{Equation 2.2}$$

Where S_y is the specific yield (dimensionless), h (cm/hr) is thel linear slope of the nighttime decline between 0:00 and 5:00 hours corresponding to groundwater exchange (uncorrected for S_y), and s (cm/day) is the net water level decline (+) or rise (-) over 24 hours (McLaughlin & Cohen, 2014a)

(**Figure 2.2**). Specific yield (S_y) is defined as the fraction of water being released from or added to storage in porous media divided by the total system (Healy & Cook, 2002). On a per unit area basis, S_y represents the input (rain) or output (ET) depth divided by the observed change in the water level.

Specific yield is commonly assumed equal to 1.0 for flooded areas areas (Mitsch & Gosselink, 2007) but this assumption merits careful evaluation (McLaughlin & Cohen, 2014a). Assuming a specific yield of one was justified for the tanks of this study due to the minimal presence of vegetation.

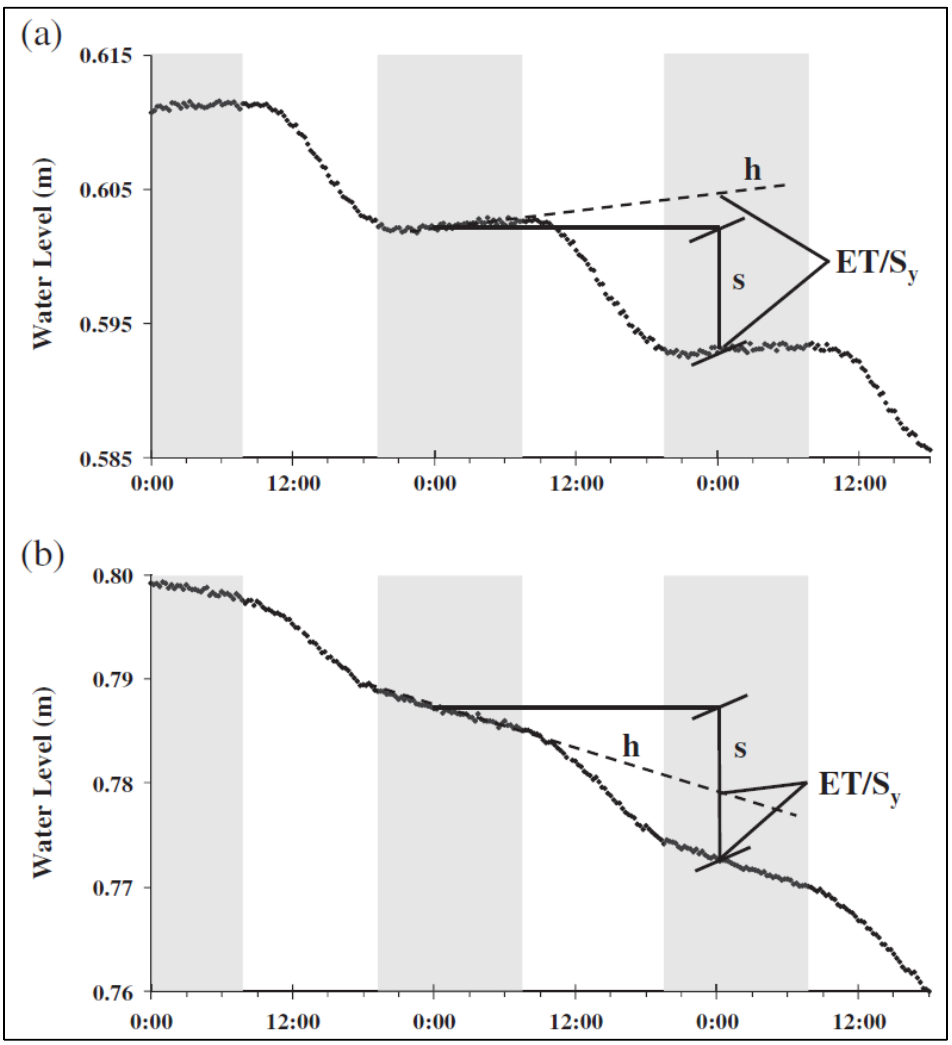

Figure 2.1: Diurnal water level fluctuations showing the cases of groundwater (a) exfiltration, and (b) infiltration. Nighttime periods are signified using gray bars (McLaughlin & Cohen, 2014b).

2.4 Models for estimation of local and watershed scale impacts of RWH tanks

As described above, field estimation of groundwater recharge can be difficult, expensive, and time consuming. As a result, modeling has been viewed as a favorable means to understand the impacts of RWH structures, particularly at the watershed scale. A number of modeling approaches have been applied to RWH systems including numerical modeling (Massuel et al., 2014), water balance models (Glendenning & Vervoort, 2010b); (Gore et al., 1998; Jayatilaka et al., 2003; Pandey et al., 2011), and lumped watershed models such as TEDI (Tool for Estimating Dam Impacts). Additional modeling approaches such as HYLUC (Hydrological Land Use Change) model (Calder et al 2008), and ROSES (Reservoir Operation Simulation Extended System) (Sakthivadivel et al., 1997) have also been used.

Water balance models have been the most common modeling approach used for estimation of groundwater recharge from RWH structures (Glendenning & Vervoort, 2010; Gore et al., 1998; Jayatilaka et al., 2003; Pandey et al., 2011; Sharma & Thakur, 2007). For example, Sharma & Thakur 2007 coupled a catchment scale water balance model with remotely sensed land use information and found that the addition of RWH structures in the landscape could potentially reduce runoff by 60% while only improving recharge 5%. It was concluded that a shift toward increased evapotranspiration was the principal change in the water balance. However, this study was conducted in the absence of any field data from the RWH structures. Using a groundwater modelling approach coupled with a water balance model, Gore et al 1998 inferred that RWH increased the total recharge of a watershed by 16%, or an increase of 2% of annual rainfall over the natural recharge rate. While this study was based on field information, no measurements were taken in the RWH structures. Similarly, a watershed scale conceptual water balance model was created by Glendenning and Vervoort 2011 to represent the surface-groundwater interactions for a watershed in Rajasthan. Using field measurements from four RWH structures, it was found that RWH buffered drought years through increasing the reliability of groundwater storage (Glendenning & Vervoort, 2010b).

While water balance models have largely been applied to one or a few isolated RWH structures, the approach has also been applied to a hydrologically connected tank cascade in Sri Lanka (Jayatilaka et al., 2003). In these studies the hydrologic interactions between tanks were simulated, with the resulting model providing a means of predicting water availability in the cascade system to improve agricultural production. Similarly, Pandey et al 2011 developed a simple water balance modeling approach for estimating the water storage and partitioning of fluxes from RWH structures in Texas, USA and West Bengal, India. As will be discussed, this modeling approach was adapted for use in the modeling portion of the present study.

Despite the dominant use of water balances for modeling the water storage in RWH structures, a number of other modeling methodologies have also been used. Lumped water shed models such TEDI and CHEAT have been applied to farm dams in Australia, which are very similar in function to the RWH systems of India (Nathan et al 2005). Using TEDI, Savadamuthu 2002 found the hydrologic impact of farm dams to be high during drier years but relatively small in wetter years. Furthermore, (Calder et al., 2008) applied a version of the HYLUC model adapted for tank cascades, concluding that RWH structures could be the cause of basin closure. Sakthivadivel et al 1997 similarly applied the ROSES model in Sri Lanka to simulate the daily hydrologic behavior for a cascade of fifteen interconnected tanks. Most recently, Massuel et al 2014 applied a numerical modeling approach to a single tank in Andrha Pradesh. Here, it was found that the amount of groundwater pumping downstream of the tank could have a significant effect on the hydraulic gradient of the underlying aquifer and thus influence the contribution of recharge to groundwater by the tank (Massuel et al., 2014).

As mentioned, many of the reviewed modeling studies followed a water balance approach for understanding watershed scale impacts. However, such studies commonly utilized limited field data collected from one or a few RWH structures in order to extrapolate to the watershed scale. Likewise, when applied to the watershed scale, modeling methods such as HYLUC, TEDI, and ROSES share a dependency on limited field data. It follows that without adequate investment in field data, modelling cannot adequately assess the hydrological impacts of RWH structures.

2.5 Summary

Numerous studies have estimated the hydrologic impacts of tanks at the local and watershed scale. These hydrologic impacts have been assessed in many different ways and frequently require the quantification of groundwater recharge and evapo-transpiration. Due to the complexities associated with quantifying these components, a number of methods have been developed. A careful review of previous approaches allowed for limitations in the existing methods to be determined, informing the development of the current study. Due to these limitations, the estimation of groundwater exchange and evapotranspiration in this study was done using the White Method, the execution of which required the collection of several field datasets. In the next chapter, the field portion of this study is described in detail, including methods, analysis procedures, and results.

Chapter 3

Impact of RWH Systems at the Tank and Watershed Scale: Field Study

"In the field one has to face a chaos of facts. They are absolutely elusive, and can be fixed only by grasping what is essential in them. Therefore, field work consists only and exclusively in the interpretation of a chaotic reality."

—Bronislaw Malinowski

3.1 Introduction

Spatial and temporal variance in water availability are a primary driver of water stress, and also characterize the climatic regime of the south Indian landscape. In this region, tank systems have for millennia provided a means of meeting seasonal water demands despite extreme hydrologic variability. While over time tanks have fallen largely into disrepair, increasing interest has been directed towards restoration and evaluation of these structures for enhancing groundwater recharge. Such an evaluation is crucial to understanding how tanks function in the landscape, especially in the face of shifting climatic and anthropogenic controls. In the current study, several questions are posed to further this understanding.

Here, the focus is primarily on the field methods and data analysis using the White method to quantify temporal patterns in water fluxes from tank systems. First, methods used for sensor installations (rain gauges, water level sensors, and barometer) and field data collection (bathymetric surveys, sluice discharge measurement, command well survey, and focus group discussions), conducted from September 13th – December 13th 2013 are described. This data is analyzed to explore the following questions: (1) At the local scale -- How do tanks partition water, and what is the spatial variability in this partitioning behavior along a tank cascade (2) At the catchment scale -- How do tanks alter the water balance in a basin (3) What percentage of the irrigation requirements do tanks meet, and can they be managed more efficiently to increase this fraction?

3.2 Field Methods

3.2.1 Site Selection

Site selection was largely facilitated through a working relationship with the Development of Humane Action (DHAN) foundation, an NGO group leading tank rehabilitation efforts across South India (DHAN, 2010). An initial site visit was conducted in January 2013, during which a cascade of tanks was selected for the study. The Thirumal Samudram tank cascade was determined to be large enough to provide a representative understanding of tank systems while also small enough to do an adequate characterization based on available resources.

3.2.2 Site Description

The study site is located in the South Indian state of Tamil Nadu, in the foothills of the Western Ghats mountain range (**Figure 3.1a**). The region is semi-arid, receiving a mean annual rainfall of 850 mm. Here, rainfall occurs during three distinct periods: the South West monsoon from June to September (25% of annual rainfall), the North East monsoon from October to December (50% of annual rainfall), and the dry season from January to May (25% of annual rainfall) (Government of Tamil Nadu, 2011; Vose et al., 1992). Evapo-transpiration is greater than rainfall from January through July, while it is less than rainfall during the monsoon months (**Figure 3.1b**). For the year in which the field study was done (2013), rainfall over the northeast monsoon season (October – December) was 355 mm, which is slightly less than the 70-year average of 425 mm.

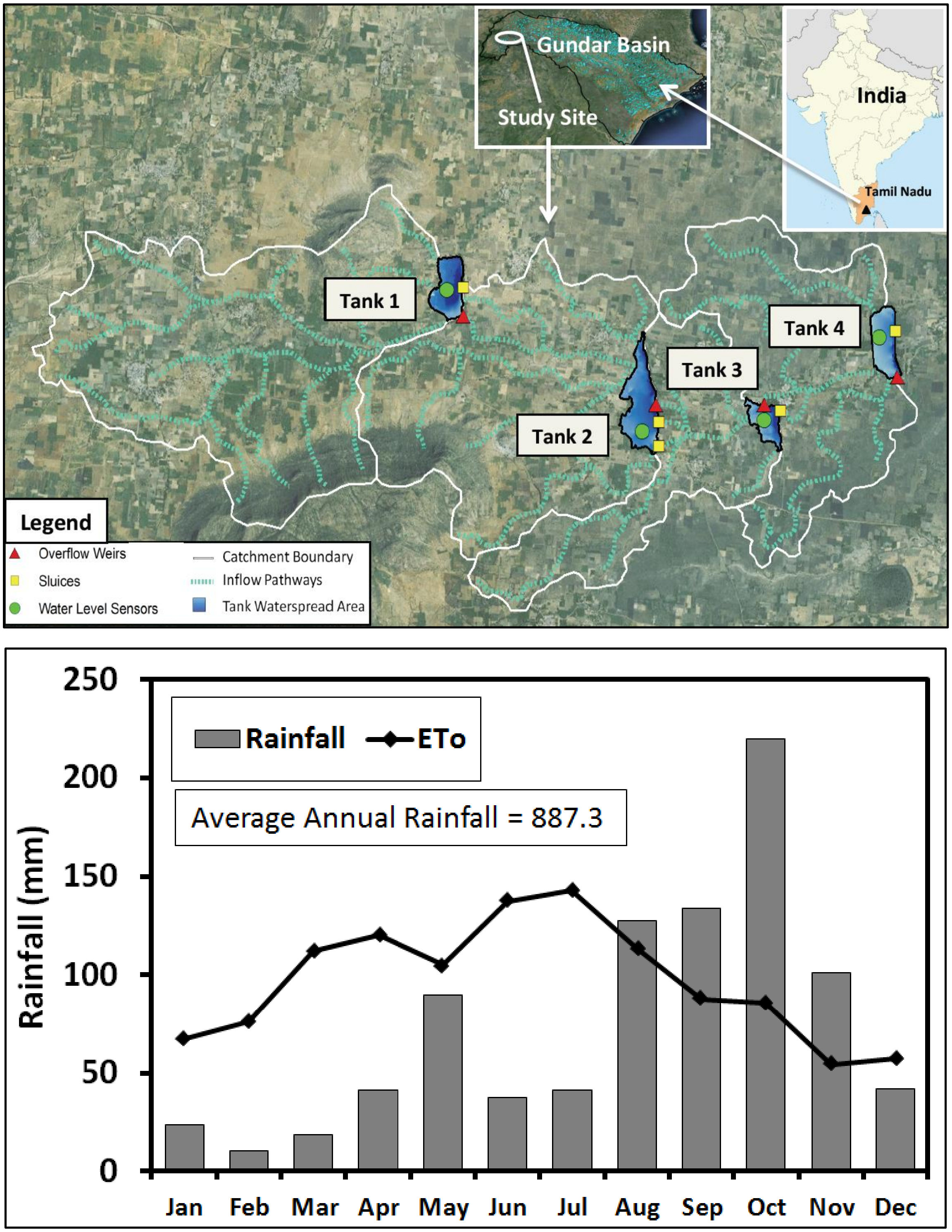

Figure 3.1: a) Location of the Thirumal Samudram cascade within Tamil Nadu. The dotted lines indicate flowpaths calculated based on a digital elevation map (DEM) for the area. Extent and major attributes of the tank cascade and data collection network are also shown. b) Monthly average Rainfall and Potential Evapotranspiration (PET) (1906-1970) measured at Peraiyur weather station, 10 km from the study cascade. PET was estimated as in (Sato & Duraiyappan, 2011) using the penman monteith method.

As noted, the focus of this study is the Thirumal Samudram (TS) tank cascade, a hydrologically connected group of four rainwater harvesting tanks that encompass an overall catchment area of 28 km^2, in the Madurai district of Tamil Nadu near the headwaters of the Gundar river basin (**Figure 3.1a**). All four tanks in the cascade have undergone renovation through a joint effort of local stakeholders and the DHAN Foundation, including regular desiltation, strengthening of tank bunds, and repair of surplus weirs and sluices structures. The four tanks provide irrigation water for three village revenue districts: Pappanaickenpatti (Tank 1), Kudipatti (Tanks 2 and 3), and Ketuvarpatti (Tank 4), from upstream to downstream. The population of the tank cascade area is 6,057 (Government of India, 2011), and 88% of the working population hold jobs either as farmers or agricultural laborers (**Table 3.1**).

Table 3.1: Population and land-use data for the study cascade

Tank #	Village Revenue District	Population				Land Use					
		Total Population	Workforce	Farmers & Agricultural Laborers		Agriculture			Forest	Settlements	Other
				total	% of Workforce	Active	Fallow	Total			
Tank 1	Pappinaickenpatti	3313	1986	1724	87%	48%	25%	73%	16%	2%	9%
Tank 2	Kudipatti	2122	1300	1172	90%	74%	13%	87%	13%	3%	11%
Tank 3						91%	-	91%	-	5%	4%
Tank 4	Ketuvarpatti	622	356	316	89%	99%	-	99%	-	1%	-
Cascade		6057	3642	3212	88%	68%	13%	81%	9%	3%	7%

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 3.2** (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 3.2**), which is characteristic of tank systems found in this area (M. von Oppen, K.V. Subba Rao, 1987; Weiz, 2005). **Table 3.2** also includes measurements made in the present study for comparison (discussed later).

Table 3.2: Summary of tank attributes based on historical tank data (made available by DHAN Foundation) and the current study.

Tank #	Soil Type	Historical				Current	
Tank #	Soil Type	Tank Capacity (m^3)	Maximum Tank Surface Area (ha)	Tank Command Area (ha)	Command Area/Surface Area Ratio	Tank Capacity (m^3)	Current Capacity/ Historical Capacity
Tank 1	Alfisol	357,700	28	27	0.96	276405	0.77
Tank 2	Vertisol	656,500	59	45	0.77	407513	0.62
Tank 3	Vertisol	237,000	20	19	0.93	217633	0.92
Tank 4	Vertisol	168,000	19	24	1.25	139270	0.83

The landscape surrounding the tank cascade has a gentle slope, ranging from 0.5%-1.0%, and is characterized by heavy, clay-rich red (alfisol) and black (vertisol) soils underlain by fractured rock of granitic origin (CGWB 2012; ICRISAT, 1987; Palaniappan et al., 2009) . Land use for the study area is primarily agricultural. Within the study cascade, 81% of the land is devoted to agricultural use, with 42% of this total being irrigated (**Table 3.1**) (DHAN, 2010) . During the North East monsoon season (October-December), paddy (rice) is the primary crop in the region, while during other periods of the year, a variety of other crops are cultivated, including cotton, groundnuts, and pulses (Government of Tamil Nadu, 2011).

3.2.3 Sensor Installations

Rain Gauges

Precipitation was measured using Onset RG3-M automatic tipping bucket rain gauges (Onset Computer Corporation, Bourne, MA) installed near each of the four tanks in the cascade. Installations were done on the land of farmers who had a close relationship with the DHAN foundation. The rain gauges were fixed to a 1 inch diameter metal pipe approximately 5 feet above the ground surface. All installation locations were open field areas sufficiently far away from trees to avoid any interference. Rain gauges were levelled and fixed via zip ties to ensure proper collection of precipitation (**Figure 3.2**). Data from the rain gauges were downloaded approximately every three weeks to make any necessary adjustments.

Figure 3.2: Field installation of Onset RG3-M rain gauge (Automatic tipping bucket) fixed via zip ties to 1” diameter metal pipe.

Pressure Transducers

Tank water levels were continuously measured during and in the months immediately following the 2013 Northeast Monsoon season (October 2013 - February 2014) using total pressure transducers (Solinst Levelogger Edge, accuracy = ± 0.3 cm, resolution = 0.01 cm (Solinst Canada Ltd.)) installed in housing wells at the estimated deepest point of each tank (**Figure 3.3**). The transducers were deployed inside these wells to mitigate the pressures of rapid inundation, protect against contact with livestock, and reduce measurement error from wind.

The pressure transducers measured total pressure (m H_2O) at 5-min intervals, and these measurements were corrected for variations in barometric pressure based on measurements collected at the same intervals using a barometric pressure transducer (Solinst Barologger, accuracy = ± 0.5cm (±.05 kPa), resolution = 0.001 cm (.0001 kPa)). The barometric pressure transducer was installed in a dry well open to atmospheric pressure but below ground to buffer changes in temperature (McLaughlin and Cohen 2011). A central location within the tank cascade was chosen to install this transducer to ensure measurements were as representative as possible. The recommended maximum distance between Barologger and Levelogger installations is noted to be 30 kilometers. All corresponding distance intervals for this study were well within this recommended range.

The tank stage data were verified based on frequent direct stage measurements made at the study site. Pressure transducers were installed on September 26th before the start of the rainy season, and retrieved on January 20th for Tanks 1 and 2, and March 7th for Tanks 3 and 4, generally when wells became dry. In addition, theft of the transducers was a potential concern since they were installed on community land. Through discussions with the DHAN Foundation and conversations with local farmers, assurance was given that the transducers would be protected by the farmers themselves.

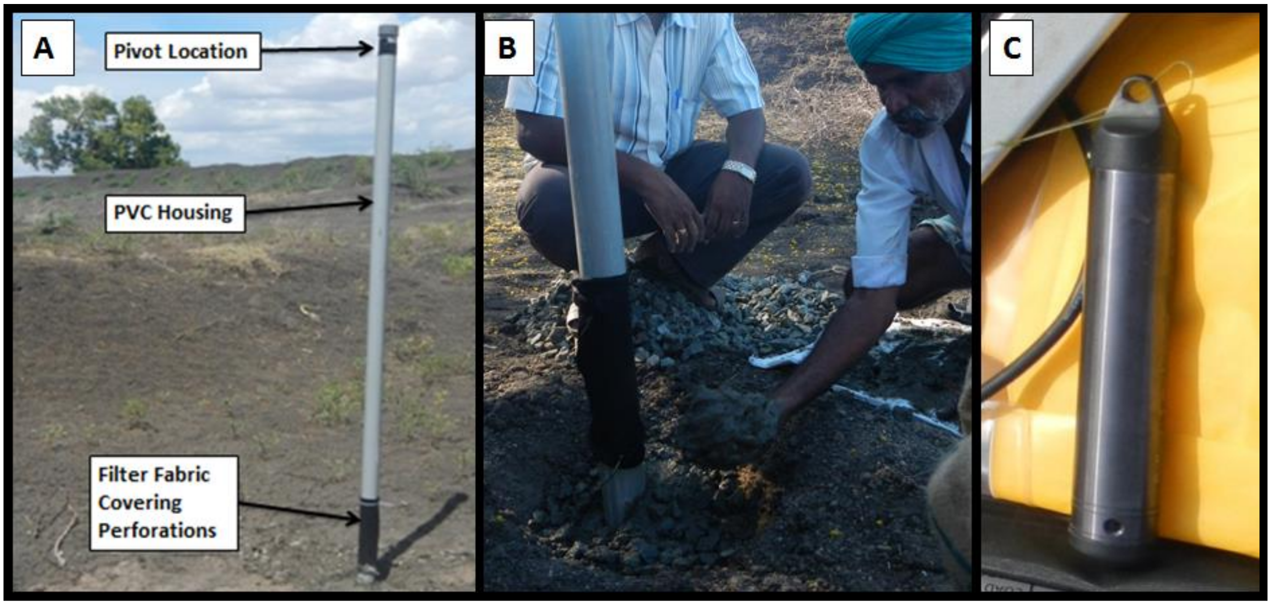

Figure 3.3: Water level sensor installation showing a) Well housing components. b) Housing well installation and secured with concrete. c) Sensor attachment via 10lb test fishing line.

3.2.4 Sluice Discharge Measurements

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 release from the sluices is controlled by a sluice gate that can be opened to different degrees by a sluice rod. For the tanks in this study the degree of sluice openness remained primarily unchanged during the study period, and thus the major factor that controlled sluice discharge was found to be the tank water level. The connection between sluice discharge and tank water level, was represented by measuring sluice outflow at a range of tank water levels. Specifically, 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 (**Figure 3.4c**). This section was selected based on width uniformity and channel straightness. Approximately 20-40 measurements were made at each stage to obtain a reliable velocity estimate. Sluice discharge-water level relationships were then developed for each sluice and used to estimate volumetric daily sluice outflow rates; these rates were then converted to area-normalized rates (S_o, cm/day) based on tank stage-area relationships (**Section 7.1.4**).

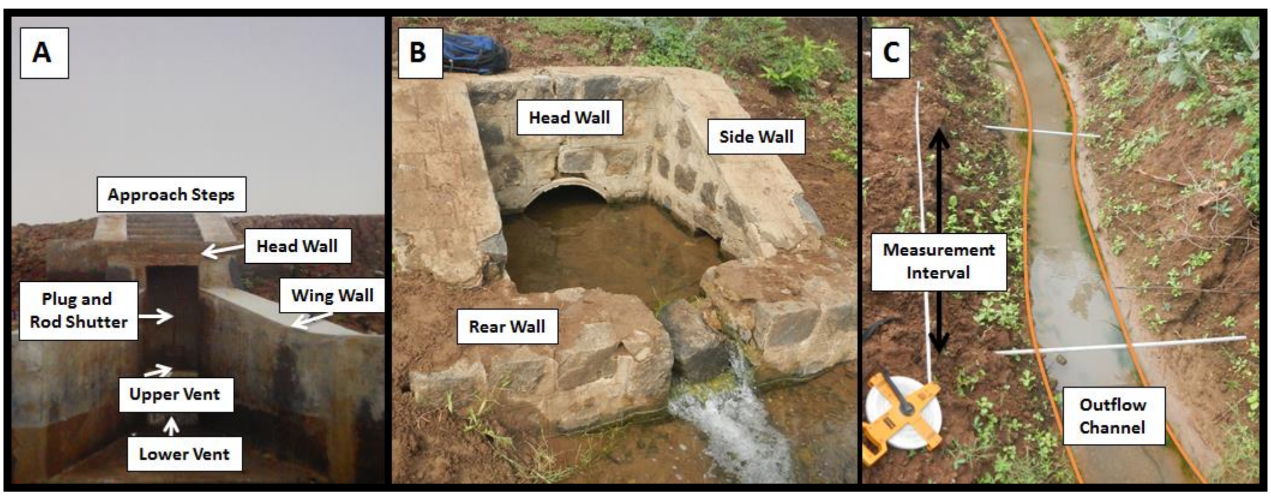

Figure 3.4: Characteristic Sluice Components of a) a typical sluice structure inlet. b) Sluice structure outlet. c) Outflow channel measurement interval.

3.2.5 Bathymetric Surveys

Bathymetric surveys were conducted using a combination of measured water depths in flooded areas (i.e., ground elevations relative to water surface), and a Trimble ProXRT2 GPS receiver paired with a Juno handheld computer for absolute ground elevations in exposed areas. Operated through use of a backpack (**Figure 3.5a**), the GPS receiver and antenna were worn while walking evenly spaced transects throughout the entire survey area. Since Tank 4 had a large number of acacia trees that interfered with the accuracy of the Trimble, a Sokkia Total Station was used for ground elevation surveys (**Figure 3.5b**). Sixteen to twenty-four transects at a grid-spacing of 40 m were taken in each tank (**Figure 3.5c**), and all surveyed elevations were converted to ground elevations relative 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 3.2**).

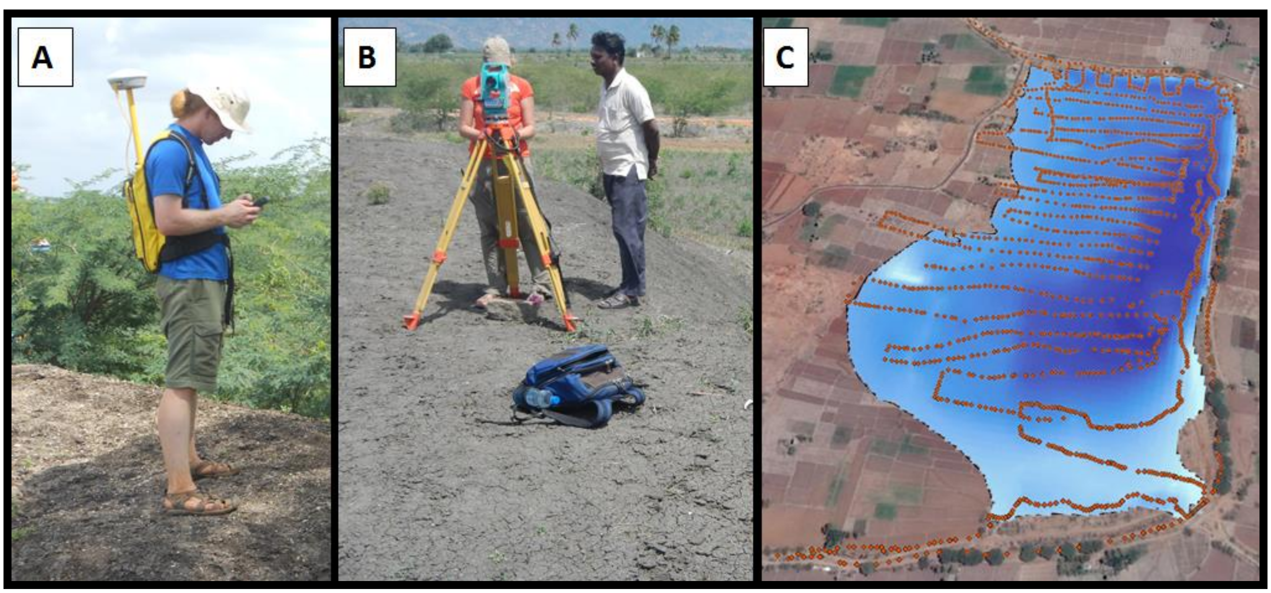

Figure 3.5: Bathymetry methods showingA) Trimble ProXRT2 backpack GPS system. B) Sokkia Total Station Surveying Equipment. C) Tank 1 survey points and resulting elevation surface.

3.2.6 Water Level Corrections

Water level sensor data was corrected for barometric pressure fluctuations. In addition, two other corrections were applied so that water levels could be used for subsequent analysis. These include sensor depth below the ground surface in the housing well and the difference between ground surface elevation at the housing well and the lowest tank elevation, or tank base (**Equation 3.1**). After these corrections, water levels are given as depth above the tank base. Visual representation of this process is shown below in **Figure 3.6**.

$$h_5 = h_1 - h_2 - h_3 + h_4 \qquad \text{Equation 3.1}$$

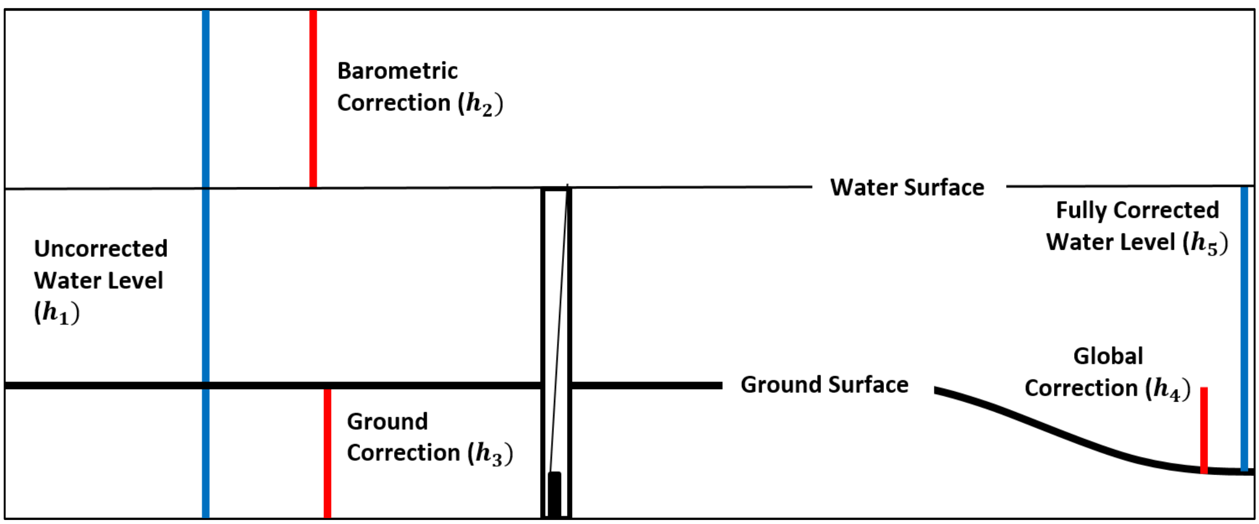

Figure 3.6: Water Level Corrections proceeding from left (Raw water level) to right (Corrected Water Level). Red and Blue lines signify applied corrections measured water level, respectively.

3.2.7 Focus Group Discussions

A series of focus group discussions were conducted with members of the tank farmer associations (TFA) in order to understand the functioning of the tanks and the sluices, and the cropping patterns and decision making in the command area. Discussions were open invitation to anyone in the community but the panel of questions was directed toward the functionality of tanks and their uses. Meetings at Pappanaickenpatti (Tank 1) and Vandapuli (Tank 2) consisted predominantly of tank farmer's association members whereas discussions at Kudipatti (Tanks 3) and Ketuvarpatti (Tank 4) had a much larger community presence. Questions were posed directly to TFA members as they had more intimate knowledge of the tank systems. **Figure 3.7** shows the discussion conducted with the Tank 1 farmer association members.

Through these meetings, much was learned regarding current tank uses and sluice operation protocol. Similarities shared by all tanks include use as grazing ground, the presence of temples and festivals, and temporal changes in water availability. Insight was also gained into the water management schemes used during drought conditions, among other details. As a result, it was also possible to infer the relative functionality of each tank farmers association. **Appendix 7.1.2** includes a complete table of findings from the focus group discussions.

Figure 3.7: Focus group discussion with farmers of Pappanaickenpatti. All aspects of tank function were documented; hydrologic, economic, social, and cultural.

3.2.8 Data Analysis

3.2.8.1 Adaptation of White Method to Tank Systems

In this study, the White (1932) method, is proposed as an innovative, cost-effective approach of obtaining spatially integrated, direct measurements of both ET and GE in RWH tanks. Compared to systems studied thus far using the White method, tanks systems are more complex. Due to the presence of additional outflows (overflow and sluice outflow), and much larger spatial extents (~1 ha v. 20-60 ha) some adaptation was required to apply the White method to the tanks.

Similar to the WBM, application of the White method required that all system inflows and outflows be accounted. Since tanks are governed by intense, short duration rain and filling events, inflow to the system was not measured. Instead, the few days of rainfall and tank inflow were not considered. Periods of surplus overflow were also excluded from estimation. In this way, sluice outflow was the only flow requiring direct measurement (**Section 3.3.1.3**).

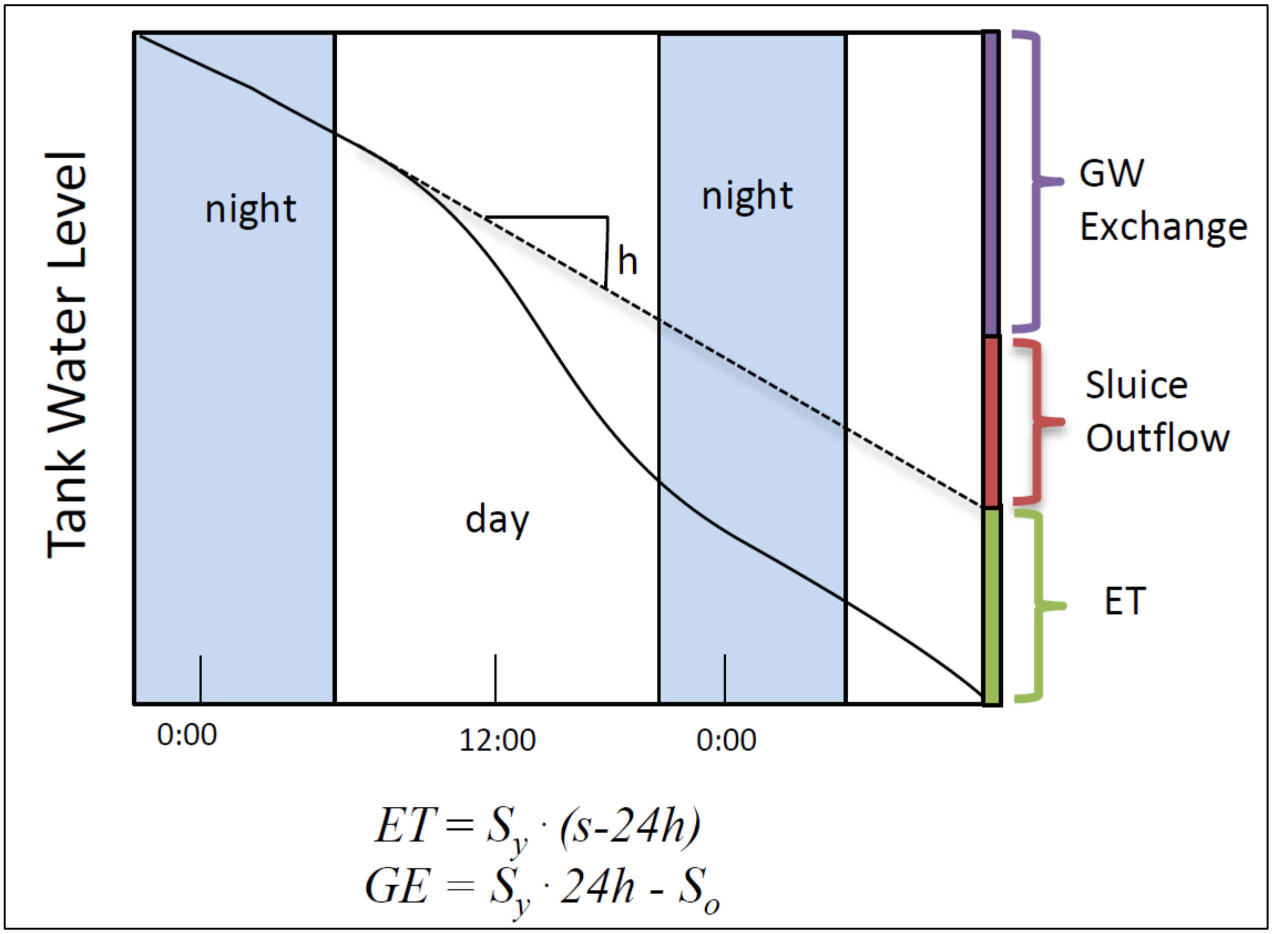

Figure 3.8: The White Method for estimating ET and groundwater exchange using diurnal water level fluctuations. Gray bars denote nighttime.

Groundwater Exchange Estimation

Groundwater exchange was estimated from the slope of the nighttime (12 am – 5 am) drop (or rise) in water level following the White method (McLaughlin & Cohen, 2014a). Days in which rain occurred, and days in which the coefficient of determination (R^2) of the trendline was less than 0.75 were removed from the dataset. This led to exclusion of 31 days in tank 1 and 2, and 35 days in tank 3 and 4. The slope of the nighttime drop (or rise) provided an estimate of the sum of the groundwater exchange and the sluice outflow rate. Groundwater exchange was calculated by subtracting sluice outflow (m/d) from the measured slope.

Evapotranspiration Estimation

Evapotranspiration (ET) was estimated as the difference between the total water level decline in a day and the nighttime slope of the water level drop (McLaughlin & Cohen, 2014a). The water level decline in a day is a function of three sinks, namely groundwater exchange, sluice outflow and ET, while the nighttime decline depends only on groundwater exchange and sluice outflow. Thus, by subtracting the nighttime slope (groundwater exchange + sluice outflow) from the 24 hour water level decline, ET can be estimated. The water level decline in a day is estimated as the difference in water levels from midnight to midnight of two consecutive days. Days in which recharge estimates were not available, and days when ET estimates were negative were removed from analysis. All data used for ET estimation was additionally scanned visually for abnormalities resulting from, for example, unobserved rain events.

3.2.8.2 Tank Water Balances

Volumetric water balance calculations were carried out at both the individual tank and the tank catchment scales across the Northeast monsoon season to answer questions regarding the partitioning of rainfall into the various outflow components (e.g. S_o, ET, GE). For individual tank water balances, daily data were utilized for water levels, rainfall, 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 assumes a constant groundwater flow and therefore cannot account for rainfall-related inputs (McLaughlin & 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, ET values were estimated 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 24-hour change in tank water levels, estimated ET rates, measured precipitation, and estimated runoff (McLaughlin & Cohen, 2013). Runoff was estimated using the Strange method (Shanmugham & Kanagavalli, 2013), an empirical method developed to compute runoff yield from catchments with irrigation tanks and small reservoirs and that is widely used throughout India by government departments dealing with irrigation (Latha, Rajendran, & Murugappan, 2012a). In this method daily runoff is calculated as a percentage of daily rainfall, based on tabulated values in which % runoff is expressed as a function of (a) rainfall on that day, (b) antecedent rainfall conditions, and (c) catchment characteristics (Shanmugham & Kanagavalli, 2005). For example, with a 50-mm rainfall, runoff could range from 10% for a dry catchment to 34% for a wet catchment, with the catchment condition (wet, damp or dry) being determined based on the days since last rainfall and the intensity of the preceding rainfall events. The Strange Method has been shown to provide results comparable to those obtained with the more commonly used SCS Curve Number method (Latha et al. 2012), but is more representative of the south Indian conditions that are the focus of our study. Stage-to-area relationships (**Section 3.3.1.2**) 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 October 17, 2013-January

13th, 2014, a period that spans the entire monsoon season and for which water-level data is available for all four tanks.

3.2.8.3 Catchment Water Balances

Water balances were also calculated at the catchment scale using a nested catchment design (**Figure 3.9**) 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. Delineation of the tank catchment was done using a digital elevation model (DEM), paired with documented inflow channel locations. The presence of two flow diversions in the watershed (between tanks 1 and 2 and tanks 2 and 3) were also considered. Since the precise degree of partitioning was not known, the diversions were assumed to split flow equally between the two receiving tanks. The resultant nested catchment design enabled exploration into the effect of varying catchment sizes and tank to catchment ratios on the water partitioning.

Figure 3.9: Catchment water balance scenarios for (a) the with-tank (WT) scenario to represent current conditions within the catchment (i.e., four existing tanks); and (b) the no-tank (NT) scenario, with all other conditions (e.g., rainfall, ET on the catchment area) being the same.

Further, in order to understand the impact of the tanks at the catchment-scale, two scenarios were explored 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 & Kanagavalli, 2013) and daily rainfall over the monsoon season. Following the Strange method, runoff is calculated using empirical rainfall-runoff curves created for low, average, and high runoff yielding catchments. Where runoff is estimated as a percentage of rainfall according to the catchment classification chosen (Latha et al., 2012b). Remaining rainfall was assumed to exit the system through ET and groundwater recharge. For the WT case, the sluice outflow from the most downstream tank in the catchment (T1 for C1, T2 for C2, T3 for C3 and T4 for C4) was assumed 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, the mean recharge was assumed 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 (**Section 3.3.1.4**) was used, (2) tank command area: 50% of the sum of rainfall and sluice outflow (based on typical values for paddy fields (Hundertmark & 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 3.2.

3.3 Results

The current section is divided into two broad subsections. In the first, measurements are reported of tank water levels, and fluxes (ET and GE); these data are used as a basis for discussing tank water level dynamics across the monsoon season. Also included within this section are the bathymetric and sluice-discharge relationships, as well as a comparison between the groundwater recharge results of this study and the existing literature. In the second subsection, an analysis is provided of the aforementioned measurements 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.

3.3.1 Tank Measurements

3.3.1.1 Water Levels in Tanks over the Northeast Monsoon Season

Water levels in the tanks rose sharply in mid-October following the monsoon rains, and then dropped over the next three months as water left the tanks through ET, sluice outflow, and groundwater recharge (**Figure 3.10**). 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 exceed catchment infiltration capacity. Two distinct fill events can be observed, one on October 16th and the second on Nov 17th for all tanks except Tank 1, for which the second fill event is not as apparent. Upstream encroachment of the feeder channel to Tank 1 may be the cause of this difference. Between Oct 16th and Nov 17th, the trajectories of tanks 1 and 3 parallel each other, while those of tanks 2 and 4 are similar. Towards the later part of the season, the water level trajectories of the 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, a discussion is presented on how the outflow fluxes in the four tanks vary over the course of the monsoon season.

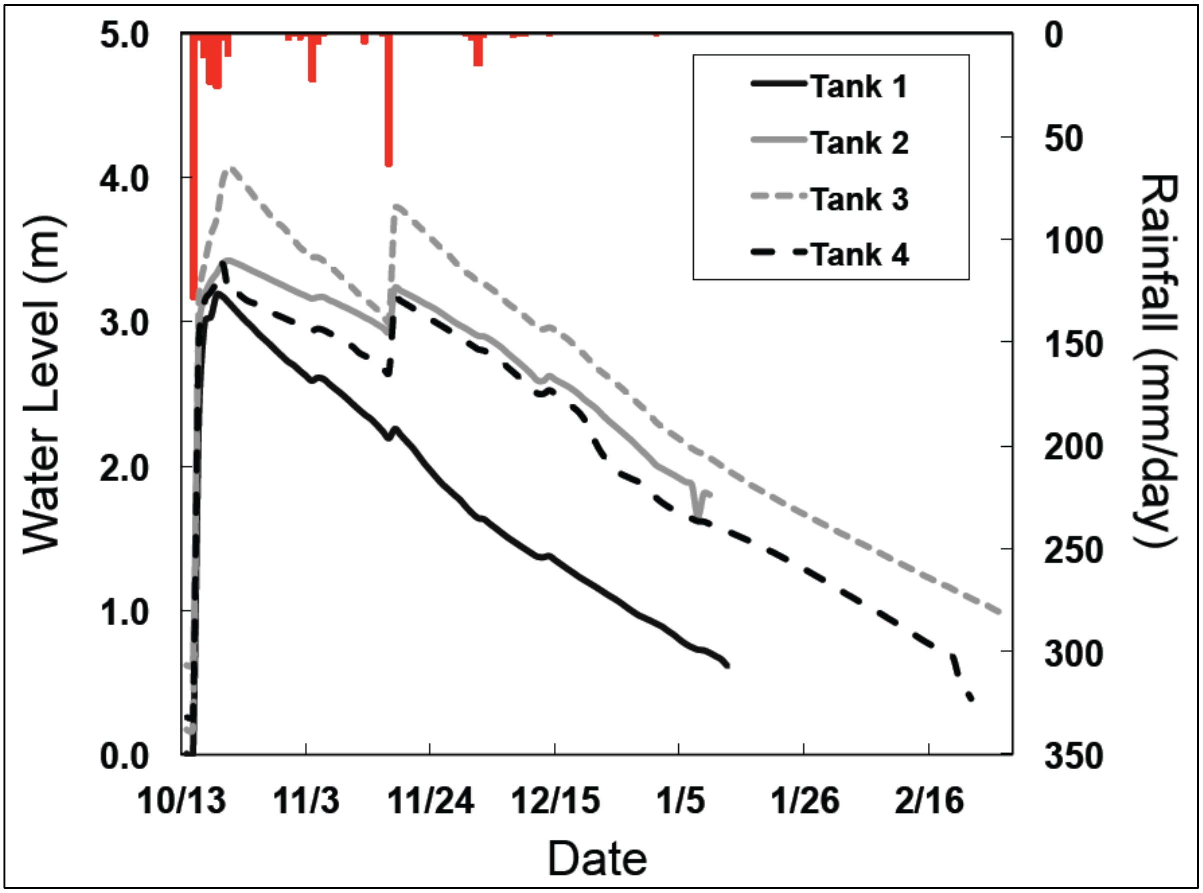

Figure 3.10: Tank Stage and Daily Rainfall for the four tanks over the North East monsoon season

3.3.1.2 Bathymetric Relationships

Tank bathymetry surveys showed a general pattern of the presence of a deeper area of smaller extent surrounded by a much shallower water spread area (**Figure 3.11**). This is consistent with the general understanding of the tank structure, in which there exists a deeper area where water is retained for a longer duration of time, and generally used for livestock. The shallower water spread area fills up quickly during the monsoon, and becomes dry earlier than the deeper area due to irrigation, groundwater exchange and evapotranspiration. Interestingly, the surveys also reveal a pattern with respect to tank shape, with tanks 1 and 3 having a flatter profile, while a deeper incised area was apparent in tanks 2 and 4. This probably is a function of management choices that govern how desiltation has been done in the tank beds. In later sections differences in the shape characteristics of the tanks are discussed with respect to altering how they fill up and drain.

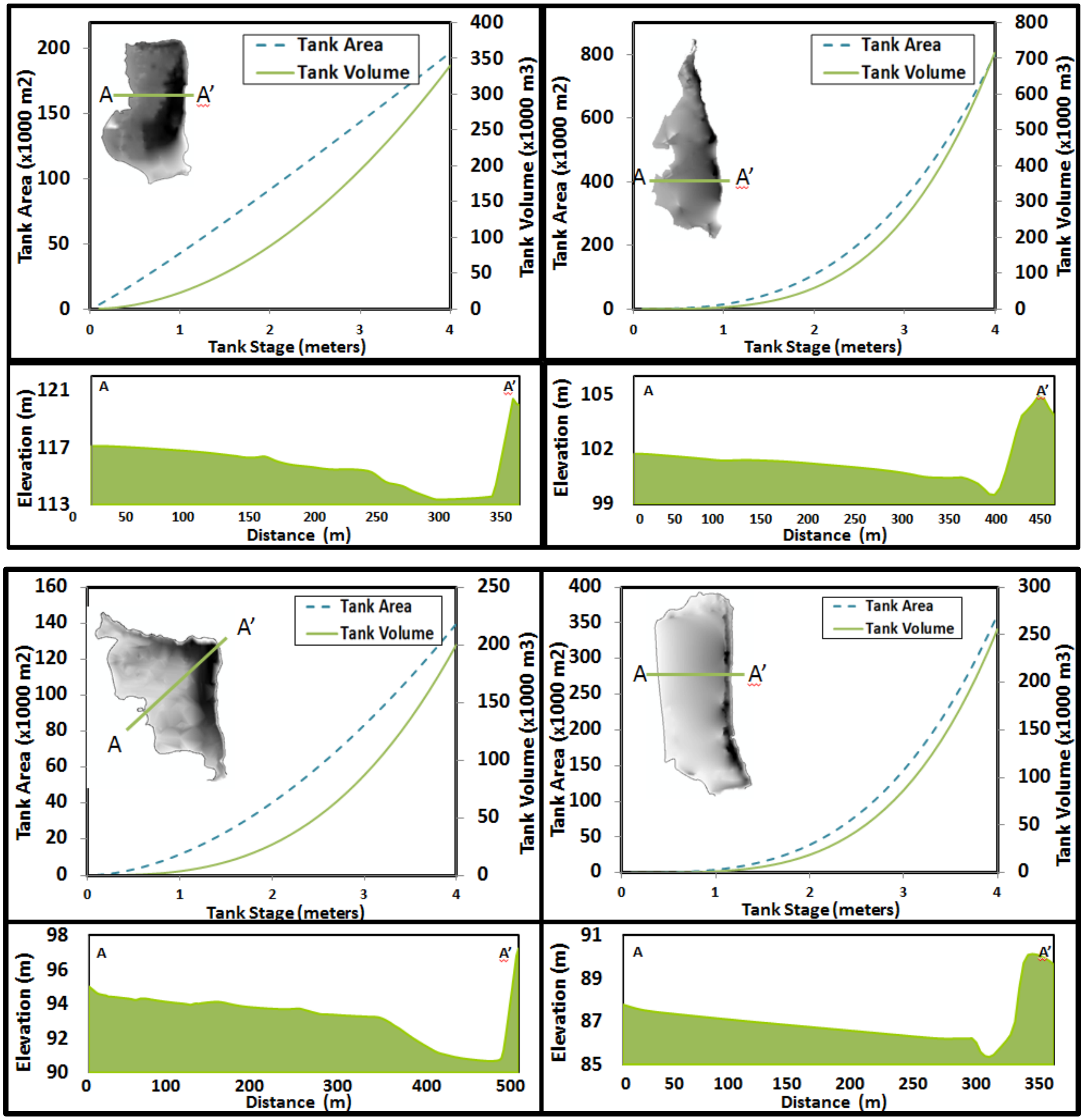

Figure 3.11: Bathymetry relationships for the four tanks: Stage-Area (Blue dashed), Stage-Volume (Solid Green line), Tank Elevation Cross-Section

Additionally, the tank bathymetry surveys were used to estimate tank capacity by assuming that the maximum observed water depth corresponded to the maximum tank volume, except in Tank 4 where the water level data actually documented the occurrence of overflow for a few hours. Thus, in tank 4 the height at which overflow occurred was used to estimate the tank capacity. For the other tanks, water level data does not show any noticeable change in slope, but field observations confirmed that overflow did occur. The capacities estimated by this method led to reasonable values, with current capacities being between 62 – 92 % of the historical capacities (**Table 3.2**).

Bathymetry of the tanks was explored further by looking at stage-volume and area-volume relationships, described adequately by power functions (**section 7.1.3**). The coefficient and exponent of the power function relationships (**Table 3.3**) varied significantly among the tanks. However, a strong correlation was observed between the coefficients and exponents (**Figure 3.12a, b**). A similarly strong correlation was found by (Rodrigues & Liebe, 2013) for 103 small reservoirs (1 – 40 ha) in two semi-arid watersheds. Further, a distinct pairing of coefficients and exponents exists for tanks 1 and 3 and tanks 2 and 4 (**Figure 3.12**) which is suggestive of similarity in shape (for example openness and concavity) between these pairs of tanks.

Table 3.3: Stage-Volume and Area-Volume relationship parameters for the tanks

Tank Number	Volume = k*Depth$^{\alpha}$				Volume = k1*Surface_Area$^{\alpha 1}$			
	k	**α**	**R2**	**Max. Depth**	**k1**	**α1**	**R2**	**Max. Surface Area**
T1	22914	1.95	0.997	3.595	0.0003	1.72	0.976	175292
T2	4852.2	3.60	0.988	4.75	0.0308	1.25	0.993	1311579
T3	3584.7	2.90	0.995	3.78	0.0012	1.59	0.980	126170
T4	1390.1	3.76	0.980	3.21	0.0791	1.17	0.996	178355

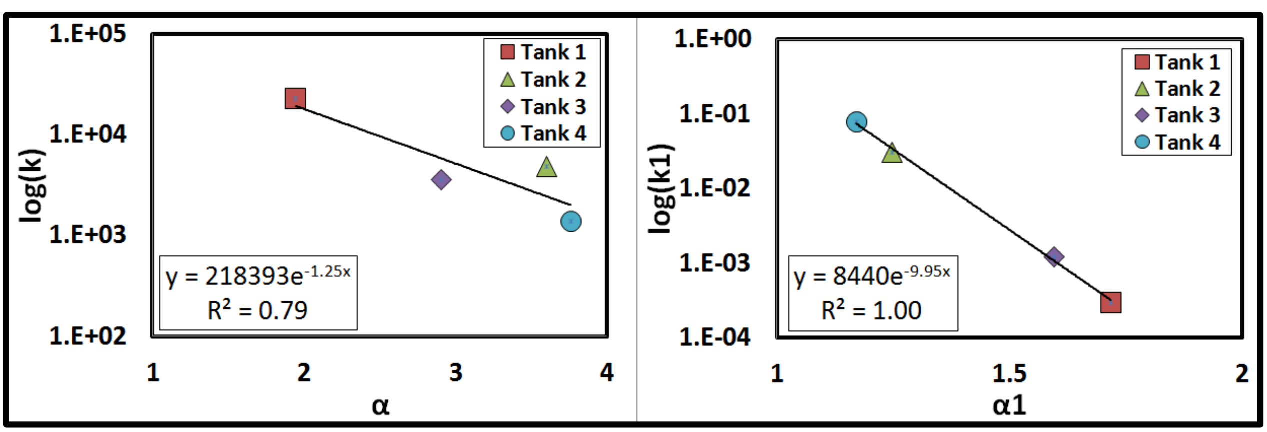

Figure 3.12: Log(k) – α and Log(k1) – α1 Relationships a) Log(k) – α (left) for parameters of depth – volume relationship. b) Log(k1) – α1 (right) for parameters of area – volume relationship.

3.3.1.3 Sluice Discharge-Water Level Relationships

As mentioned, estimation of groundwater exchange and evapotranspiration depends on accounting for sluice outflow. Therefore, relationships were created between measured sluice discharge and tank water level for each sluice, to account for sluice discharge on days in which no measurement was made. All relationships were described by linear behavior and can be found in the Appendix (**Section 7.1.4.**). Best judgment was used to remove points compromised by external factors such as wind and timer error. In addition to estimates of groundwater exchange and evapotranspiration, the relationships allowed for water budgets to be estimated at the tank and cascade scale.

3.3.1.4 Spatio-temporal Patterns in Groundwater Recharge

The temporal pattern in groundwater exchange, estimated using Equation 2, is presented in **Figure 3.13** together with trends in tank water levels and daily precipitation. Groundwater exchange rates across the monsoon season appear to be driven by a combination of both tank water levels and the occurrence and magnitude of rainfall events. Tank 2, for example, has relatively lower recharge rates (positive values in Figure 3.12) in the earlier part of the season, with values decreasing with the occurrence of each major rainfall event, and then increasing incrementally over time until the next rainfall. The last period of significant rainfall occurs in mid-December, and shortly after this time, recharge magnitudes for Tank 2 reach a peak, and then slowly decrease with decreasing tank water levels.

A similar pattern can be seen for Tank 4, where the peak recharge value occurs during the mid-December period, followed by a steady decline in recharge magnitudes as tank water levels decrease. In contrast, Tanks 1 and 3 appear to be less impacted by rainfall events; for these tanks, recharge magnitudes begin to decrease with decreases in tank water levels much earlier in the season, after the last major rainfall (64 mm) on November 17th. In the last few weeks of the monsoon season, Tanks 2-4 all switch over to a groundwater inflow regime (negative GE values). Lower recharge rates as well as these switches to groundwater inflow towards the end of the season may be due to tank water levels consistently having greater declines compared to the surrounding aquifer, resulting in decreases and potential reversals of hydraulic head gradients. This period is also, however, punctuated by some distinct, very high groundwater outflow events that may correspond to observed groundwater pumping in the vicinity, highlighting a potential direct human influence to tank recharge rates. Indeed, incidents of pumping in the tank beds were observed and correspond to some of those days.

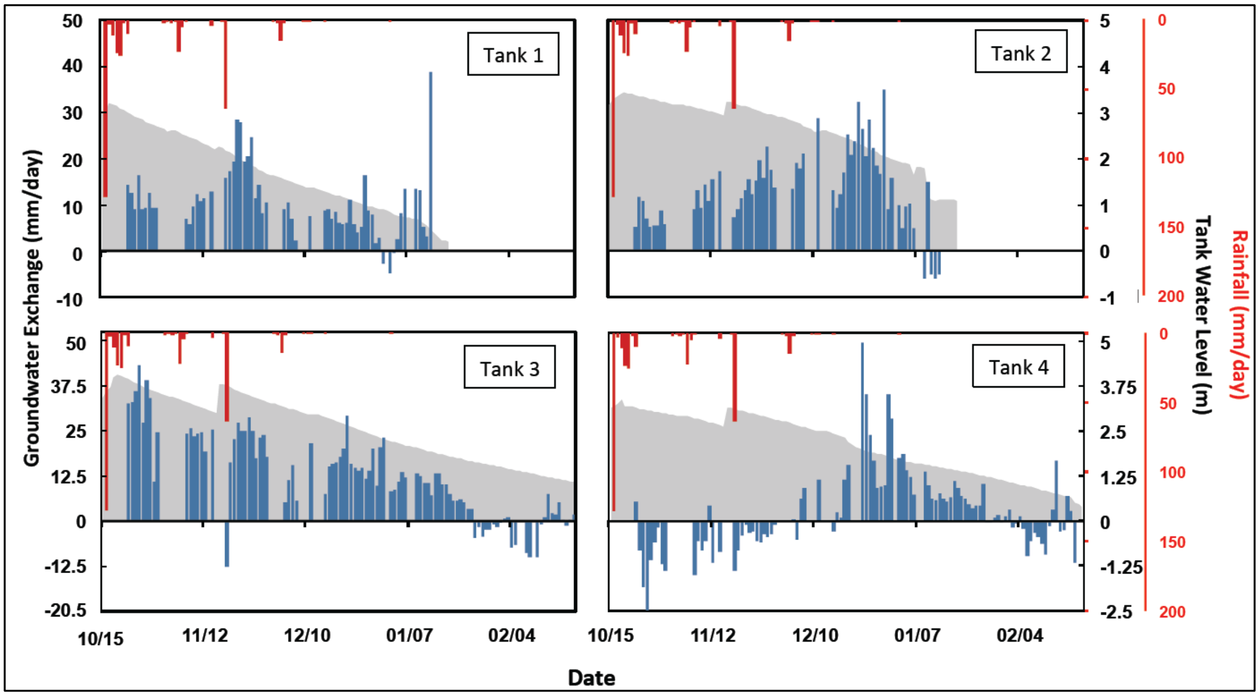

Figure 3.13: Daily groundwater exchange (cm/d) magnitudes over the course of the northwest monsoon season, shown as blue bars. Positive values indicate infiltration (flow out of the tank), while negative values are exfiltration days. Groundwater exchange magnitudes generally decrease towards the end of the season, when tank water levels (shown in grey and plotted on the secondary y-axes) decrease. There are some very high infiltration events towards the later part of the season that corresponds to pumping in the vicinity. Infiltration events dominate the exchange behavior with exfiltration occurring primarily on days following a rain event (rainfall shown as red bars).

To better characterize the dominant drivers for the magnitude and direction of GE, with the overall goal of generalizing these observations to larger scales, GE was plotted as a function of days since last rainfall for all four tanks (**Figure 3.14a**). For Tanks 2 and 4, there is a threshold value of days since rain (14 days for Tank 2 and 16 days for Tank 4) that separates rainfall-GE relationships. That is, there is significant scatter in the rainfall-GE relationship at values less than this threshold, but strong negative relationships emerge between the two variables at higher values of day since rain (**Figure 3.14a**).

In contrast, Tank 1 and Tank 3 have much lower threshold values of only 1 and 2 days, respectively. This pattern of decreasing recharge with days since last rainfall is reasonable, as water levels in the tank steadily decrease over time, leading to decreased hydraulic head and thus lower rates of recharge. In 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 (**Figure 3.14b**).

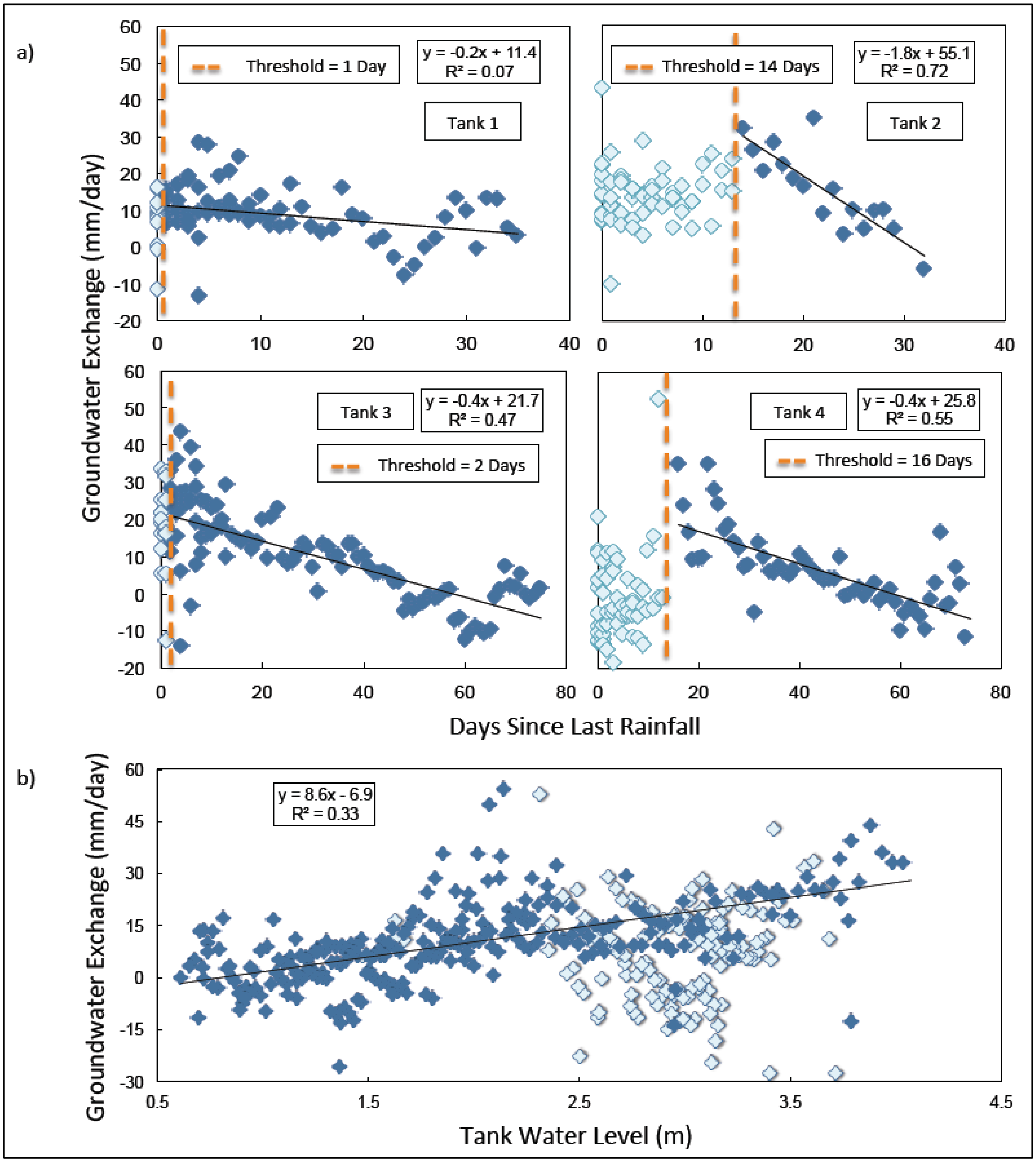

Figure 3.14: (a) Relationship between groundwater exchange and days since last rainfall, shown separately for the four tanks. The threshold line (dashed orange) separates the more erratic rainfall-driven groundwater exchange behavior following rain events (shown as light-blue diamonds) from the more 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 exchangeshown for all four tanks combined. Lighter blue diamonds correspond to the rainfall values below the threshold shown above in part a.

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 **Figure 3.13**, can be seen to dominate the exchange dynamics of Tanks 1-3, Tank 4 is more discharge-driven. As shown in **Figure 3.15a**, 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 (**Figure 3.15b**), 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.

The 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., 2012b) have focused on individual tanks, with no consideration of the position of the tank in a cascade as an important control on its functioning. These 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.

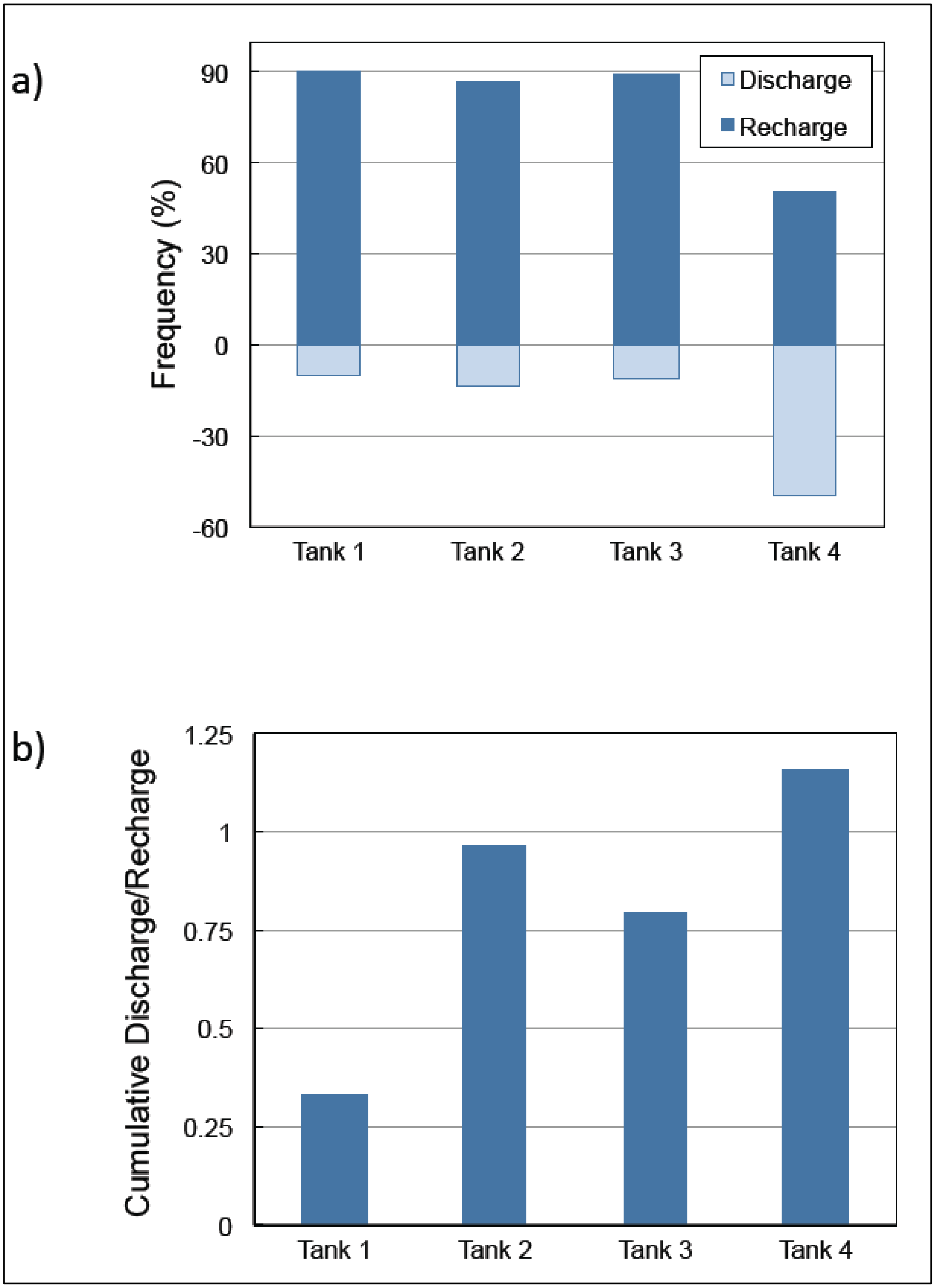

Figure 3.15: (a) The frequency of daily recharge (outflow) and discharge (inflow) events over the Northeast Monsoon season, and (b) the ratios of cumulative discharge to cumulative recharge magnitudes. The results for the four tanks indicate that all tanks function as both recharge and discharge systems, but that Tank 4 is much more dominated by discharge behavior based on both frequency and overall magnitudes.

3.3.1.5 Comparison of Recharge Efficiencies with Literature Values

The metric most commonly used for quantifying the hydrologic impact of RWH structures is the tank recharge or percolation efficiency (R_{eff}), described as the ratio of total recharge (m^3) to total outflow (m^3) for a RWH structure (Glendenning & Vervoort, 2010; Massuel et al., 2014; Perrin et al., 2010; Raju, 1998; Sukhija et al., 1997). Review of literature focusing on RWH systems in India, Sri Lanka and Africa reveal that R_{eff} can vary significantly for RWH structures, from 1.3% to as much as 80% ((Fowe et al., 2015; Glendenning & Vervoort, 2010b; Jayatilaka et al., 2003b; Raju 1998; Matsuno et al., 2003b; Perrin et al., 2010b; Sharda et al., 2006b; Sukhija et al., 1997)). In order to understand what tank attributes control the recharge efficiency, recharge efficiencies were plotted against the ratio of maximum area (A in m^2) and capacity (C in m^3) of the tanks (**Figure 3.16)**. A saturation type relationship is observed between the two variables with R_{eff} being low at small values of A/C, increasing as A/C increase, and reaching a plateau of 60% for A/C > 0.8. Tanks with a larger area to capacity ratio are flatter having more surface area for exchange and thus higher recharge efficiencies. The recharge efficiencies of the tanks in the study cascade fall within the measured recharge efficiencies of other studies. However, the other studies provide estimates at a single point in time, or an integrated value over the entire season. In this study a quantification of the temporal patterns in recharge over the northeast monsoon season are provided.

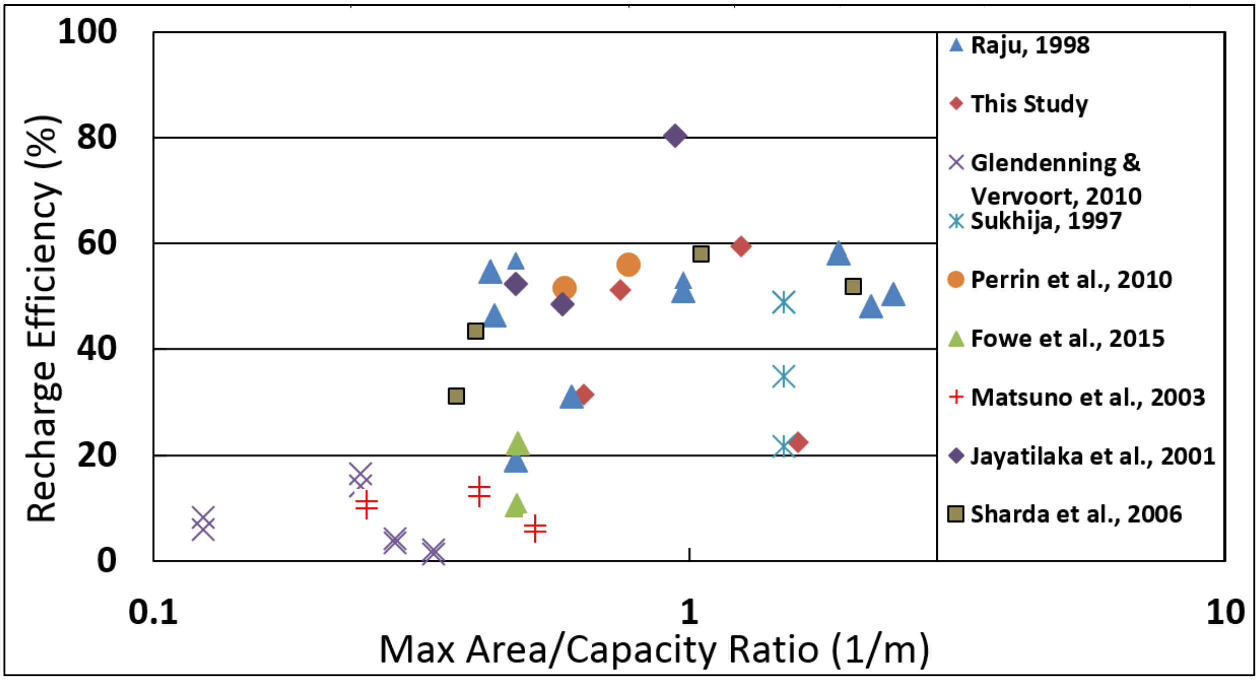

Figure 3.16: Recharge Efficiency (%) versus RWH structure shape, where shape is the ratio of maximum area (A) to tank capacity (C).

3.3.1.6 Spatio-temporal Patterns in Evapotranspiration

Evapotranspiration (ET) fluxes estimated with Equation 1 for the four tanks are shown in **Figure 3.17**. ET rates derived with the White method are reasonable for the region and season (Potential ET (PET) ranges between 3 – 12 mm/day for Madurai (Rao et al., 2012)), ranging from 5.5 ± 1.0 for Tank 1 to 10.1 ± 0.8 mm/day for Tank 3 during periods when the tank inundated area is greater than 25 % of maximum area. Below this 25% threshold (shown in **Figure 3.17** with dashed line), ET estimates for the tanks exceed PET rates by factors of 2-3.

Two mechanisms can explain this effect of smaller inundated area on ET rates. First, small areas of flooding surrounded by comparatively extensive areas of exposed soils can create an oasis effect (Drexler et al., 2004; Paraskevas et al., 2013), particularly in arid regions where advection of dry air from exposed areas can increase ET rates in flooded areas beyond typical values (and PET) for that same land cover at larger inundated areas. Second, the White method requires a known S_y (see Equation 1) to determine ET and groundwater exchange from diurnal fluctuations of water levels. S_y can be considered as the ratio of input (rain, discharge) or output (ET, recharge) depth relative to the induced water level change (Healy & Cook, 2002).

Open water S_y values of 1.0 are typically assumed for flooded areas (Mitsch and Gosselink, 2007), and this value was used here. In contrast, soil S_y values range from 0.1 to 0.35 (Loheide et al., 2005), meaning that belowground water levels experience a greater decline compared to flooded areas for an equal ET flux. As such, a hydraulic gradient for water subsidy from a flooded area to adjacent exposed areas can establish, and any rapid equilibration means that daytime decline from the flooded area includes subsidy to adjacent exposed areas (McLaughlin & Cohen, 2014a). Accordingly, ET estimated with the White method for small flooded areas includes both ET from standing water plus any daytime flux to adjacent exposed areas to equilibrate greater ET-induced declines in belowground water levels. McLaughlin and Cohen (2014) measured ET rates using the White method (and a $S_y = 1$) that exceeded PET by a factor of 5 or more when flooded areas were small, compared to ET/PET ≈ 1.0 at moderate to maximum flooded area. While ET estimates greatly exceed PET at low stage, inclusion of the full ET dataset in the water budgets is justified given the two mechanisms likely causing such high rates.

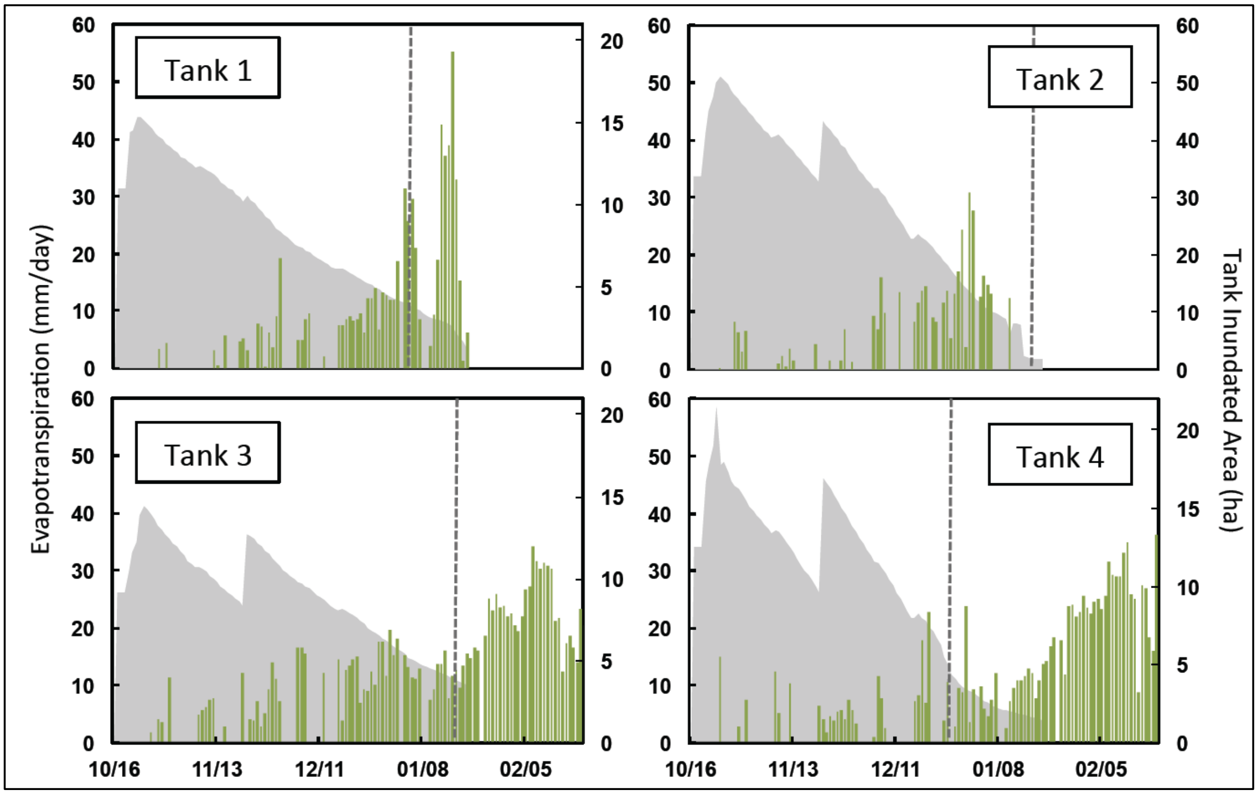

Figure 3.17: The temporal variation in daily ET over the monsoon season, shown as green bars. There are data gaps in the figure since estimates were made using the White method only on non-rainfall days. ET increases towards the later part of the season, coincident with decreases in tank surface area (shown as the grey shaded area). ET rates are reasonable for the region and season when the inundated area is greater than 25 % of maximum area, as indicated by the dashed line.

A comparison was also made between daily evapotranspiration values, estimated using the White method, and temperature. However, the results of this comparison revealed no correlation.

3.3.2 Exploring Biophysical vs. Management Controls on Tank Water Balance at the Tank and Catchment Scales

Three questions were posed in section 3.1, including 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, measured data is used to provide answers to these questions in the context of a discussion of physical versus management controls on tank functionality.

3.3.2.1 Water Balance at the Tank Scale

The first question asked was how tanks partitioned the incoming water (direct rainfall on tank and surface runoff from tank catchment) into various outflow components, namely evapotranspiration, groundwater recharge, and sluice outflow to the fields in the tank command area. The flow volumes corresponding to these components over the length of the northeast monsoon season are plotted by week in **Figure 3.18** and summarized in **Table 3.4**.

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 **Figure 3.18a**, 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.

Table 3.4: 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*
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%

*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.

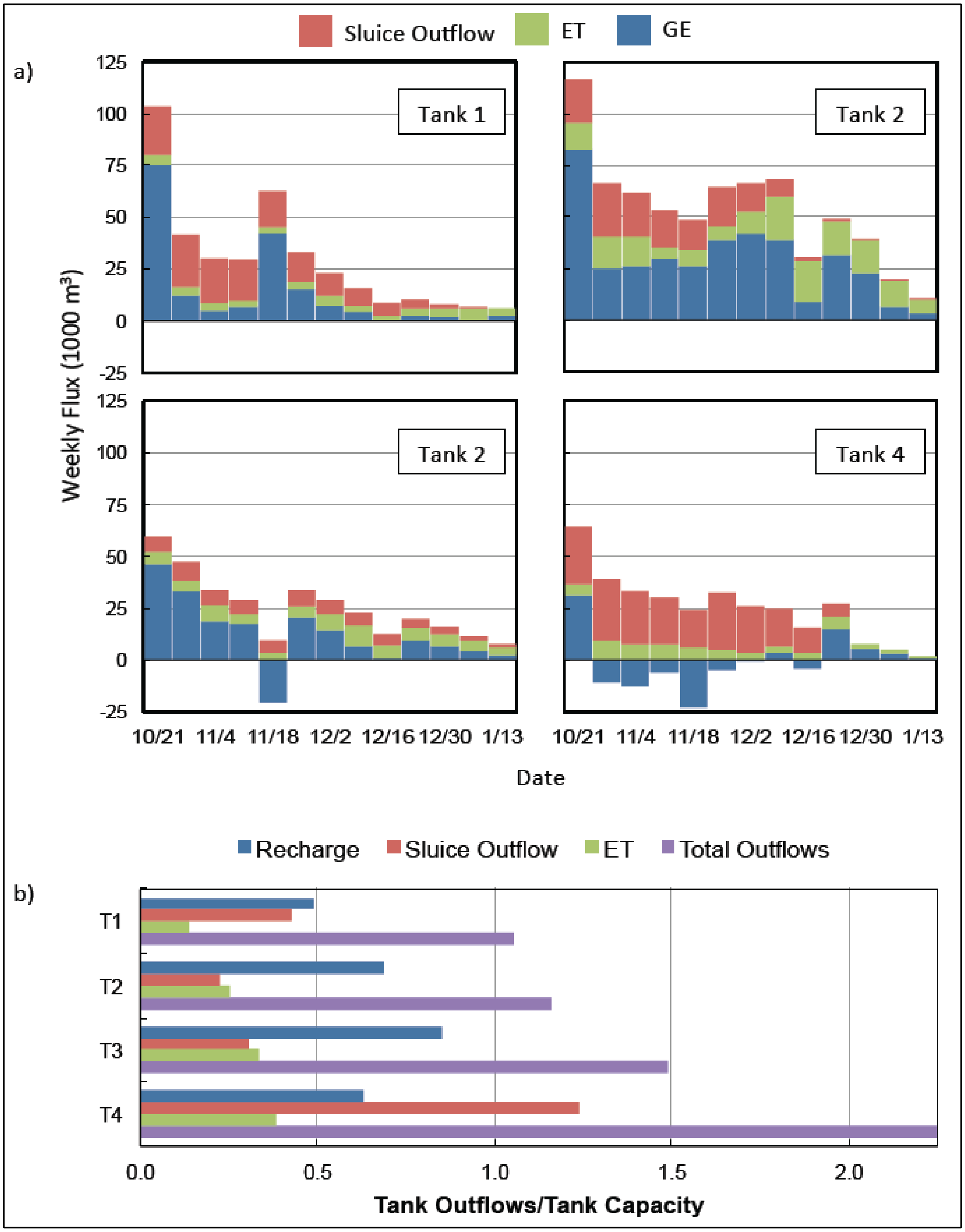

Figure 3.18:(a) Tank outflow dynamics (ET in green, sluice outflow in red and GE in blue) shown as weekly integrated volumes for all four tanks. These are stacked bar graphs with the areas shown in the different colors representing the subcomponents of the outflow. (b) Tank water outflows as a fraction 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 forTank 4 over the study period are more than double the total tank capacity.

Although the volume of water lost to ET is substantial (0.48 – 1.64 million cubic meter over the 83-day study period), it is a relatively small fraction of the overall water budget. On a cumulative scale (Table 4.2), 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, Ghosh, Patel, Singh, & Ravindranath, 2006). 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 relatives 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 (**Figure 3.18b**). Moving 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 (**Figure 3.15**). 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 requirements 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.

3.3.2.2 Water Balance at the Catchment Scale

The second question asked was how tanks alter the partitioning of rainfall (P) into (a) runoff at the catchment outlet Q, and (b) recharge within the catchment R. Water balance calculations were done at the tank and catchment scales for the four nested catchment scenarios described in **Section 3.2.8**. Further, scenarios were simulated for both with and without tanks to understand the contribution of tanks towards altering catchment scale water partitioning.

The 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. A significant decrease in Q was found at the four nested scales, from 22% of rainfall in the no-tank scenario to 5-9% of rainfall with tanks (**Table 3.5**). 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 3.5**). This approximately 70% decrease is consistent with other work showing large decreases in runoff due to the presence of tanks (Kumar et al., 2008a). Conversely, catchment-scale net recharge was observed to increase from 17% of rainfall without tanks to 24-27% with tanks (**Table 3.5**), 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 & 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 (U. A. Amarasinghe, Singh, Sakthivadivel, & Palanisami, 2009; Government of Tamil Nadu, 2011; Palanisami & Meinzen-Dick, 2001b). 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 leave a catchment as runoff within hours of falling. These water balance calculations show that tanks provide a mean groundwater recharge benefit of 5,600 m^3 per hectare of tank waterspread area. At the scale of the Gundar basin, with its 2276 village-scale RWH tanks, each covering an area of approximately 40 ha (DHAN, 2010), these results suggest that fully functional tanks could provide a groundwater recharge benefit of

522 MCM. However, with the currently reduced tank functionality, the yearly recharge volume is likely closer to 157 MCM, a difference of 365 MCM. With a population of approximately 3,000,000, this difference translates to a difference in water availability throughout the Gundar Basin of 122 m^3 per capita. It is currently estimated that all of India is experiencing some degree of water stress, with per capita availability ranging from 1000-1700 m^3/year (U. Amarasinghe et al., 2005). Accordingly, maintaining tanks at full functionality has the potential to increase per capita water availability in the Gundar by approximately 10%.

It should be noted that the recharge benefit suggested by the results in this tank cascade is significantly larger than that reported for a watershed in Gujarat, a state in Western India, where it was shown that the construction of new rainwater harvesting structures would lead to a 60% decrease in catchment runoff, but only a 5% increase in recharge (Sharma & Thakur, 2007c). In the Gujarat catchment, however, annual rainfall is approximately half that in this South India catchment, and ET rates are estimated at more than 50 mm/day, suggesting that variations in climate can strongly impact the contribution of rainwater harvesting structures to groundwater recharge.

Table 3.5: 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 P (MCM)	1.8	5.8	8.1	10.2
Runoff, Q (MCM)				
with tanks	0.15	0.30	0.37	0.69
without tanks	0.40	1.31	1.81	2.29
Recharge, R (MCM)				
with tanks	0.48	1.44	1.97	2.42
without tanks	0.31	0.99	1.37	1.73
Q/P				
with tanks	0.09	0.05	0.05	0.07
without tanks	0.22	0.22	0.22	0.22
R/P				
with tanks	0.27	0.25	0.24	0.24
without tanks	0.17	0.17	0.17	0.17

3.3.2.3 Management Controls on Irrigation Efficiency

While the first two questions focused on the physical controls on tank water dynamics, the third question focused on understanding how tank water management affects water balances and, in doing so, contributes to meeting the irrigation requirements of the tank command areas. To answer this question the supply-and-demand curves over the growing season were plotted (**Figure 3.19**). The supply curves are the sluice outflow volumes from the four tanks. The demand curve in this case is the crop water requirement mm/d which is adjusted by the available rainfall to get the Irrigation Water Demand (IWD = Crop Water Requirement – Rainfall). Crop water requirement data in mm/day were obtained from (Brouwer, Prins, & Heibloem, 1989) for the four growing stages of paddy. Paddy planting dates, which differed dramatically between the four tanks (10/17, 10/17, 9/25, and 9/13 for Tanks 1, 2, 3, and 4), are based on field observations. The earlier planting dates in the command areas of Tanks 3 and 4 were most likely due to the availability of borewell water for those areas. As can be seen in **Figure 3.19**, the difference in planting dates leads to different demand curves for the four tanks.

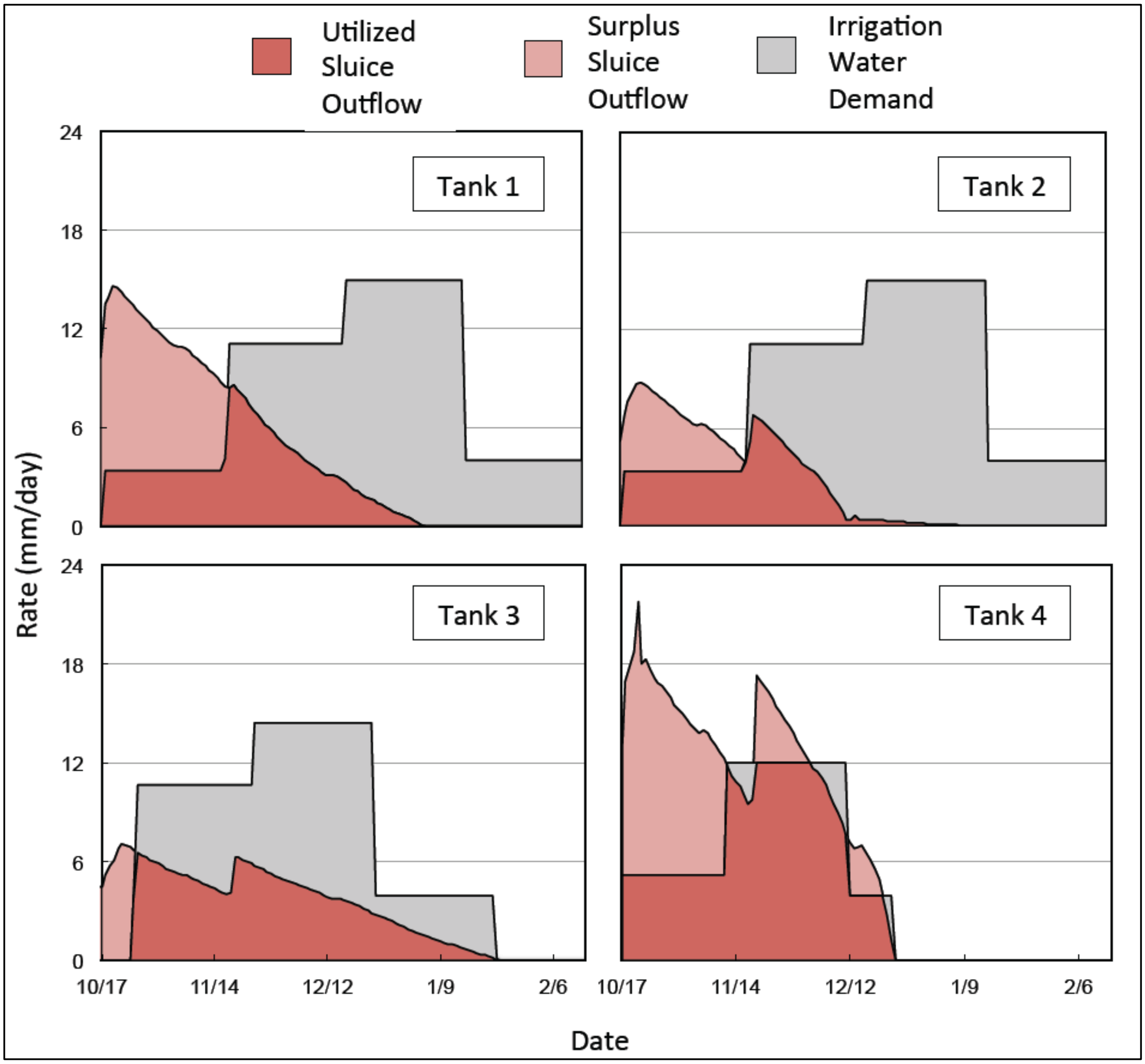

Figure 3.19: Water supply-and-demand portraits in the tank cascade. The grey area represents the Irrigation Water Demand (IWD), which is calculated as the difference between crop water requirements and rainfall (Brouwer et al., 1989). Planting dates were 10/17, 10/17, 9/25, and 9/13 for Tanks 1, 2, 3, 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."

The supply-and-demand curves assess the ability of the tanks to meet paddy water demand by comparing IWDs to sluice outflows. The darker red areas in **Figure 3.19** denote sluice water used to meet the IWD, while the lighter red areas represent sluice water that is "wasted," as it is flowing out at a time when crops are not requiring that water. The grey areas in the figure represent the IWD unmet by sluice outflow. Notably, large quantities of surplus sluice water leave the tanks soon after filling. These surplus sluice outflows are not needed by the crops at the time they leave the tank and will ultimately leave the catchment by evaporation or as downstream runoff. Because the sluices are for the most part not actively managed or appropriately maintained, there is substantial wastage through sluice outflow in these systems, with the sluices remaining perpetually open and outflows being purely a function of water levels in the tank. As reported in **Table 3.6**, it was found that anywhere from 31-79% of IWD within the study cascade remains unmet, while approximately 15-50% of available sluice outflows leave the tank cascade unutilized. This remaining irrigation water demand would in many cases be met by farmers using groundwater pumping to supplement tank water, and would in other cases remain unmet, leading to reduced yields or crop failure. In the case of groundwater pumping, it should be noted that a significant portion of the tank water does leave the tanks as groundwater outflow, and is subsequently extracted by groundwater wells for irrigation, thus helping to meet the crop water requirements by a non-direct route. The magnitude of this contribution of tank outflows to the crop water budget, however, is difficult to ascertain, and thus has not been included herein.

The timing of planting also has a significant impact on the ability of the tanks to meet crop water requirements (**Figure 3.19**), with the later planting dates in Tanks 1 and 2 leading to more than 70% of the IWD being unmet by sluice outflows (**Table 3.6**). Conversely, Tank 4, with its much earlier planting time (9/13), more effectively meets crop water requirements with sluice outflow. First, the early planting time leads to the lowest total IWD of all the tanks (752 mm), as more of the crop water requirements can be met by rainfall. In addition, there is a better temporal match for Tank 4 between the unregulated sluice outflows at high tank water levels (**Figure 3.19**) and the crop water needs of the plants. Accordingly, more than 500 mm of the IWD is met by sluice outflows, and only 31% of the overall demand remains unmet. These results suggest that, to optimize tank operations and to maximize the water-provisioning capabilities of the tanks, earlier planting times could be utilized by farmers. Such a change in management, however, would be dependent on both groundwater availability and the economics of groundwater pumping.

Table 3.6: 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				
a *Total (mm)*	996	996	872	752
Unmet Demand (mm)	713	786	540	235
Percent Unmet	72%	79%	62%	31%

3.4 Summary

In this chapter, the methods used for data collection and analysis were described, and several questions were explored. The first question aimed to answer how tanks partition water over the monsoon season and what the spatial variability is for flux partitioning along a cascade. Measurements made in the tanks over the monsoon season were essential for understanding this partitioning behavior. Tank water levels were found to not rise immediately following arrival of the monsoon rains, but rather, a lag effect was observed. This indicates a threshold, where runoff to the tanks occurs after the catchment infiltration capacity is exceeded.

Estimates of groundwater exchange (**Figure 3.13**) show GE to be driven by a combination of tank water levels and the occurrence of rainfall events. Similar patterns were observed in tanks 2 and 4, where recharge values were lower earlier in the season, reached peak in mid-December, and then declined steadily with decreasing tank water levels. In contrast, tanks 1 and 3 were affected less by rainfall events. Here, recharge magnitudes began decreasing with tank water levels much earlier in the season, following the last major rainfall event ((64 mm) on November 17th). While the tanks were generally characterized by recharge, a switch to groundwater discharge was observed in the last few weeks of the monsoon season for tanks 2-4. Patterns of groundwater exchange were generalized by plotting GE as a function of days since last rain. Thresholds of days since last rain suggest GE in each tank is affected differently by rainfall events, with tanks 2 and 4 having a much longer period of erratic GE behavior following rainfall than tanks 1 and 3. In addition, spatial variation in GE along the cascade was observed, where the discharge-to-recharge ratio increased proceeding from upstream to downstream along the cascade. This finding suggests that the position of a tank in a cascade is an important factor to consider for understanding the catchment and regional scale impact of tanks. Estimates of evapo-transpiration derived using the White method were found to be reasonable for the region and season (Potential ET (PET) ranges between 3 – 12 mm/day for Madurai (Rao et al., 2012)), ranging from 5.5 ± 1.0 for Tank 1 to 10.1 ± 0.8 mm/day for Tank 3 during periods when the tank inundated area is greater than 25 % of maximum area. Below this 25% threshold (shown in **Figure 3.16** with dashed line), ET estimates for the tanks exceed PET rates by factors of 2-3. Two mechanisms explained the effect of a smaller inundated area on ET rates, the oasis effect (Drexler et al., 2004; Paraskevas et al., 2013), and rapid lateral equilibration of water in the tank with adjacent exposed areas.

A second question regarded how tanks partition water within a tank cascade, and the ways in which tanks alter the catchment water balance in a basin. Water balance calculations done at the tanks scale revealed groundwater recharge to be the primary outflow component for tanks 1-3. Due to the groundwater discharge behavior of tank 4, the main outflow mechanism for tank 4 was instead sluice outflow. ET was a relatively small component of the water balance, ranging from 13-22% of the water balance for the tanks. This finding contradicts the established view that tanks as losing a large portion of storage to ET. Interestingly, a pattern in tank outflows was found to exist along the cascade, where moving down the cascade the ratio of outflows to capacity increases. This is suggestive of an increasing presence of return flows proceeding towards the downstream, a factor which further emphasizes the importance of studying tanks with respect to position in a cascade rather than in isolation. At the catchment scale water balances were calculated to understand changes in the partitioning of rainfall into runoff (Q), and recharge (R) for the scenarios of with and without tanks. In response, Q was found to decrease significantly from 22% without tanks to 5-9% of rainfall with tanks (**Table 3.5**). The approximately 70% decrease in runoff is consistent with previous work which shows large decreases in runoff due to tanks (Kumar et al., 2008a). In contrast, recharge increased substantially from 17% of rainfall without tanks to 24-27% with tanks (**Table 3.5**).

The third question was to explore how well tanks are able to meet current irrigation requirements and whether tanks can be managed more effectively to improve the meeting of such requirements. For the 2013 monsoon season planting date among the four tanks varied significantly from Oct 17th (Tanks 1 and 2), Sept 25th (Tank 3), and Sept 13th (Tank 4). Earlier planting dates in tanks 3 and 4 were made possible by supplemental groundwater irrigation. For the tanks, it was found that 31-79% of irrigation water demand remained unmet, while substantial amounts of sluice outflow were unutilized (15-50%). Notably, the date of planting significantly affected how well irrigation water demands were met. While later planting dates in tanks 1 and 2 left over 70% of IWD unmet, earlier planting dates in tanks 3 and 4 led to IWD being met much more effectively. These findings suggest changes in planting times, though dependent on groundwater availability, could allow for smaller temporal mismatches between water supply and demand. It should also be noted that since the current study focused specifically on a cascade of four tanks for the 2013 monsoon season, the generalizability of the results presented here are somewhat limited in spatial and temporal extent.

Chapter 4

Model Development and Scenario Analysis

4.1 Introduction

The overall objective of the chapter is to develop a tank water balance model to capture the spatio-temporal dynamics of water storage observed in the four tanks. The model is then used to answer the following questions: (1) For the 2013 NE monsoon season, can changes in management affect the ability to meet irrigation requirements for individual tanks and along a tank cascade? and (2) What are the effects of climatic variability and changes in management controls on tank system sustainability, and the water balance in a basin? While the first question focused only on the 2013 NE monsoon season, a 65-year (1906 – 1969) rainfall time series was used to explore the second question.

This chapter is divided into two main sections. In section 4.2, descriptions are provided for all components of the tank water balance model, including adjustments necessary to model the tanks for the 2013 monsoon season and 65 year simulations. Results are presented in section 4.3, and include a scenario analysis, in which the primary questions posed in this chapter are discussed in detail.

4.2 Modelling Methods

4.2.1 Tank Water Balance Model

A tank water balance model was developed for the four tanks in the study cascade following the approach of Pandey et al 2011. The model proposed in Pandey was modified to account for the inclusion of sluice discharge, and surplus flow. Here, the tank water balance was conceptualized as a function of seven fluxes defining the rate of change in tank water storage (dS/dt (m^3/time)) (**Equation 4.1)**. These fluxes are; rain falling directly on the inundated tank area (Q_{DR}), runoff inflow to the tank from the upstream catchment area (Q_C), evapotranspiration from the tank(Q_E), groundwater exchange (Q_R), sluice discharge (Q_S), and surplus overflow (Q_{OF}). All fluxes are estimated at an hourly rate (m^3/h) for the 2013 simulation for comparison with the high resolution water level measurements. A daily rate (m^3/d) was determined to be adequate for the 65 year simulation. Through field observations, pumping directly out of the tank was found to occur at low tank stage, after sluice outflow ceased. For this reason, an additional outflow (Q_P) was included to represent pumping from the tank at low stages. A conceptual representation of the tank water balance model is shown in **Figure 4.1**. Stage-area relationships (**Section 3.3.1.2**) were used to convert the fluxes Q_{DR}, Q_E, and Q_R from depth (m) to volume.

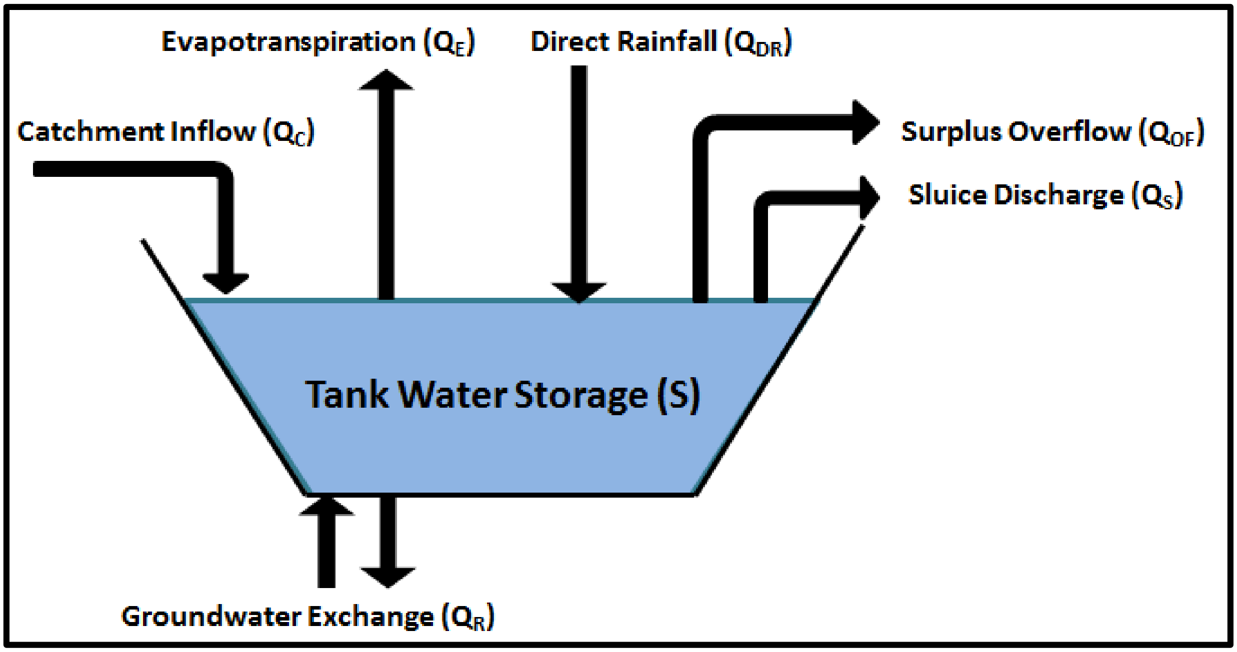

Figure 4.1: Schematic of the tank water balance model.

$$\frac{dS}{dt} = Q_{DR} + Q_C - Q_E - Q_R - Q_S - Q_{OF} - Q_P \qquad \text{Equation 4.1}$$

4.2.2 Tank Fluxes

Rainfall on the Tank

Inflow contributed by rainfall directly on the tank (Q_{DR}) was computed as the product of rainfall (P (m)) and the inundated tank surface area (TSA (m^2)), which was calculated using the stage-area and stage-volume relationships (**Section 3.3.1.2**) (**Equation 4.2**). Here, tank storage (S (m^3) from the previous time step is used to calculate the tank stage (m) via the stage-volume relationships, which is then utilized within the stage-area relationships to calculate TSA.

$$Q_{DR} = \mathrm{TSA} * \mathrm{P} \qquad \text{Equation 4.2}$$

Catchment Runoff

Surface runoff triggered by rainfall in the upstream tank catchment area (Q_C) was estimated using the SCS curve number method modified for Indian conditions as in Sharda et al. 2006 (**Equation 4.6**). Here, use of the curve number method modified for Indian conditions was deemed appropriate given the south Indian context of the study site. The SCS method relies on rainfall data (P) and the abstraction (S), or water intercepted by soil and vegetative processes. Abstraction is estimated as a function of the curve number (CN) of the landscape, which depends on the land use classification of the catchment and the existing antecedent moisture conditions. Where the antecedent moisture condition is noted as either AMC I (dry), AMC II (average), or AMC III (wet). Using **Table 4.1** and **Equations 4.3 and 4.4** the value of CN was adjusted from average conditions (CN_{II} = ~80) to represent dryer (CN_I) or wetter (CN_{III}) conditions. Depending on the AMC conditions CN_I, CN_{II}, or CN_{III} was then used to calculate the initial abstraction (S) (**Equation 4.5**).

After estimation of runoff depth using **Equation 4.6**, the delineated tank catchment area and inundated tank area (TSA) were used to convert runoff depth to volume (**Equation 4.7**). Determination of the tank catchment areas (TCA) was described previously in **section 3.2.8**. A list of variables used for the estimation of Q_C is given in **Table 4.2**.

Table 4.1: Antecedent moisture condition determination thresholds

AMC	Total Precipitation Over Previous 5 Days	
	Dormant Season	**Growing Season**
I	Less than 13 mm	Less than 36 mm
II	13 – 28 mm	36-53 mm
III	More than 28 mm	More than 53 mm

$$CN_I = \frac{(4.2 * CN_{II})}{(10 + .058 * CN_{II})}$$ Equation 4.3

$$CN_{III} = \frac{(23 * CN_{II})}{(10 + .13 * CN_{II})}$$ Equation 4.4

$$S\ (mm) = \frac{25400}{\left(CN_{I,\ II,\ or\ III}\right)} - 254$$ Equation 4.5

$$Q_c(mm) = \frac{(P - .3S)^2}{(P + .7S)}$$ Equation 4.6

$$Q_C\ (m^3) = \frac{Q_c}{1000} * (TCA - TSA)$$ Equation 4.7

Table 4.2: Variables for Catchment Runoff Determination

Variable	Value	Description
CN_{II}	~80	Runoff Curve Number
S	Dependent on AMC condition	Initial Abstraction (mm)
P	Rainfall (mm)	Hourly/Daily rainfall (mm)
TCA	Tank Dependent	Tank Catchment Area(m2)
TSA	Tank Dependent	Inundated Tank Area (m2)

Sluice Discharge

Section 3.3.1.3 detailed the creation of sluice discharge-water level relationships for the sluice(s) of each tank. These linear relationships were used in the current study to estimate the sluice discharge component of the water balance (Q_S). Simulated tank water levels (TWL) were also necessary for this estimation, calculated using the stage-volume relationships (**Section 3.3.1.2**). Volumetric sluice discharge was calculated as in **equation 4.8** for each sluice. In this calculation, (a) is the linear equation coefficient of the sluice discharge-water level relationship (**Table 4.3**), TWL is the tank water level, and SIE is the sluice invert elevation (measured during the field study for each sluice).

$$Q_S\ (m^3) = a * TWL - SIE \qquad \text{Equation 4.8}$$

Table 4.3: Sluice Discharge-Water Level Relationship Coefficients

Sluice ID	Coefficient
T1S1	5.19
T1S2 pt1	9.68
T1S2 pt2	4.92
T2S1 pt1	33.91
T2S1 pt2	16.98
T2S2	2.35
T3S1	6.49
T4S1	44.55

Groundwater Exchange

Groundwater exchange was simulated for each tank using the GE-days since last rain relationships (**Section 3.3.1.4; Figure 3.14)**. A comparison was made between simulated values and measured data in each tank for the 2013 Northeast monsoon season (**Appendix 7.2.2**).

Evapotranspiration

Evapotranspiration was approximated using the Penman-Monteith equation (**Equation 4.9**). Constants required for this approximation (**Table 4.4**) were calculated specific to the study location (**Appendix 7.2.1)**. Volumetric outflow by evapotranspiration was calculated using equation 12.

Table 4.4: Constituent variables used with the Penman Evaporation Equation.

Variable	Value	Description
Δ	.243	Slope of Sat. Vapor pressure curve
Λ	2.45 MJ/Kg	Latent heat of vaporization (water)
Γ	.066 Kpa/C	Psychometric coefficient
Rn	4.73	Net water surface irradiation
Fu	2.488 (m/s)	Wind function
D	2.121 Kpa	Vapor Pressure Deficit

$$E(m) = \frac{(\Delta)}{(\Delta + \gamma)} * \frac{(R_n)}{(\lambda)} * \frac{(\gamma)}{(\Delta + \gamma)} * \frac{6.43 * (f_u) * D}{(\lambda)} \qquad \text{Equation 4.9}$$

$$Q_E\ (m^3) = E * TSA \qquad \text{Equation 4.10}$$

Weir Overflow

Surplus storage in each tank is conveyed to the downstream by a rectangular overflow weir, or weirs in the case of tank 4. Flow over rectangular weirs is commonly calculated using the Francis formula (**Equation 4.11**). Here, the flow of surplus storage over the tank weir(s) is calculated following this formula and converted to an hourly rate for the 2013 simulation, and a daily rate for the 65 year simulation. Parameters required for this calculation are (1) the depth of water flowing over the weir (h), and (2) the weir length which was measured manually for each tank during the field study. Depth of water flowing over the weir was calculated as the difference between the surveyed weir elevation and simulated tank water level. Actual overflow was estimated as the lesser of two quantities: a) overflow estimated using equation 14, and b) the storage volume in excess of the tank capacity (Jayatilaka et al., 2003).

$$Q_{OF}\ (m^3/s) = \ (3.33 * h)^{1.5} * (L - .2h) \qquad \text{Equation 4.11}$$

Table 4.5: Variables used for Francis formula

Variables	Value	Description
L	Tank Dependent	Weir Length
h	Tank Dependent	Head on Weir

Pumping from the tank

In section 3.3.1.4, the observed pumping of water from the tanks was mentioned. This activity was likewise confirmed with tank farmer association members during the focus group discussions (**Section 3.2.7**) to occur when tank water levels drop to below the sluice invert, i.e. the dead storage, to irrigate the downstream command area. Based on this feedback, it was regarded as necessary to represent the pumping of water from the tank. Therefore, several measurements were made via the bucket method, to approximate a flowrate for the aforementioned pumping. For the type of pump which would be used to pump water from the tank (5 horsepower) the measured flow rate on a daily basis equates to 12.62 cubic meters. When pumping from the tank occurs, it is assumed that pumps run 24 hrs per day since supplemental irrigation from the sluice, at this point, has ceased.

4.2.3 Estimation of Command Area Infiltration

In addition to the fluxes directly associated with tank water storage, the contribution of command area irrigation to groundwater storage was also considered. Estimates by the Food and Agriculture Organization of the United Nations (FAO) indicate this contribution by infiltration to be approximately 50 percent of the total irrigation water supplied. This information is used in the current study to estimate groundwater recharge facilitated by the command area (**Equation 12**). This contribution is included in the calculation of the catchment water balance.

$$Q_{Commad\_Area\_Infiltration} = .5 * Q_{S\_Utilized} \quad \text{Equation 4.12}$$

4.2.4 Input Data

Several datasets from the field study (rainfall, tank water levels, and measured data) were used for comparison to more appropriately characterize the model and better simulate the spatial and temporal variability of the Thirumal Samudram tank cascade. For the 2013 monsoon season, rainfall data collected over the same period (**Section 3.2.3**) were used. Daily rainfall from the national oceanic and atmospheric administration (NOAA) for Peraiyur rainfall station (10km from the study site) was used for the 65–year simulation (Vose, 1992). To ensure appropriate representation of all system fluxes, measured values of groundwater exchange, evapotranspiration, sluice outflow, and tank stage were used as a basis of comparison for simulating the dynamics of tank water storage over the 2013 Northeast monsoon season. Such a representation was desired before simulating the management scenarios

4.2.5 Scenario Analysis

A scenario analysis is used to explore the effects on the tank system in response to changes in the seasonal rainfall distribution and two management controls (1) Regulation of sluice outflow, where regulation is either not present or 100% effective, and (2) Changes in planting date timing between October 1st and September 1st. Here, 100% effective sluice management implies that sluice outflow can be turned completely on or off in accordance with irrigation demands, and the other components of the tank water balance vary dynamically in response. In the first scenario, the effects of sluice management are evaluated for the 2013 monsoon season, while planting dates remain based on field observation. In the second scenario, changes in both sluice management and planting date timing are explored in the context of long term variations in the northeast monsoon rainfall distribution. Through this analysis, questions regarding tank system sustainability as well as impacts on the catchment scale water balance are explored. General changes in the northeast monsoon season rainfall distribution are now described, followed by characterization of the two management controls which underlie the scenarios.

In the long-term rainfall dataset used for the 65 year simulation, changes were found in the temporal distribution of rainfall over the Northeast monsoon season. It was generally observed that rainfall in August, November, and December has decreased while increases were observed for September and October (**Figure 4.3**). This suggests that the northeast monsoon has become more concentrated over time. In scenario 2 these changes are explored by estimating % IWD_{Unmet} as well as the catchment water balance each year of the 65 year simulation.

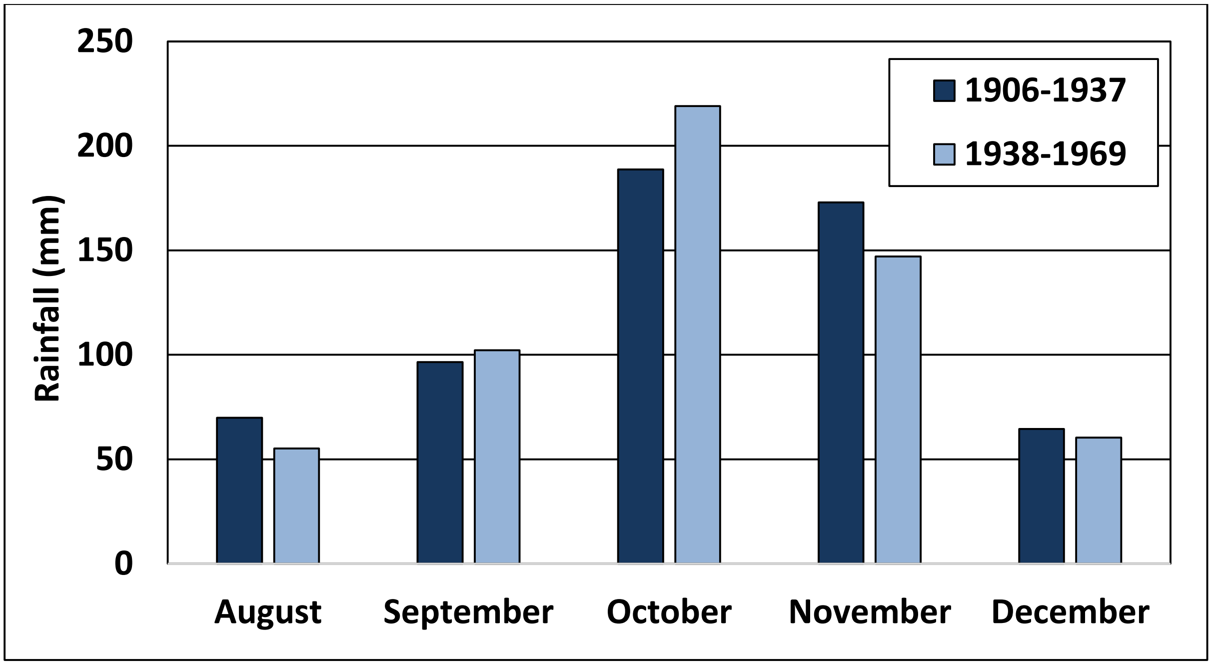

Figure 4.2: Average monthly rainfall for 1906-1937 (Dark Blue), and 1938-1969 (Light Blue)

Presently in the Thirumal Samudram tank cascade, sluice outflows are largely dependent on tank water level changes. This is described as the No Regulation scenario. However, to explore the effects of actively managing sluice outflow, water leaving the sluice is assumed to be influenced by both tank water levels and management decisions. For the scenario of 100% sluice management, sluice outflow may be switched on or off entirely, depending on the irrigation water demand of the command area where:

$$If\ IWD > Q_S,\quad Q_S\ is\ dependent\ on\ tank\ water\ level \qquad \text{Equation 4.13}$$

$$If\ IWD < Q_S, Q_S\ is\ set\ equal\ to\ IWD \qquad \text{Equation 4.14}$$

Changes in planting date determine the temporal alignment of water supply versus demand and thus impact the success of the irrigation scheme. Here, two planting dates were used for the 65 year simulation, October 1st and September 1st, while planting dates for the 2013 monsoon season were based on field observations. The planting dates are meant to represent two modes of decision making. An October planting date corresponds to planting being done upon monsoon arrival and thus filling of the tank. Conversely, a September planting date indicates the use of supplemental groundwater irrigation in advance of monsoon arrival to provide a better temporal match between IWD and sluice outflow. Note that irrigation water demand in this study was estimated in the same manner as described in section 3.2.8, where IWD is the amount of water required to meet plant needs after accounting for the contribution of rainfall.

4.2.6 Definition of Metrics for Evaluating Sustainability of the Tank System

In the introduction, a question was posed on the effect of climate variability and management controls on the sustainability of the tank system. The use of sustainability metrics is increasing recognized as an effective means of evaluating different policy scenarios in water resource systems. Here, the metrics developed by Solis et al. 2010 (reliability, resilience, and vulnerability) are used to understand changes in tank system sustainability. Calculation of these metrics for different management and climatic conditions makes it is possible to quantify changes in the overall probability of success, the likelihood of recovery from failure, and the expected severity of failure when irrigation requirements are not met. As such, the metrics required a success-failure threshold to be established. In this study, success is defined in terms of how well the annual irrigation water demand is satisfied (**Equations 15 and 16**).

$$If\ \%IWD_{Met} \geq 50, \quad Success = 1 \qquad \text{Equation 4.15}$$

$$If\ \%IWD_{Met} < 50, \quad Success = 0 \qquad \text{Equation 4.16}$$

Reliability is then estimated as the number of successful years divided by the total number of years (**Equation 17**). Resilience, generally defined as the capacity to adapt to changing conditions, is more specifically described as the likelihood of a successful year following a year classified as a failure (**Equation 18**). Lastly, the concept of vulnerability has been articulated in several different ways including the average value during failure years, and the probability of exceeding a defined failure threshold (Solis et. al. 2010). This study estimates vulnerability using the first method, as the average value during failure years.

$$Reliability = \frac{No.of\ times\ Success = 1}{n} \qquad \text{Equation 4.17}$$

$$Resilience = \frac{No. of\ times\ Success = 1\ \ follows\ \ Success = 0}{No.\ of\ times\ Success = 0} \qquad \text{Equation 4.18}$$

$$Vulnerability = \frac{\sum(\ \%\ IWD_{Met}\ when\ \ Success = 0)}{No.\ of\ times\ Success = 0} \qquad \text{Equation 4.19}$$

4.3 Results

In this section, a comparison is first made between measured data and simulated tank water levels and fluxes, serving as a basis for further analysis. A scenario analysis is then presented, with the overall goal of understanding the effects of management and monsoon rainfall variability on tank system sustainability, and the ability to satisfy irrigation requirements. Within this section, two scenarios are proposed for simulation. In the first scenario, the effects of imposing sluice regulation for the 2013 monsoon season are explored along the cascade. In the second scenario, the following questions are addressed for a 65 year simulation: (1) How are tank system sustainability, and the catchment scale water balance affected by climatic variability (changes in the northeast monsoon season rainfall distribution) and the imposition of management controls?

Modelled and measured tank water level profiles for the four tanks in the cascade are presented in **Figure 4.3**. Note how the inclusion of pumping from the tank (Q_P) significantly improved the representation of water storage dynamics in the tanks. This improvement coupled with the knowledge that some pumping from the tanks did occur, justified the inclusion of pumping from the tanks as an additional flux. A comparison was also made between modeled and measured fluxes (**Appendix 7.2.2**), and are included for each tank. Overall, the model was able to capture the tank water dynamics across the monsoon season very well.

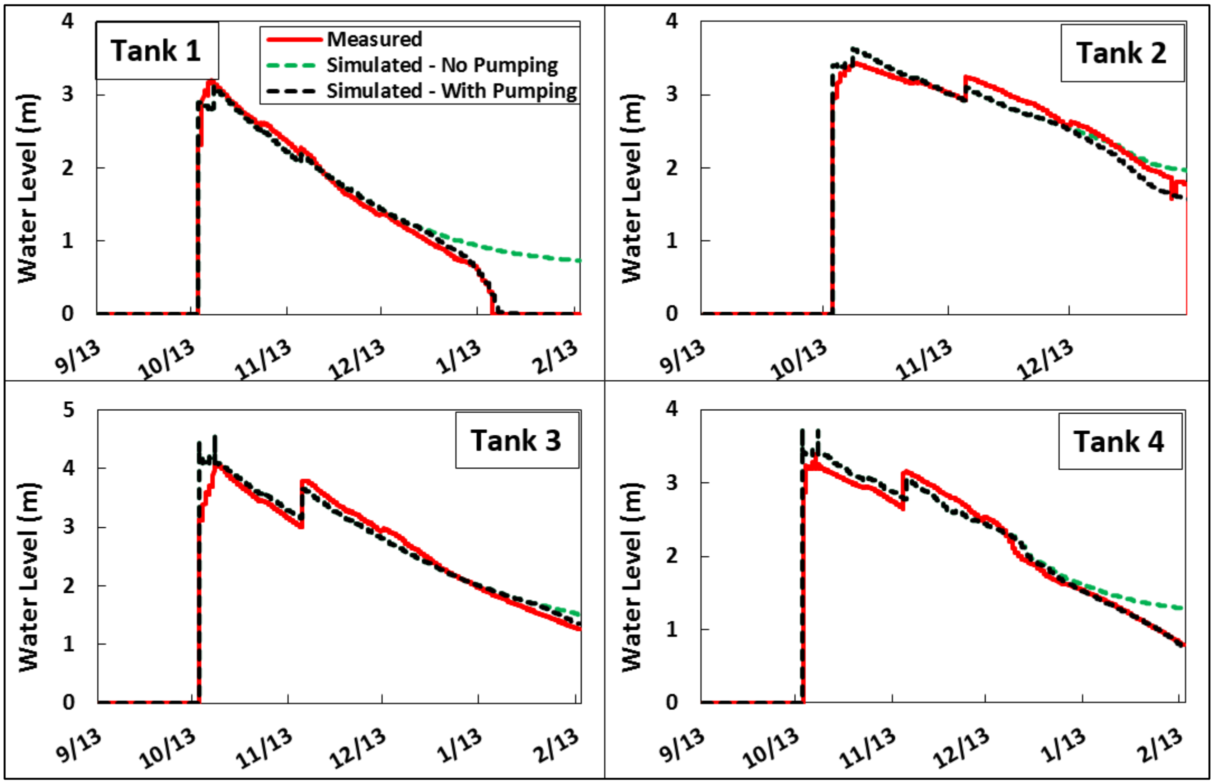

Figure 4.3: Measured and simulated tank stage over the 2013 Northeast monsoon season (a) Without pumping from the tank, and (b) with pumping from the tank

4.3.1 Scenario 1 - Effects of Sluice Management for the 2013 Monsoon Season

The results of imposing 100% sluice regulation was simulated for the 2013 NE monsoon season (**Figure 4.4)**. Imposition of sluice management had observable effects on the tank water level profiles of tanks 1, 2, and 4 while no observable effect was found in tank 3. Surplus sluice outflow in tank 3 was significantly less than that of the other tanks which may explain why an effect was not observed. In tanks 1, 2, and 4, water levels do show a marked rise and corresponding increase in the duration of tank water storage. This follows expectation for tanks 1 and 2, where a later planting date contributed to large amounts of surplus sluice outflow. In tank 4, sluice outflow was the largest water balance component, of which about 40% was surplus sluice outflow. Therefore, changes in the water level profile as a result of sluice management are also reasonable for tank 4.1

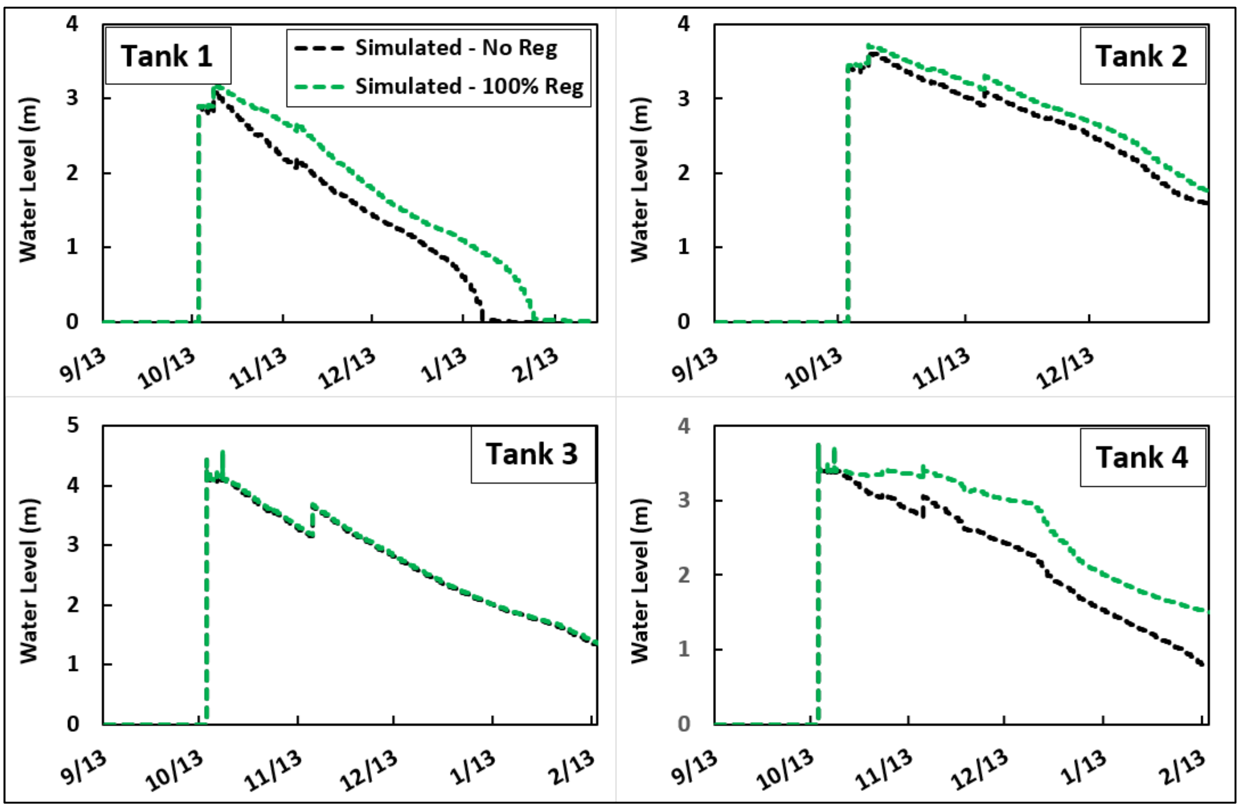

Figure 4.4: Comparison of simulated tank water levels with (green dashed lines) and without (black dashed lines) imposition of sluice regulation.

By imposing 100% sluice regulation, surplus sluice outflow is eliminated, generally leading to increases in the other fluxes, namely ET (5-21%), GE (24-54%), and utilized sluice outflow (9-54%) (**Figure 4.5**). Conversion of surplus sluice outflow into surplus overflow was also observed in tank 3 (50%), and tank 4 (39%). In response to sluice management, significant increases are seen in utilized sluice outflow and groundwater recharge. Such increases improve the ability to meet irrigation water requirements, and enhance recovery of groundwater storage. Therefore, improved management of sluice outflow may over time augment groundwater storage; thus providing a source of supplemental irrigation water, and corresponding mobility to shift the planting date to more appropriately coincide with monsoon surplus. Additionally, increases in surplus overflow emphasize the role of sluice management for improving the water availability of downstream users.

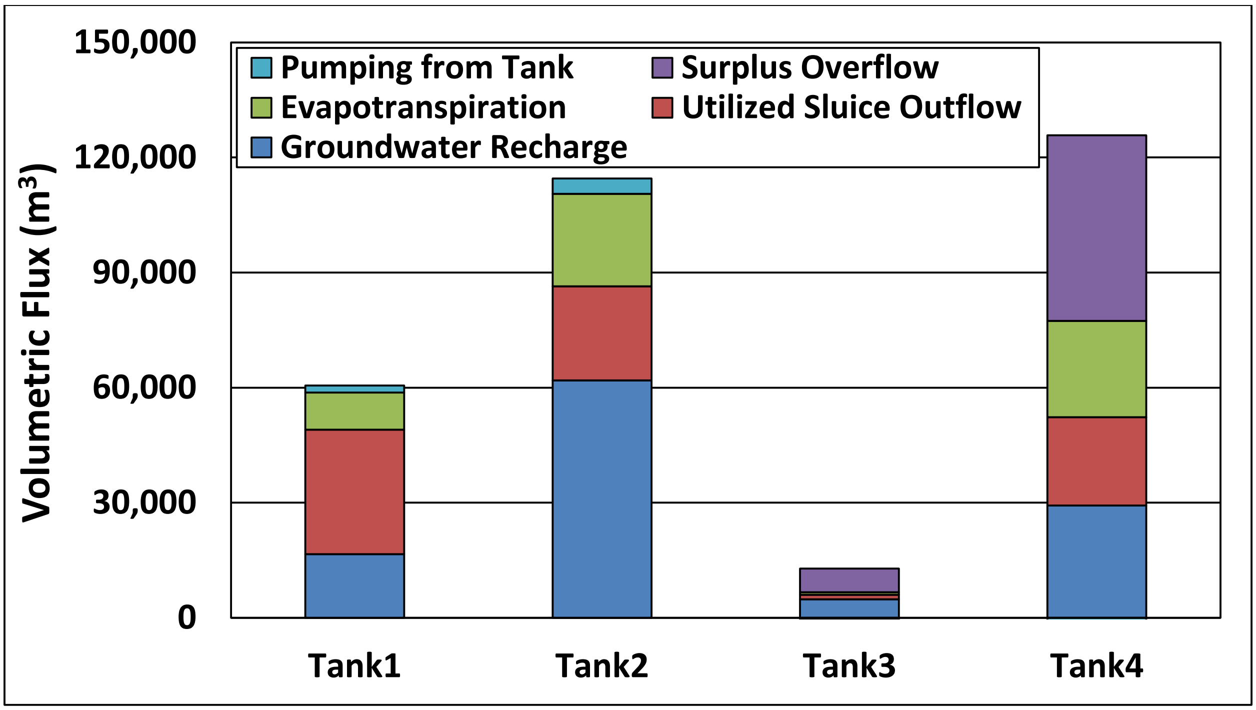

Figure 4.5: Changes in the partitioning of tank fluxes as a result of sluice management

The increase in usable sluice outflow also increased the available irrigation water, and decreased the Unmet Demand IWD_{Unmet}. (**Figure 4.6**). As mentioned, significant increases in utilized sluice outflow were observed for tanks 1, 2, and 4. These increases were mirrored by corresponding decreases in the percent IWD_{Unmet}. For tanks 1 and 2, a late planting date led to temporal mismatches in water supply and demand, causing substantial amounts of surplus sluice outflow. Imposing sluice regulation here led to decreases of 6-12% in IWD_{Unmet}.

In contrast, the planting date in tank 3 was roughly 3 weeks earlier than tanks 1 and 2, allowing for a much better match between irrigation supply and demand. Surplus sluice outflow in tank 3 was thus significantly less than the other tanks, and so IWD_{Unmet} was impacted only marginally. Although tank 4 had the earliest planting date, surplus sluice outflow here was largest, likely due to tank 4 being the most downstream in the cascade and therefore the recipient of more return flow from upstream. Similar to tanks 1 and 2, the large amount of surplus sluice outflow in tank 4 led to an appreciable decrease in IWD_{Unmet} (12%).

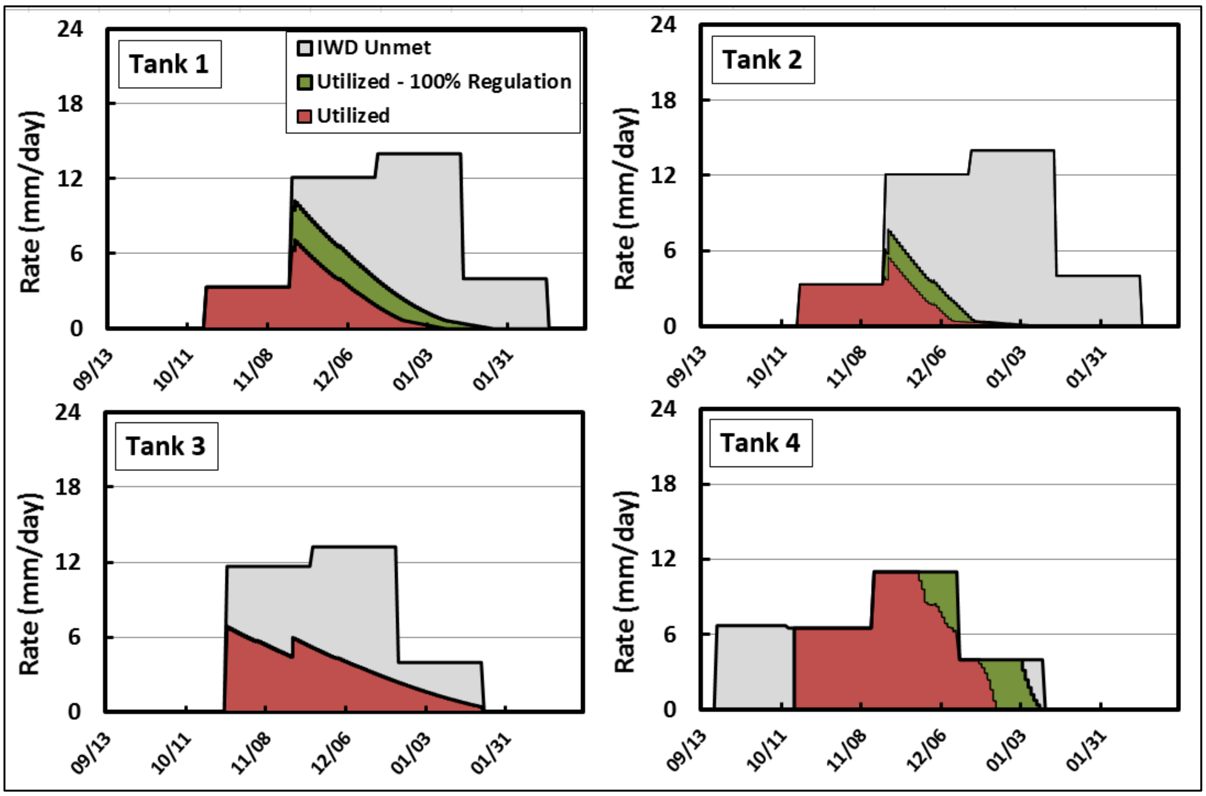

Figure 4.6: Water supply and demand portraits for the four tanks., where utilized sluice outflow with no regulation is shown in dark red, and additional utilized sluice outflow after regulation is shown in green.

4.3.2 Scenario 2 - Effects of Rainfall and Management Controls on Tank Water Availability

In this section, changes in tank water storage dynamics for a 65 year time period are simulated to answer how management controls and climatic variability effect (1) the ability to meet IWD, (2) tank system sustainability, and (3) the catchment scale water balance. Here, sluice management is represented by two sluice outflow conditions (no regulation and 100% regulation). In addition, two planting dates are simulated (October 1st and September 1st), with the intent of representing the conditions in which planting is commenced upon arrival of the monsoon season (October 1st), and where the presence of supplemental groundwater irrigation allows for pre monsoon planting (September 1st).

4.3.2.1 Changes in Ability to Meet Irrigation Water Demand

In general, IWD_{Unmet} was found to decrease in accordance with increasing seasonal rainfall. However, due to temporal variation in the monsoon rainfall distribution this was not always the case, indicating instances where large amounts of overflow occurred. In these instances IWD_{Unmet} was somewhat higher relative to the magnitude of seasonal rainfall. As a result of increases in utilized sluice outflow from sluice management, IWD_{Unmet} generally decreased, irrespective of changes in seasonal rainfall (**Figure 4.7 and 4.8**). This notion highlights the importance of imposing management controls since results indicate benefits to occur regardless of seasonal rainfall fluctuations. Tanks 1, 2, and 4 showed the largest benefit from imposing sluice management, while the effect in tank 3 was minor. This difference may be a result of sluice outflow rates in tank 3 being much less than in the other tanks, leading to overall lesser amounts of surplus sluice outflow.

Interestingly, ability to meet IWD in tanks 1 and 4 appears to be more sensitive to seasonal rainfall variability, where % IWD_{Unmet} fluctuates widely. In these tanks the imposition of sluice management seems to be particularly important for improving the ability to meet irrigation water demands. Conversely, tanks 2 and 3 are relatively less dependent on changes in seasonal rainfall and fall consistently short on meeting irrigation requirements. In tank 2 this may be due to having an extensive command area, making it difficult to fulfill IWD regardless of rainfall. The command area values that we used are based on historical assessments, and most likely the farmers would decrease planting area based on lower water availability. For these tanks, switching to an earlier planting date showed significant decreases in IWD_{Unmet} (20-30% in some years).

As mentioned, an early planting date is meant to demonstrate the condition where groundwater is available for supplemental irrigation, allowing for planting to be done ahead of monsoon arrival. Such a change in planting date can have a large impact on how well irrigation water demands are met. Accordingly, it can be inferred that continual management of sluice outflow will result in augmented groundwater storage by substantially increasing tank recharge. In essence, adopting better sluice management may lead to increased control over the planting date by improving both the ability to meet short term irrigation water demands as well as long term groundwater availability.

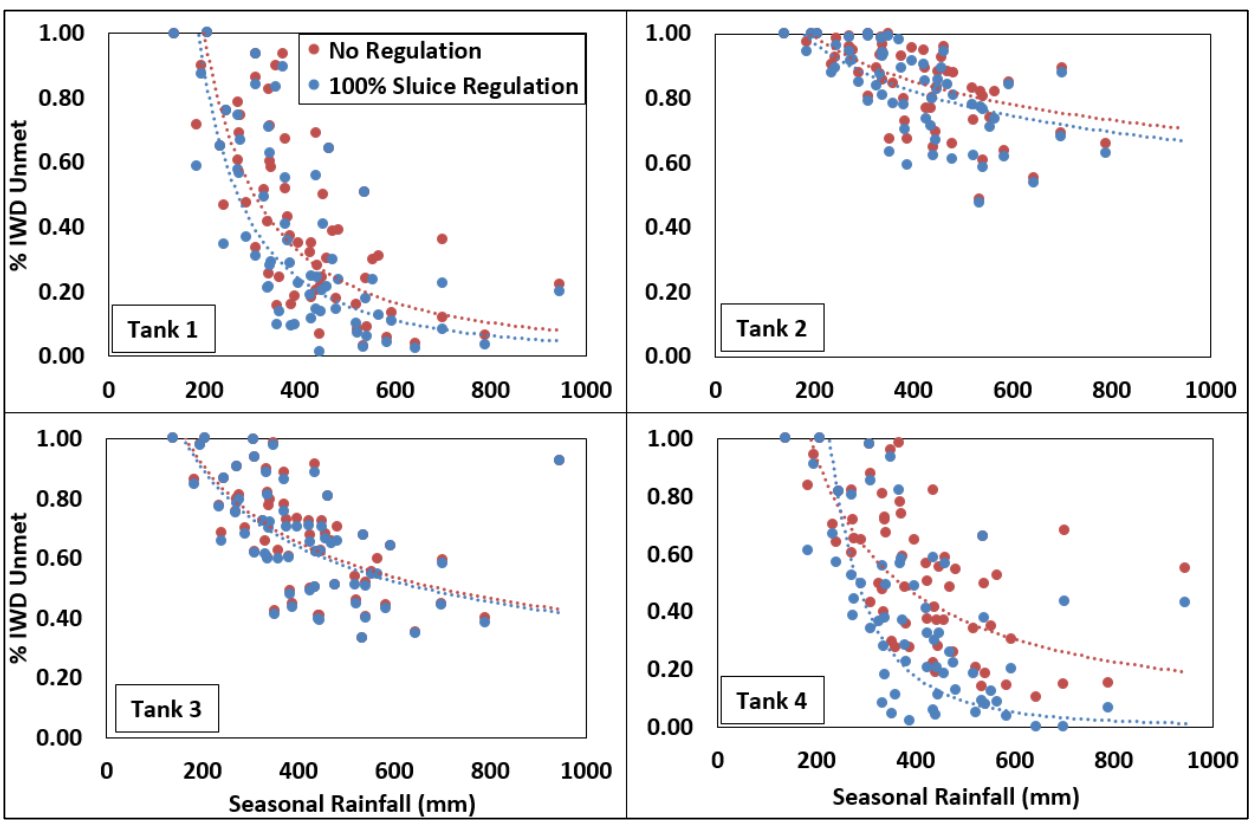

Figure 4.7: Changes in % IWD Unmet as a result of sluice regulation and climatic variability over the 65 year time period (1906 – 1969) (October Planting Date).

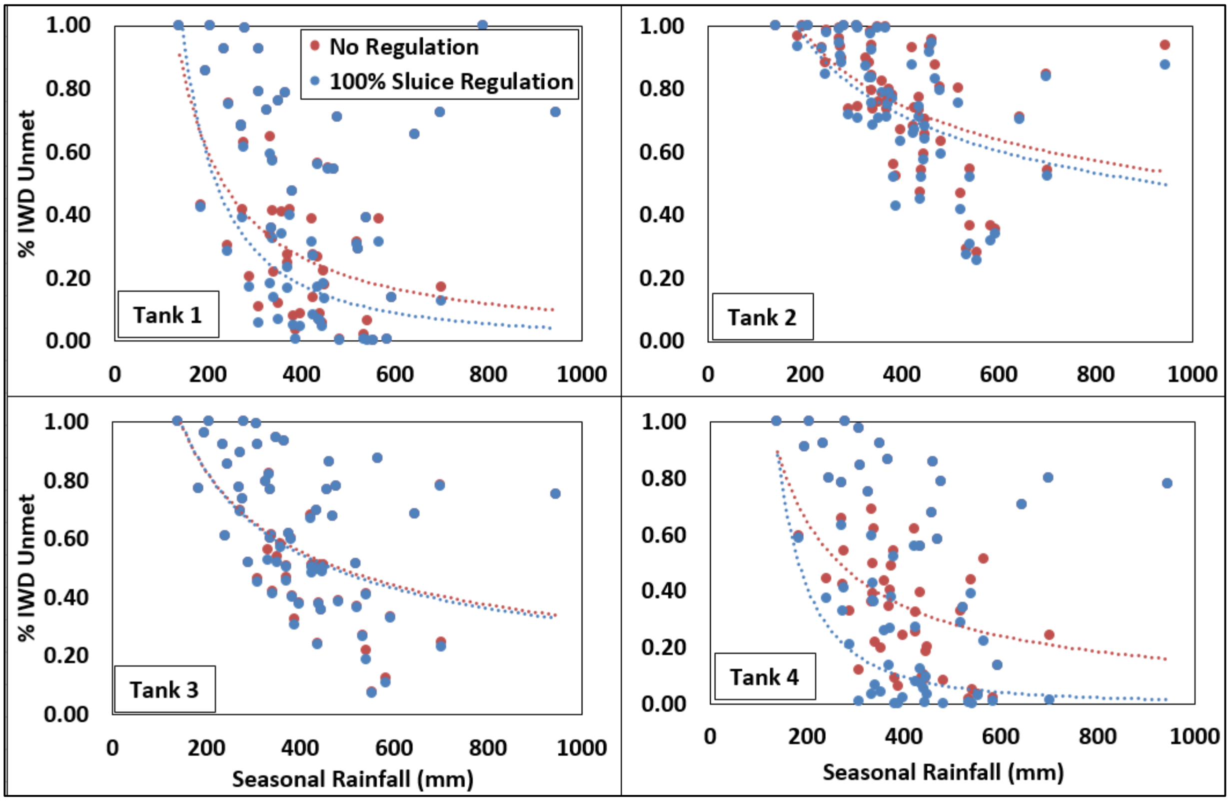

Figure 4.8: Changes in % IWD Unmet as a result of sluice regulation and climatic variability over the 65 year time period (1906 – 1969) (September Planting Date).

4.3.2.2 Effect of Management Controls on the Sustainability of Meeting Irrigation Water Demands.

Observable increases in tank system reliability were found for tanks 1 and 4 as a result of imposing sluice management, while tanks 2 and 3 were instead more strongly affected by a shift in the planting date to September. Resilience showed a similar pattern with large increases after sluice regulation in tanks 1 and 4, and likewise increases in tanks 2 and 3 as a result of shifting the planting date to September. The vulnerability metric, which is an indication of the average % IWD_{Unmet} during a failure year, showed small increases in tanks 1 and 4 from switching to a September planting date while steady decreases were seen in tank 2 after the imposition of management controls.

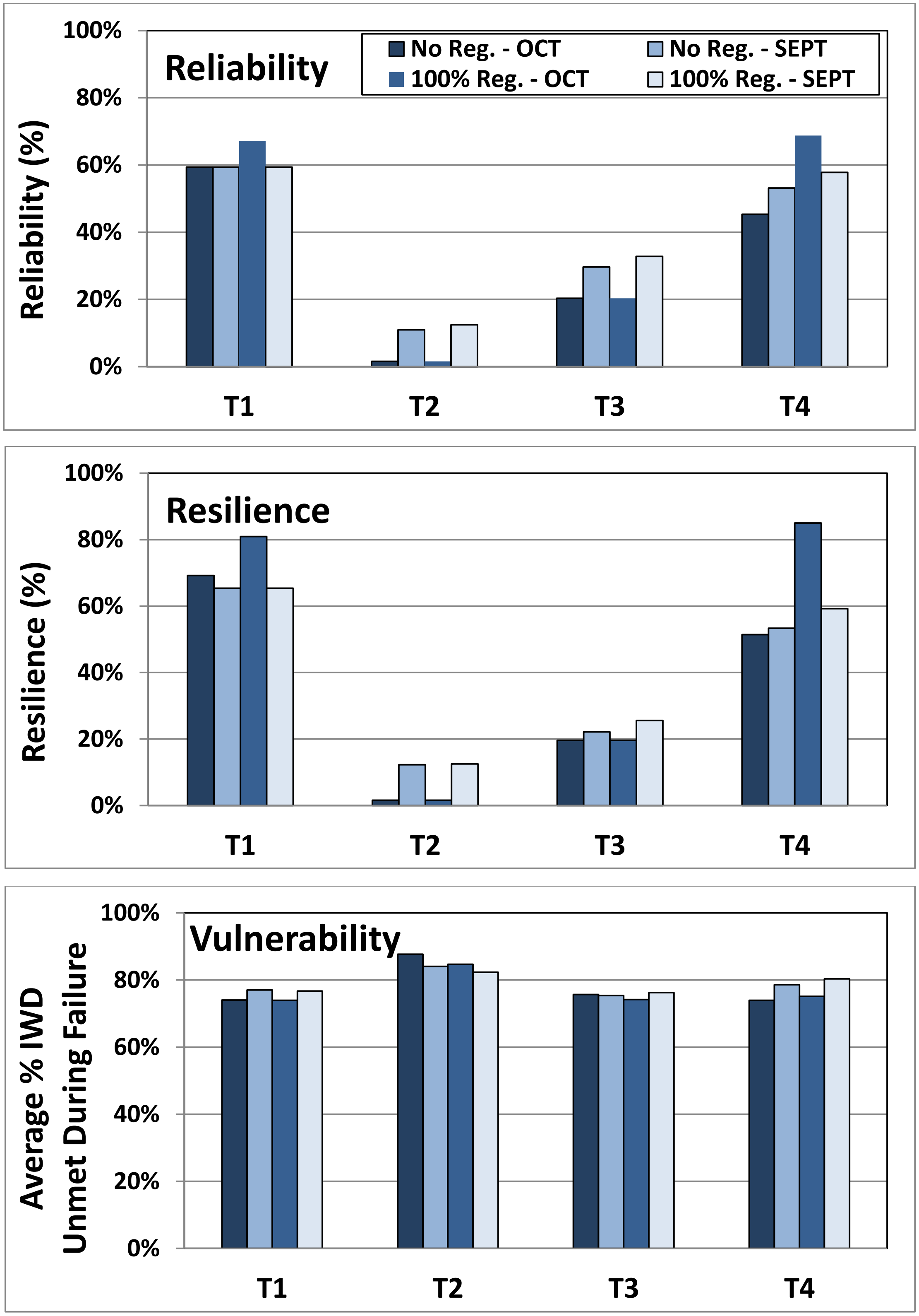

Figure 4.9: (a) Reliability, (b) Resilience, and (c) Vulnerability metrics for the tanks under each management scenario.

4.3.2.3 Effect of Management Controls on Catchment Water Balances

The final question posed in this study regards how the catchment water balance is affected by changes in monsoon season rainfall and the imposition of management controls (sluice regulation and planting date timing) for two general cases; with tanks (WT), and without tanks (NT). Catchment water balances were calculated for each year of the 65 year simulation following the same procedure as in section 3.2.8. For the no tank case, runoff was calculated each year using the curve number runoff method modified for Indian conditions as in section 4.2.2, while recharge was assumed as 17% of rainfall. For the with tank case, catchment runoff was assumed to be the summation of tank sluice outflow and overflow from the most downstream tank. Further, recharge for the case with tanks in the landscape was calculated as the sum of tank recharge, command area infiltration (section 4.2.3), and 17% of rainfall from the catchment area.

Results of the catchment water balance indicate that tanks have a significant impact in the landscape for reducing monsoonal runoff regardless of changes in season rainfall, with Q/P ranging from 3-9% for tanks without regulation (**Figure 4.10**). Further, this reduction in runoff increases proportionally with seasonal rainfall in comparison to the no tank case. This point demonstrates the ability of tanks to buffer against large fluctuations in seasonal rainfall, consistently offering drastic reductions in catchment scale monsoon runoff. The inclusion of management controls increases this ability, reducing Q/P by an additional 1-2% of rainfall. In contrast, with no tanks in the landscape Q/P fluctuates from 10-40% depending on variations in seasonal rainfall.

Results indicate the presence of tanks in the landscape not only reduce catchment runoff drastically, but also facilitate a significant improvement in catchment scale groundwater recharge (**Figure 4.11**). In comparison with the no tank case, the presence of tanks increased recharge by an additional 3-9% of rainfall, an average increase of approximately 30% over the no tank case. These results demonstrate that despite highly variable seasonal rainfall, tanks can consistently improve catchment scale recharge by substantial amounts.

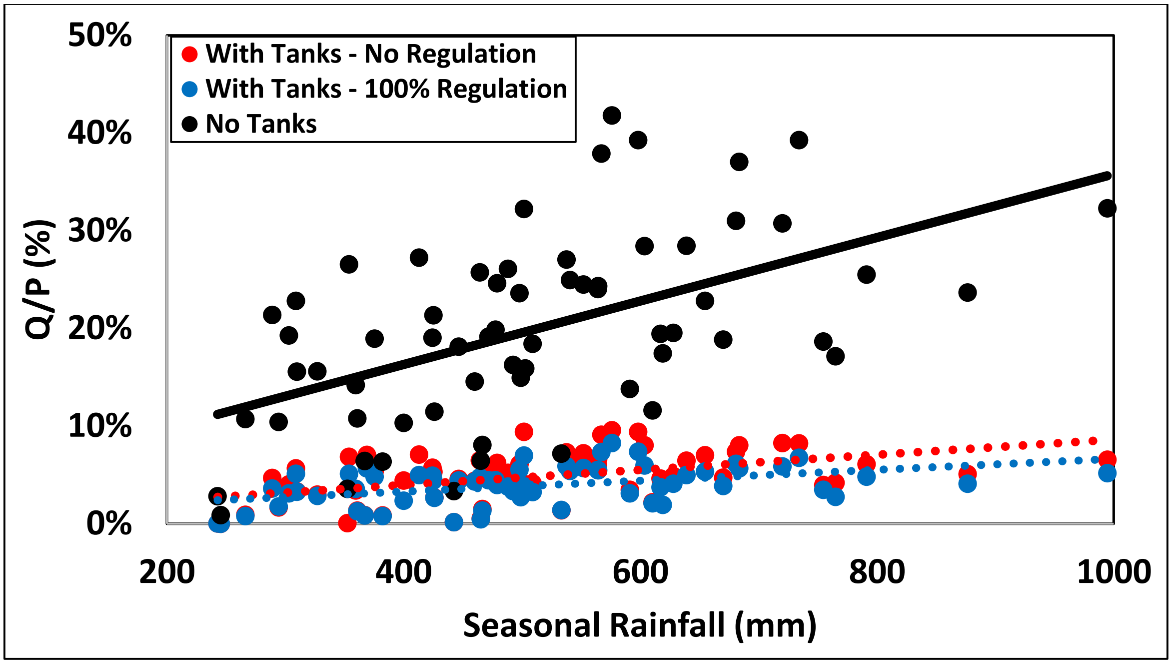

Figure 4.10: Runoff as a percent of seasonal rainfall for the No tank case (black), With tanks but no regulation (red), and with tanks and regulation (blue)

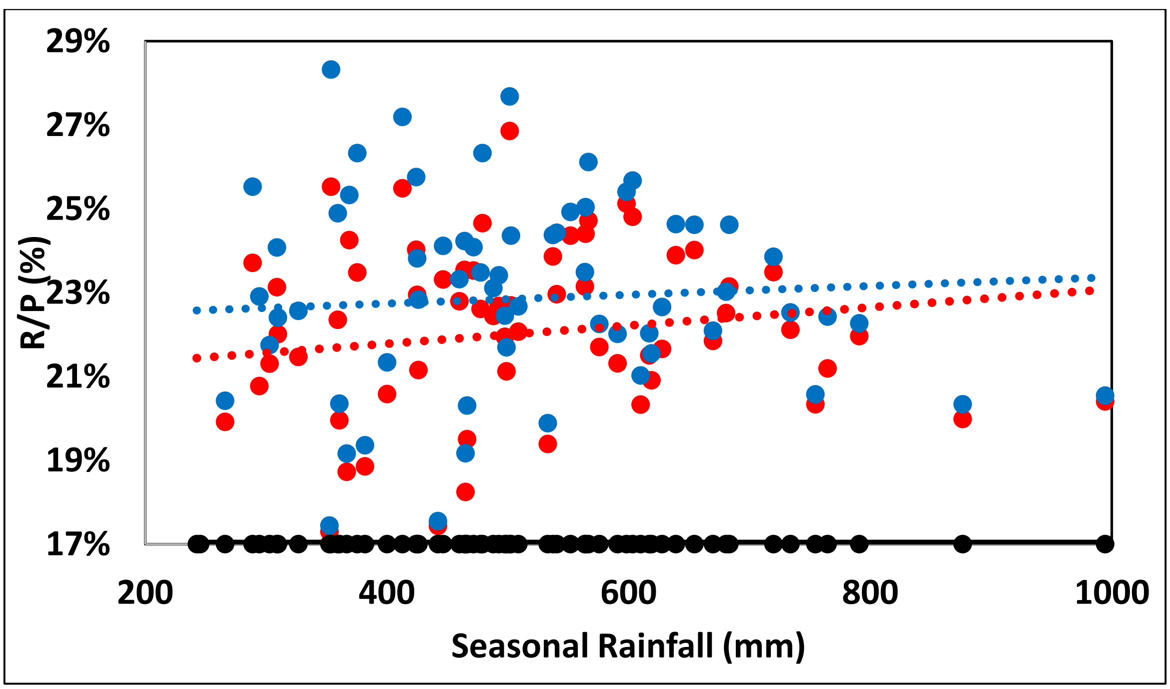

Figure 4.11: Recharge as a percent of seasonal rainfall for the No tank case (black), With tanks but no regulation (red), and with tanks and regulation (blue)

4.4 Summary

In this study, a tank water balance model was created to understand the effects management controls at the tank, and catchment scales. This was done by exploring two key questions: (1) How do management controls effect the ability to meet irrigation requirements along a cascade, and (2) For a 65 year simulation – How do changes in management effect tank system sustainability, and the water balance in a basin. To address these questions two scenarios were created. The first explored the effects of sluice management on the partitioning of tank fluxes and the ability to meet irrigation water demands over the 2013 monsoon season. In the second scenario, the effects of management controls and climatic variability were addressed with respect to changes in ability to meet IWD, the sustainability of the tank system, and the catchment scale water balance for conditions of with and without tanks.

For the 2013 monsoon season, several commonalities were observed for the tanks. Following sluice management, increases in utilized sluice outflow and groundwater recharge were found to be much more significant than increases in ET. Further, substantial increases in surplus overflow for tanks 3 and 4 suggests sluice management may improve water availability for downstream users. As a result of increases in utilized sluice outflow, the water supply and demand portraits for the tanks also changed. In tanks 1, 2, and 4, IWD_{Unmet} decreased by 6-12% following imposed sluice management, while minor effects were observed in tank 3. As mentioned, the results of imposing sluice management also indicate significant increases in tank recharge. An increase which would likely augment groundwater storage and allow for supplemental groundwater irrigation. In this way, improved sluice management has the potential of offering more control over the planting date, leading to further decreases in $IWD_{Unmet.}$

In the 65 year scenario, IWD_{Unmet} was found to decrease consistently with improved sluice management despite large fluctuations in seasonal rainfall. Again these decreases were more substantial in tanks 1, 2, and 4 where surplus outflow was generally much higher. IWD_{Unmet} also decreased as a result of changing the planting date. These effects were more pronounced for tanks 2 and 3, leading to large decreases in IWD_{Unmet} of 20-30% in some cases. Evaluation of tank system sustainability metrics revealed increases in reliability for tanks 1 and 4 following sluice management, while similar increases were seen in tanks 2 and 3 after switching to an earlier planting date. Increases in system resilience were likewise observed and mirrored the changes in reliability. Changes in vulnerability were smaller, with tanks 1 and 4 becoming somewhat more vulnerable after switching to an earlier planting date, and tank 2 generally seeing decreased vulnerability after the imposition of management controls.

Results of the catchment water balance indicate that tanks have a significant impact in the landscape for reducing monsoonal runoff and increasing recharge, regardless of changes in season rainfall (**Figure 4.10 and 4.11**). Here, the runoff-rainfall ratio (Q/P) decreased from 10-40% without tanks to 3-9% with tanks and no regulation. The addition of management controls further reduced runoff by an additional 1-2% of rainfall. Significant effects were also observed regarding catchment scale recharge. Relative to the no tank case, the presence of tanks in the landscape increase catchment scale recharge by 3-9% of rainfall, an average increase of approximately 17-53% over the no tank case.

Chapter 5

Conclusions

5.0 Conclusions and Future Work

In recent decades there has been growing interest in the revival and expanded use of rainwater harvesting tanks across the agricultural landscapes of India and other semi-arid regions to address issues of water scarcity and aquifer depletion. While it is well established that these tanks can increase local water availability, leading to higher crop yields and direct socioeconomic benefits (Palanisami, Meinzen-Dick, & Giordano, 2010b), the impact of widespread use of small, distributed storage reservoirs on the catchment-scale partitioning of water resources is still an open question. Furthermore, while significant resources are being used to rehabilitate tanks, there is a lack of understanding regarding how these ancient structures function in a modern landscape, under current socioeconomic and environmental pressures. The hydrology of these tanks is so intricately tied with the social system in which they are embedded that only a systems approach, accounting for interactions between natural and human systems, can allow for a full understanding to manage these systems.

Following this systems approach, the overall objective of this thesis was to better understand how tanks partition stored water into groundwater recharge (GE), evapo-transpiration (ET), and sluice outflow (S_o) at both the local and catchment scales. To meet this objective the study focused on a cascade of four connected tanks in the Gundar basin watershed in the south Indian state of Tamil Nadu. Three sub-objectives were established and met through a field study and a modeling study. These sub-objectives were to (1) evaluate the potential of a novel approach (the White Method) to estimate temporal patterns in groundwater exchange and evapotranspiration over the Northeast monsoon season; (2) describe spatial patterns of groundwater exchange and evapo-transpiration fluxes from upstream to downstream tanks in a cascade, and (3) adapt a tank water balance modelling approach to simulate the effects of changing climatic conditions and the imposition of management controls. The major conclusions of my research are presented in Section 5.1, while future work is described in Section 5.2

5.1 Major Conclusions

The following were the major conclusions of the study:

1. Groundwater recharge (28-59%) and sluice outflow (19-55%) were found to be the largest components of the tank water budget, while evapo-transpiration was relatively small in comparison, constituting only 13-22% of total outflows. Although sluice outflow constituted a large portion of the tank water balance, a significant amount of this outflow was unutilized (15-50%). Despite ongoing efforts to rehabilitate the tanks, continuous leakage through the sluices led to water being wasted at times of lower crop demand. Therefore, better sluice management may contribute to tanks meeting a higher fraction of crop water requirements.
2. Distinct spatial patterns in groundwater recharge and evapo-transpiration were observed as a function of tank location within the cascade. While the groundwater exchange dynamics in tanks 1, 2, and 3 were driven by groundwater recharge, the most downgradient tank (tank 4) was dominated by groundwater discharge (inflow). Tank 4 also had the highest ratio of outflow to tank capacity, and as a result provided more irrigation water relative to maximum tank storage. This observation indicates a strong influence of return flows from upstream command areas, which emphasizes the importance of studying tanks relative to their location within a cascade rather than in isolation.
3. A pattern of crop planting date was found in the tanks and contributed directly to the effectiveness of utilizing the available water. In the upstream tanks, planting was commenced upon the arrival of the monsoon, causing a large temporal mismatch between water supply and demand, and resulting in large amounts of surplus sluice outflow. In contrast, earlier planting dates were observed for more down-gradient tanks, leading to a better temporal matching of water supply and demand. Conversations with farmers suggested these earlier planting dates may be due to greater groundwater availability in the lower tanks in the cascade, which allowed for farmers to plant before the monsoons arrived, and to use the available water more effectively than in the upstream. This dynamic highlights the feedbacks that exist between the natural and human systems, particularly at the catchment scale. As a result, increased water availability in the downstream leads to an earlier planting date, in turn leading to more efficient use of available water.

4. At the catchment scale, the presence of tanks led to a drastic reduction in runoff of approximately 70%, while recharge increased by 40%. These findings indicate rainwater harvesting tanks can substantially increase water availability at the basin scale. However, the dramatic decrease in monsoon runoff highlights the potentially negative effects for downstream users.
5. Model simulations revealed that the imposition of sluice management led to increases in groundwater recharge and utilized sluice outflow. Surplus overflow also increased, which suggests that more effective sluice management can lead to improved water availability for downstream users. Increases in utilized sluice outflow altered the water supply and demand portraits for the tanks, decreasing the unmet irrigation water demand by 6-12%. Further, the observed increases in groundwater recharge following sluice management would likely augment local groundwater storage and allow for supplemental groundwater irrigation. Therefore, sluice management could provide more control over the planting date, and lead to more efficient use of available water.
6. Long term simulation of the tank water balance allowed for a better understanding of the effects of climate variability and management controls on the ability to meet irrigation requirements. The unmet irrigation water demand IWD_{Unmet} decreased with increasing seasonal rainfall, and decreases in IWD_{Unmet} were consistently observed following sluice management. This finding demonstrates the ability of tanks to improve the ability to meet crop water requirements in the face of changing climatic conditions. Likewise, shifting to an earlier planting date also showed marked decreases in IWD_{Unmet} of 20-30% for tanks 2 and 3.
7. Calculation of the catchment scale water balance for the 65-year simulation revealed tanks to have a consistently significant impact in the landscape despite large fluctuations in seasonal rainfall. The presence of tanks in the landscape reduced catchment runoff by 65-75%, with proportionally larger reductions seen during years of higher seasonal rainfall. In contrast recharge was found to increase by 17-53% due to the presence of tanks.
8. The imposition of management controls for the long term (65 year) simulation led to increased reliability and resilience for the tanks. These increases were associated more strongly with imposing sluice management in tanks 1 and 4, and shifting to an earlier planting date in tanks 2 and 3. Tank system vulnerability remained primary unchanged

after imposing management controls, except in tank 2, where vulnerability decreased significantly.

5.2 Future Research

An important focus for future research is to better understand the socioeconomic and cultural dynamics of tank management at tank and catchment scales. To do this, use of a system dynamics or agent based modelling approach may be appropriate. Such techniques would allow for more complex feedback mechanisms like farmer decision making and changes in land use to be represented. Use of remotely sensed information could provide additional opportunities for both extending knowledge of tank systems to broader scales but also to different geographic contexts. Studying a larger tank cascade, perhaps over a longer time period, is also of interest. This may broaden the applicability of results and reveal additional nuances about how tanks function in the landscape, affecting basin scale water storage and partitioning. Further, the upstream-downstream dynamics of tank water storage may also be understood in greater detail.

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Appendices

7.1 Field Study Appendix

7.1.1 Data Collection and Sensor Installation

7.1.1.1 Bathymetry

Bathymetry data points were imported into a GIS and filtered. Only points of less than 30cm vertical precision were utilized for further analysis (**Figure 3.5c**). Filtering was only done for points collected with the Trimble GPS system. As such, Tank 4 points were not filtered since all were collected using total station. Filtered data points were subsequently used to create a TIN (Triangular Irregular Network). TIN files were then converted to Raster via the Natural Neighbor interpolation method (**Figure 3.5c**). A functional surface command was finally employed to estimate the volume below user defined stage values at 25cm increments. Volume values were finally plotted against corresponding values of stage where stage is the height above the minimum tank elevation given in the Raster file.

7.1.1.2 Pressure Transducer Installation Procedure

The deepest point of each tank was determined by inspection and chosen as the location to install the water level sensor. Using a crowbar and local expertise, a shaft approximately 70 cm deep and 15 cm in diameter was excavated. The depth of each shaft was limited by the extremely hard clayey nature of the soil. After excavation, the housing well was inserted and slowly backfilled with the removed soil and checked for level. Backfill was placed up to 10cm from ground level and lightly tamped with a crowbar. The remaining 10cm to ground level was filled with concrete mixed and placed by hand (**Figure 7.3b**).

To ensure proper stability of the housing well, 10 gauge 2” diameter pvc pipe was chosen. The bottom 1 m of pipe was drilled with holes at equally spaced intervals to allow for instantaneous equilibration with the surrounding water. A filter sock was fit over this section to prevent sediment from entering the well. Each end of the filter sock was secured to the pipe with a 10 inch zip tie.

A 2” PVC cap was then permanently fixed at the bottom end of the housing well to prevent sediment entering from the bottom. After securing the water level sensor in the housing well a removable 2” PVC cap was installed to allow for future retrieval of the sensor under inundated conditions. A list of all materials used for installation of the housing wells is given in **Table 7.1**.

Table 7.1: Summary of housing well installation materials

Material	Purpose
3 m PVC Pipe (2” Dia.)	Provide housing for pressure transducer
2 PVC Caps (2” Dia.)	Seal ends of PVC Pipe
PVC Glue	Sealing PVC Connections
50 cm Filter Sock Material	Prevent Soil entry through perforations
2 zip ties (10” length	Secure filter sock to PVC Pipe
4 m fishing line (10lb test)	Suspend Transducer inside PVC Pipe
Measuring Tape	Check lengths of Pipe and line w/ sensor
Level	Level the PVC pipe during installation
1 Solinst Levellogger Edge	Record continuous water level data

Following bottom cap attachment, each Solinst edge water level pressure transducer was hung inside the housing well 20cm from the bottom to reduce the chance of sensor sedimentation. This was accomplished via tying 10lb test fishing line directly to the sensor using a figure eight follow through knot. The end of this line was fed through a small hole drilled 3cm from the top end of the pipe and wrapped around the pipe diameter 5 times before being securing with duct tape.

7.1.1.3 Sluice Outflow Estimation Procedure

Cross-sectional area measurements were made at the start and end points of the chosen section using two marking rods (**Figure 3.4c**). A reference rod was placed across the channel and levelled at the point of measurement while a second rod was used to measure the depth of outflow. These measurements were made at 5 cm intervals over the entire channel width and used to create a profile of outflow depth. Since each profile was a series of adjacent, 5cm wide trapezoids, the areas were estimated as such and summed to yield the total cross-sectional area. As multiple cross sections were estimated for each measurement, an average value was used. Cross sectional area was multiplied by the range of flow velocities to estimate discharge.

7.1.2 Focus Group Discussion Results

Table 7.2: Focus group questionnaire

	Tank 1	Tank 2	Tank 3	Tank 4
Availability of Water in Tanks	120 days of irrigation availability if the tank spills over and dead storage will be present until March. This year the farmers expect 60 days of irrigation availability assuming no further rain. After tank irrigation stops the dead storage water is used and then wells. If tank irrigation stops early then dead storage water is used by pumping over the bund via diesel pumps. For this, Small farmers group together to get a diesel pump while larger farmers do so individually. This activity has no common irrigator.	Normal Year- October to March 2010 – More than six months of water available 2012- Only filled half way and empty by December 2013- Currently half full but should normally be full by this date (11/28)	6 months Total. 4 months of irrigation from tank. During low rain years in the past manual and oil pumps have been used but only as needed.	40 days sluice irrigation after tank filling. Dead storage available until march.
Catchment		Good Classification Direct Catchment Area – 200 acres Additionally 500-600 acres that fills 1st tank and comes to 2nd tank		
Overflow Weir	4 of the last 10 years have had spillover. 20 Years ago the tank would spillover every year but this no longer happens due to upstream encroachment of the feeder channel encroachment from a town which has grown larger and reduced the size of the channel.	.75 m Height Contains shutter for emergencies Overflowed 7 out of the 10 past years: has not over flowed since 2010	4 of last 10 years surplus.2010,2007,2006 ,2005	5 of last 10 years Surplus: 2005, 2006, 2007, 2011, 2013
Command Area		Design: 160 Acres Present: 184 Acres during good rain 2012: 20 acres 2013: 10 acres paddy crop irrigated by well, only nurseries are grown		
Command Area Wells	10 years ago a number of borewells were attempted but all failed. Only 4 functioning borewells exist and are operated by the village panchayat, are 300-500ft deep, and supply water to 2 nearby villages.	5 open wells within command area all functioning 25 open wells in total surrounding area (12 non functioning- all functioning previous to 2011) "If tanks fill, wells fill" – Farmer Quote 4 deep bore wells, 10 side bore wells Wells are owned by 1 farmer and generally used by 1 farmer 75% of pump motors are 5 Hp and the rest 3 Hp		OW/BW have good water supply when water in tank. OW/BW used for irrigation after sluice outflow stops.
Pumping Rate	All command area wells have 5hp hispeed motors. 1 bore has 5hp, 3 bore have 7.5hp	Oct- Dec: 2013 (2-3 hours/ day), good year (8-12 hours per day) Jan-Feb.: 2013 (2 hours/day), good year (8 hours/day)	All 3hp motors	Mix of 3, 5, and 7.5 hp motors. Table values available. Borewells operating 12hrs/day all year. Open Wells: Apr-May: No water, Sept.-Oct: 6hrs pumping, Nov.-Mar.:5hrs
Crops	1st Crop – Paddy – 120 day growing season 30 day nursery period (2-3 Irrigations), 80 days in main field (20-40 Irrigations), 10 day final stage (No irrigation) 2nd Crop – Cotton or Sorghum – 3month growing season Recieves only 1 or 2 irrigations from the tank otherwise tank runs dry. Cotton starts in February, Sorghum starts in March/April.	Paddy: 2010-2011: Normal crops irrigated 40 times with tank and 0 times with well 2012: 20 acres, irrigated 40 times with well and 0 times with tank 2013: Have not started crops, only select nurseries Harvest: 30-35 bags/acre (70 kg/bag, 600-700 rupees/bag) , 2012-700 bag Irrigation: 10-15 times per month (October – December), ideal 5 cm standing water in field Fertilizer applied 3 times during season Minor Millet: (sorghum, maize, cholam) 2012: 20 acres grown during summer season Harvest: 10-15 bags/acre (70 kg/bag, 1500 rupees/bag Only well farmers can receive good yield, rain fed farmers cannot get good yields	1st Crop - Paddy - Growing season (Oct/Nov. - Jan). Irrigating 15 days per month for ~90 days. 2nd Crop - No Second Crop Minor millet is grown before paddy by rain in the command area.	1st crop – paddy (4 months), sowing in Oct., Harvest in Jan/Feb. 2nd crop – cotton/sorghum, sowing Feb-March, Harvest July-August/May-June. Normal Harvest: 35 bags paddy yield per acre (1 bag = 72kg). Farmers keep 10 bags for consumption, rest is sold at market. In Surplus years 1-2 tank irrigations for 2nd crop, rest from wells. Paddy irrigated once per week. 15 Times total from tank. Deficit years final irrigations come from wells.

	Tank 1	Tank 2	Tank 3	Tank 4
Water Trading & Purchasing:	No surplus water to sell this year. When surplus is available, water is sold for 200-300 Rupees for 12 hrs of pumping.	40 years ago water traded now there isn't trading because there isn't water	Not enough water to sell	After sluice irrigation stops, farmers buying water from well owners for 15-20R per pump hour or 100-200R per 8 hours.
Fish Rearing	Fish are not being stocked in the tank but do occur naturally. There's a village belief against the stocking/selling of fish. OBSERVATION NOTE: Groups of men go to the tank on Sunday morning to fish from the sluice structures. Fish caught are quite small and only for personal consumption.	PWD (public works department) leases tank to individual to raise fish. Lease is 20,000 to 35,000 Rupees depending on year (money goes to panchayat). Fish rearing occurs for 3 months (November – January sometimes February). Leaser purchases from fish nursery 10,000 rupees for 20,000 fish, 30,000 rupees for feed cost. 10,000 fish survive to grow to size of 1-2 kg. Net profit: 1 lock, Gross income: 60,000 (minimum 40-50,000)	No fish rearing in tank. Fish occur naturally and are harvested at the end of March by all people in the community. 500kg total. 40rupees/kg. All consumed within the community (kudipatti)	Farmers rear fish in the tank and use it for their own consumption. 300 kg fish/ year.
Tree Species	Income from tamarind trees goes to village panchayat; they sell the trees. Some farmers sell for tank maintenance. Little/No income from harvesting of Juliflora trees.	Tamarind- 2 km tank bund length, 50 trees. Leased to one person for 2000-4000 rupees/year. Net income 6000 rupees	27 Tamarind trees. In the past the village panchayat gave a lease to one farmer for 2000R per year. Usually yields 5000 rupees profit, 8000 gross income. Selling tamarind fruits and wood. The last 3-5 years panchayat has not given lease. Now fruits are harvested individually, No cutting takes place.	Income from acacia trees in water spread area goes to the forest department (they maintain the trees). 3-4 lak rupees income every 5 years from trees. Income from trees in the tank bund goes to the village panchayat.
Water Distribution During Crisis	When 5-7 days of tank irrigation are left, a system of regulated irrigation comes into place where fields are irrigated in a circular pattern one after another to reduce conveyance losses.	If irrigation crisis occurs it is within the Paddy maturity time. The sluice is permanently closed and only leakage is allowed to be used for irrigation. A farmer will receive water for irrigation every 5-6 days, rotation through the farmers occurs by relations (1 family receives water, next family receives water until the rotation begins again). Out of 10 years, 3-4 years of crisis occurs	Interval use of water. Farmers Irrigate once every 6-7 days. Sluice is only opened when needed. Irrigate nearest to tailend.	During deficit period, farmers use tubes and hoses for irrigation to reduce conveyance losses.
Silt Distribution	1 or 2 years ago silt from waterspread area was being used for commercial brick making. This use was banned by the government after the Pappanaickenpatti tank farmers association sent a letter requesting a ban be instated. Now permission must be obtained before silt may be gathered for application to fields and for bund strengthening. Permission cannot be given for brickmaking.	10 years ago – No government regulation so all farmers took silt for yield increase. After law- farmers must go through proper permission (no payment) to take silt, those caught taking silt w/o permission have their tractors confiscated. 2013- 5 farmers received permission and applied silt to 20 acres	Permission is required to collect silt for field application. People stealing silt for selling to commercial brick makers. For the last five years noone has applied for silt because it's such a lengthy process. Before 5 years ago everyone was harvesting silt and applying to fields by bullock cart.	Last year farmers took 1000 truck loads of silt from tank for field application after getting permission from government. Soil is black cotton soil and could not be used for brick making.

	Tank 1	Tank 2	Tank 3	Tank 4
Drinking Water		2 deep bore wells (450 ft) in Tank are saline piped 1km to village and mixed with fresh Vaigay River water for drinking water. It is pumped to a tower and conveyed through distribution system. No drinking water deficit in the village the only scarcity problem occurs when there is a prolonged power failure.	1 borewell exists on the tank bund and is used to supply drinking water to Kudipatti	
Grazing Ground		300 cows & 200 goats drink 2 times per day from the tank (October-March) All collect grasses and feed from command area and tank		
Pollution	No Known pollution inflows exists	No industrial 200 households domestic wastewater runs into tank, "minimal pollution" according to the farmers	No pollution problems	
Temples & Festivals	2 temples exist at the tank Sept. – Collect grains from all households. Everyone prays for rain. Feb. – Pongal Oct. – Small festival before opening the sluice for equal sharing and good yields.	1 temple for god 'Ayynar', once per year is a festival to pray to this god	Kanimar temple, Karpasami temple - Village God. During Sept. there's a festival for rain.	3 temples in th tank bund: Ayyanen temple, Kannimen temple, Madai Karpasami temple. May: festival is celebrated for the Ayyanen temple Sept: people pray god and also for getting rain. March: harvest festival
Miscellaneous Notes	All farmers clear their section of the field channels which prevents maintenance problems from occuring and ensures tailend farmers get water.	If rain is bad after rainy season then under rainfed conditions they cultivate millet during summer period (April to July)	Surplus weir is the only problem	Dead storage left for groundwater recharge. Distribution Channel in disrepair.Some tailend farmers don't get water and so leave there lands fallow. Farmers plan to further deepen tank and repair sluice. Prepare paddy in advance of tank filling using well water then transplant seedlings immediately after tank filling.

7.1.3 Bathymetry Relationships

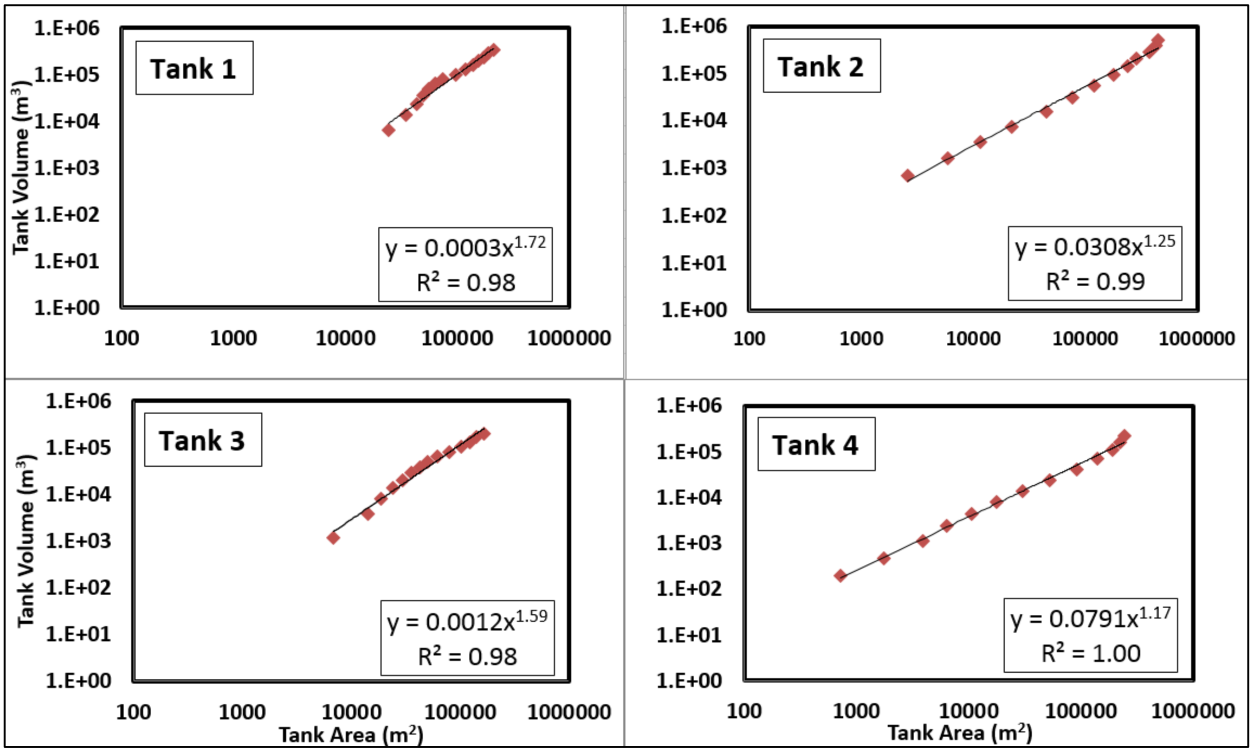

Figure 7.1: Area-Volume relationships for the tanks

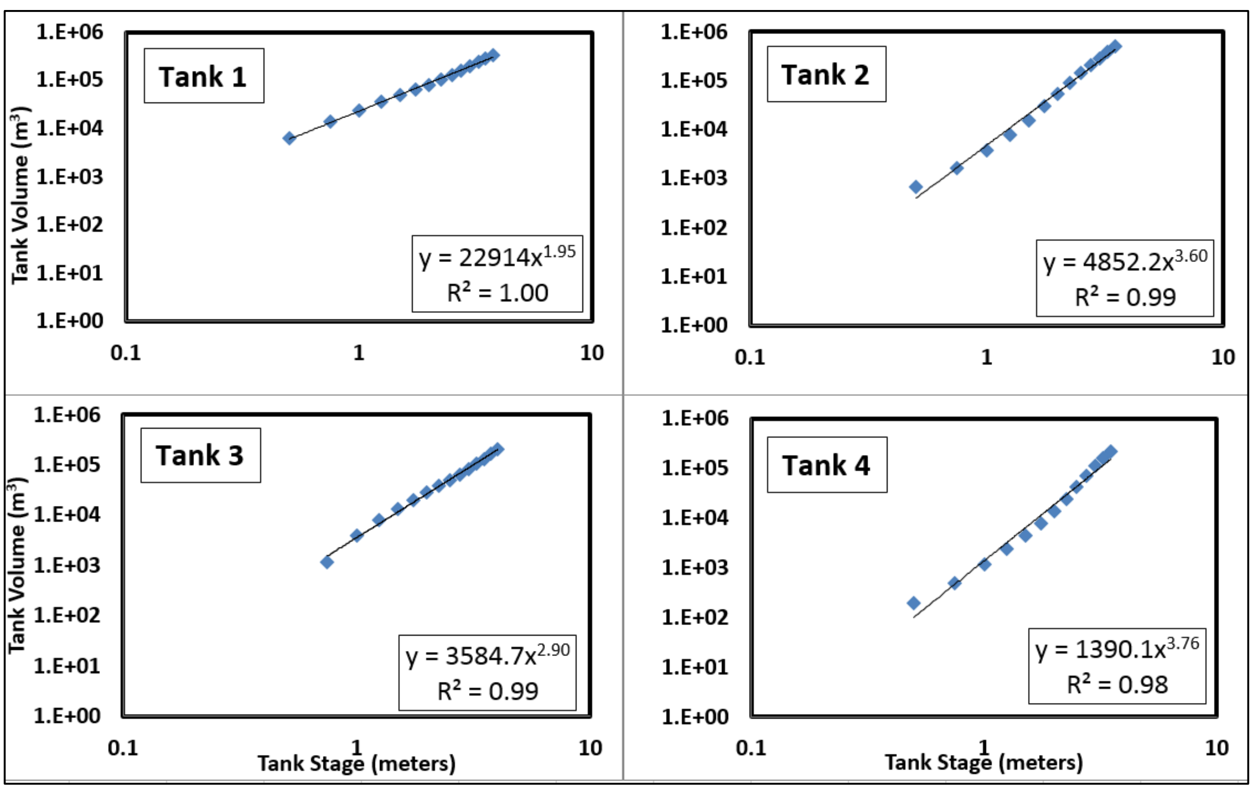

Figure 7.2: Stage-Volume relationships for the tanks

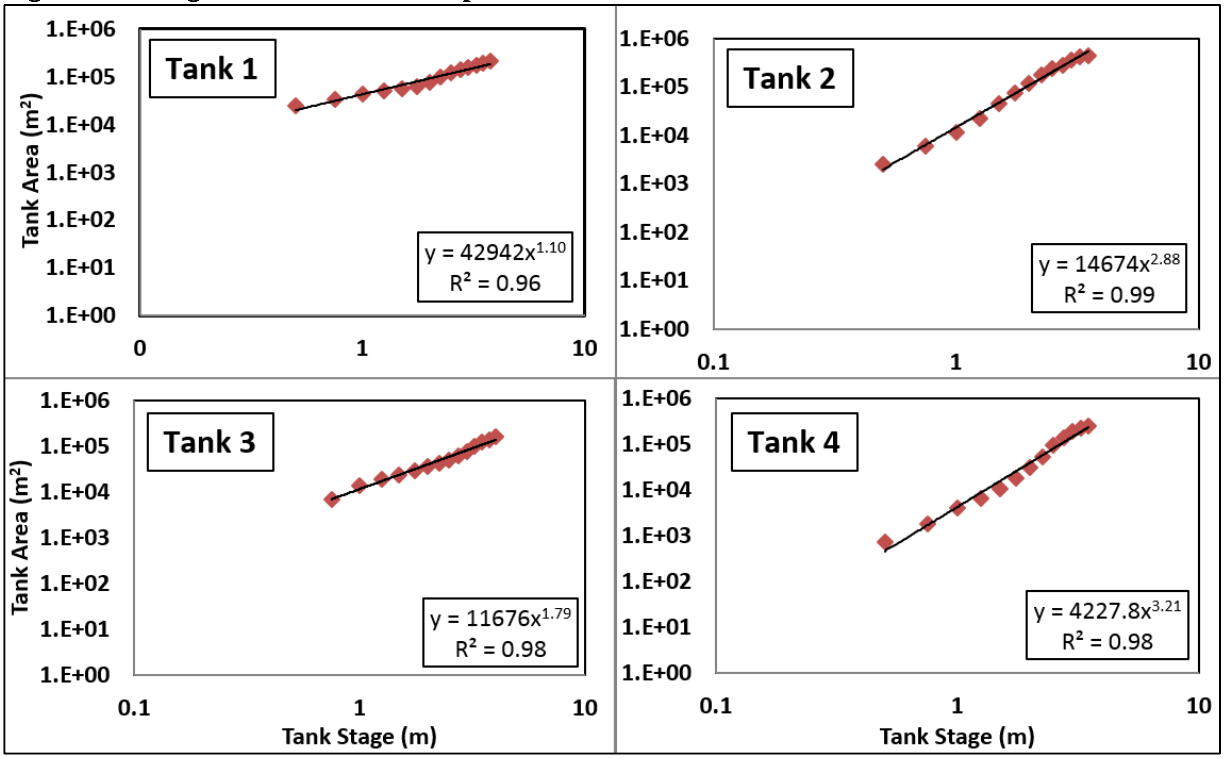

Figure 7.3: Stage-Area relationships for the tanks

7.1.4 Sluice Discharge Relationships

Measurements of sluice outflow were taken periodically throughout the NE monsoon season. However, the estimation of ET and GE over the monsoon season was contingent on continuous daily values of sluice outflow. For this reason, the measurements made at each sluice were used to create relationships between sluice outflow and tank water level, allowing for the estimation of sluice outflow on days in which no measurement was made. Linear relationships were created between specific outflow (liters per second) measurements and water depth above the corresponding sluice invert (DAS). Best judgment was used to remove points compromised by external factors (wind, timer error, etc).

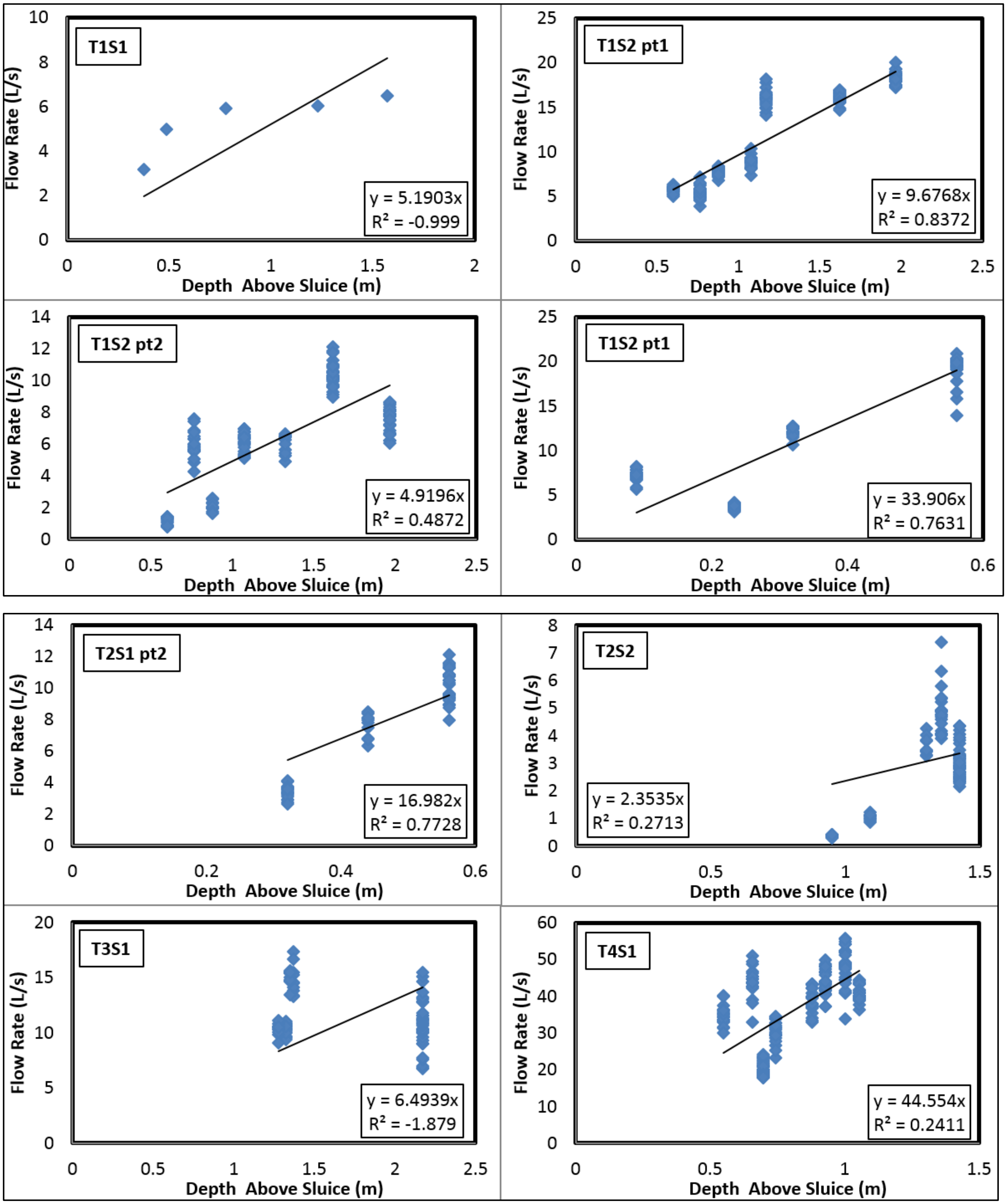

Figure 7.4: Sluice Discharge-Water level relationshipsfor each of the tank sluices

7.2 Modeling Study Appendix

7.2.1 Evapotranspiration Constants

Calculation of the Penman-Monteith equation required the estimation of several constants, summarized in table x and calculated using equations 7.2-1 to 7.2-6.

Table 7.3: Sluice Discharge-Water Level Relationship Coefficients

Sluice ID	Coefficient
$\boldsymbol{\Delta}$	5.19
$\boldsymbol{\gamma}$	9.68
$\boldsymbol{SVP}$	4.92
$\boldsymbol{AVP}$	33.91
$\boldsymbol{D}$	16.98
$\boldsymbol{F_U}$	2.35

$$\Delta = \frac{4098(.6108e^{\frac{17.27*T}{(T+237.3)}})}{(T+237.3)^2} \qquad \text{Equation 7.1}$$

Where T = 30 degrees Celsius, Δ =.243

$$\gamma = \frac{(C_{P_{air}} * P)}{(\lambda_{v\_water} * \text{MW ratio})} \qquad \text{Equation 7.2}$$

Where C_{P_air} = 1.005 KJ/Kg*K, λ_{v_water} = 2.45 MJ/Kg, $MW_{WaterVapor\_DryAir}$ = .622, P = 99.876 kPa, γ = .06586

$$SVP = Saturated\ Vapor\ Pressure = 610.7 * (10)^{(\frac{7.5*T}{(T+237.3)})} = 4.242\ kPa \qquad \text{Equation 7.3}$$

$$AVP = Actual\ Vapor\ Pressure = \frac{RH * SVP}{100} \qquad \text{Equation 7.4}$$

Where RH = Relative Humidity = 30 – 75%, $RH_{Madurai}$ = 50%

$$D = Vapor\ Pressure\ Deficit = SVP - AVP = 2.121\ kPa \quad \text{Equation 7.5}$$

$$F_U = (a_U - b_U .* U) \quad \text{Equation 7.6}$$

Where a_U = 1, b_U = .536 from Pandey et al., 2011. U = 10km/hr = 2.77 m/s at 2m above ground surface.

7.2.2 Measured and Simulated Tank Fluxes for the 2013 Monsoon Season

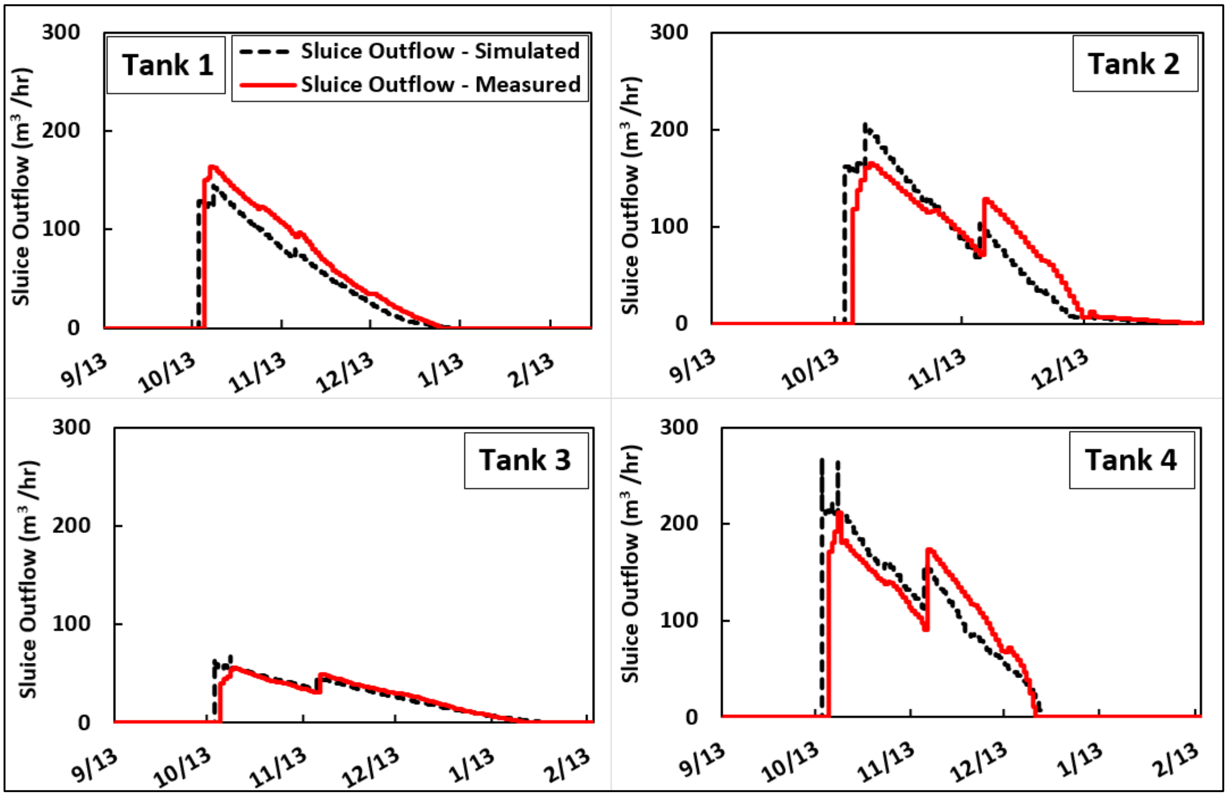

Figure 7.5: Values of measured and simulated sluice outflow for the 2013 northeast monsoon season.

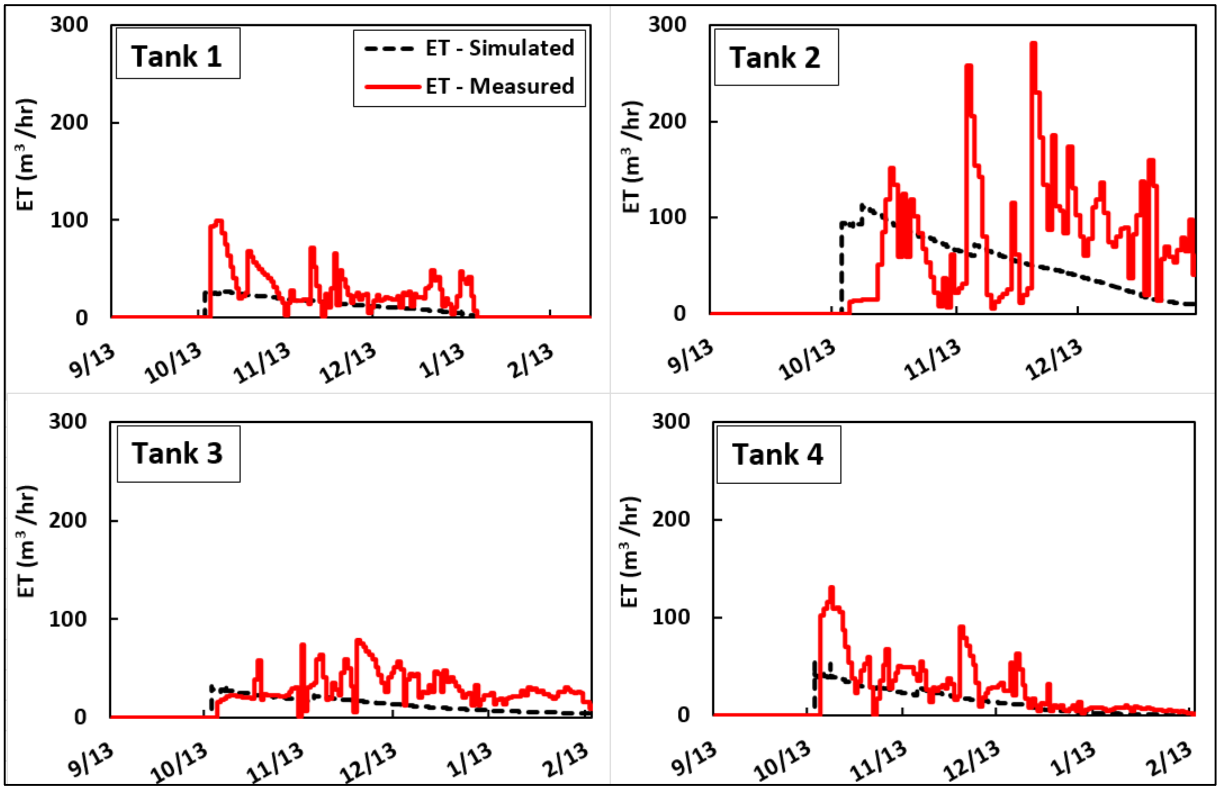

Figure 7.6: Values of measured and simulated ET for the 2013 northeast monsoon season.

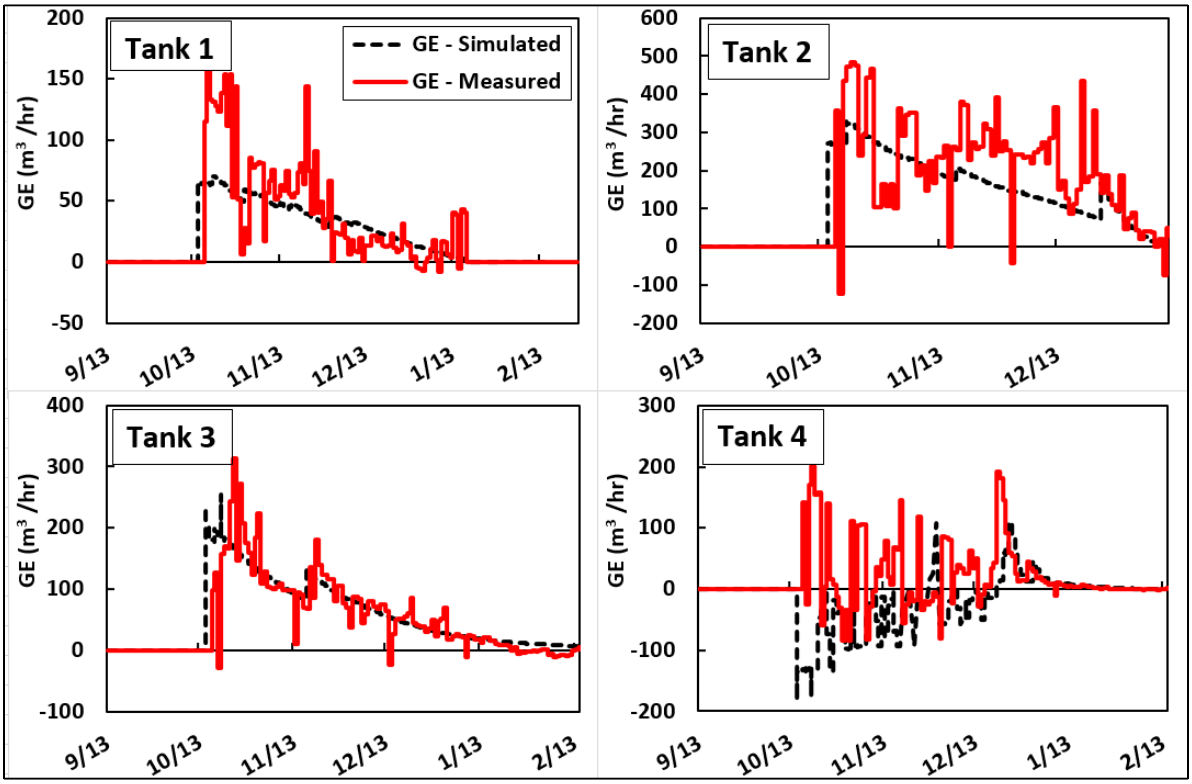

Figure 7.7: Values of measured and simulated GE for the 2013 northeast monsoon season.