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Water security and rainwater harvesting: A conceptual framework and candidate indicators

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ABSTRACT

Rainwater-harvesting tanks (reservoirs) in Tamil Nadu, India support agricultural livelihoods, mitigate water insecurity, and enable ecosystem services. However, many tanks have fallen into disrepair, as private wells have supplanted collectively managed tanks as the dominant irrigation source. Meanwhile, encroachment by peri-urban development, landless farmers, and *Prosopis juliflora* has reduced inflow and tank capacity. This exploratory study presents a conceptual framework and proposed indicator set for measuring water security in the context of rainwater harvesting tanks. The primary benefits of tanks and threats to their functionality are profiled as a precursor to construction of a causal network of water security. The causal network identifies the key components, causal linkages, and outcomes of water security processes, and is used to derive a suite of indicators that reflect the multiple economic and socio-ecological uses of tanks. Recommendations are provided for future research and data collection to operationalize the indicators to support planning and assessing the effectiveness of tank rehabilitation.

1. Introduction

Rainwater harvesting techniques have long been implemented around the world to cope with inter-annual variability in precipitation and maintain human well-being. Predominantly applied in semi-arid regions, decentralized techniques such as pits, terraces, ponds, check dams, sand dams, small reservoirs, cisterns, and open wells have been used to mitigate water and food insecurity (Akpinar Ferrand & Cecunjanin, 2014). In the South Indian State of Tamil Nadu, smallholder agriculture depends on irrigation provided by thousands of small rainwater harvesting reservoirs, known regionally as tanks. Tanks in Tamil Nadu account for approximately 18% of crop irrigation water (DES, 2011) and generate a multitude of benefits, including increasing and moderating agricultural production, alleviating poverty, and providing ecosystem services.

However, broad-scale changes in climate, urbanization, and technology are negatively affecting local-scale water security provided by tanks. Researchers and farmers have described changes in the timing, duration, and intensity of the Northeast monsoon (October–December) that provides up to 50% of regional annual precipitation, and influences decisions regarding planting and crop type (Pal & Al-Tabbaa, 2010). Urbanization and invasive vegetation are consuming land occupied by tanks and inhibiting inflow. Meanwhile, the proliferation of private groundwater extraction has led to investment declines in tank maintenance (Kajisa, Palanisami, & Sakurai, 2007). Such threats to the security of collectively managed water systems are not unique to Tamil Nadu, and occur in various forms across semi-arid regions of Asia, the Middle East, and Africa (Biazin, Sterk, Temesgen, Abdulkedir, & Stroosnijder, 2012; Geekiyanage & Pushpakumara, 2013; Hussain, Abu-Rizaiza, Habib, & Ashfaq, 2008; Molle, Shah, & Barker, 2003; Vohland & Barry, 2009).

Water availability is the most important consideration for Tamil Nadu farmers regarding what, when, and how much to plant in a season. Given the importance of tank irrigation to agricultural livelihoods, reliable measures of the provisioning characteristics of tanks could enable a baseline assessment of water security, provide advance warning when water security approaches a critical threshold, and evaluate the performance of tank restoration investments. The objective of this paper is to develop a set of water security indicators in the context of smallholder agriculture and rainwater harvesting tanks. To do so, we combine field observations and literature review to identify the core determinants and

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processes that influence water security, and model them using a causal network. We define water security in this context as the sufficient availability and equitable access to water as an input to agricultural production and associated human well-being.

The remainder of the paper is organized as follows. Section 2 describes the functions, benefits, and threats rainwater harvesting tanks in Tamil Nadu. Section 3 reviews existing frameworks that address water security themes in an agricultural context. In Section 4, we construct a causal framework of the system and use it to develop a suite of water security indicators. Section 5 concludes with recommendations for further investigation of water security in tank systems.

2. Tank systems of Tamil Nadu

For millennia, people in Tamil Nadu have used rainwater-harvesting tanks to capture, store, and deliver water-related services to local villages. Tanks are small reservoirs primarily used for crop irrigation, and were a central driver of early settlement patterns across South India. Tanks are constructed across natural depressions in the landscape, impounding water from rivers or storm runoff behind crescent-shaped earthen embankments called bunds. Sluice gates control the flow of tank water through the bund to irrigated fields downgradient in the command area. Water user associations comprised of local stakeholders collectively maintain and manage tanks, with responsibilities including distributing water among users, desilting the tank bed, and clearing supply channels (Kajisa et al., 2007). Many tanks are linked in cascades, with overflow channels providing connections to downstream tanks, forming a complex hydrologic network of manmade wetlands across the landscape (Geekiyanage & Pushpakumara, 2013; Van Meter, Basu, Tate, & Wyckoff, 2014). These tightly-coupled human and natural systems coevolved over time, as the monsoonal precipitation patterns characteristic of the region required storing water to sustain agricultural production, which in turn profoundly modified the landscape. Today, rural Tamil Nadu is a dense network of intensively farmed land and home to nearly 40,000 tanks (Fig. 1), comprising 17% of all tanks India (Amarasinghe, Palanisami, Singh, & Sakthivadivel, 2009).

2.1. Benefits

Tanks provide an array of economic, environmental, and socio-cultural benefits to farmers and villages (Ariza, Galán, Serrano, & Reyes-García, 2007). Among the leading economic benefits are significant improvements in agricultural yield (Table 1), and greater

Table 1
Major crops and water requirements in Tamil Nadu (DES, 2011; Krishna, 2010).

Crop	Water requirement (mm/ha/yr)	Yield (Kg/Ha unless otherwise noted)		Yield gain
		Rain fed	Irrigated	
Sugar cane	1500–2500	–	101[a]	–
Rice	900–2500	–	3070	–
Cotton	700–1300	333	456	37%
Maize	500–800	3264	6384	96%
Groundnut	500–700	1435	3377	135%
Chilli	500–700	534	–	–
Sorghum	450–650	830	1808	118%
Black gram	400–600	380	–	–
Green gram	400–600	345	–	–
Pearl millet	400–450	1379	2635	91%
Finger millet	400–450	1781	3188	79%

[a] Cane-tonnes.

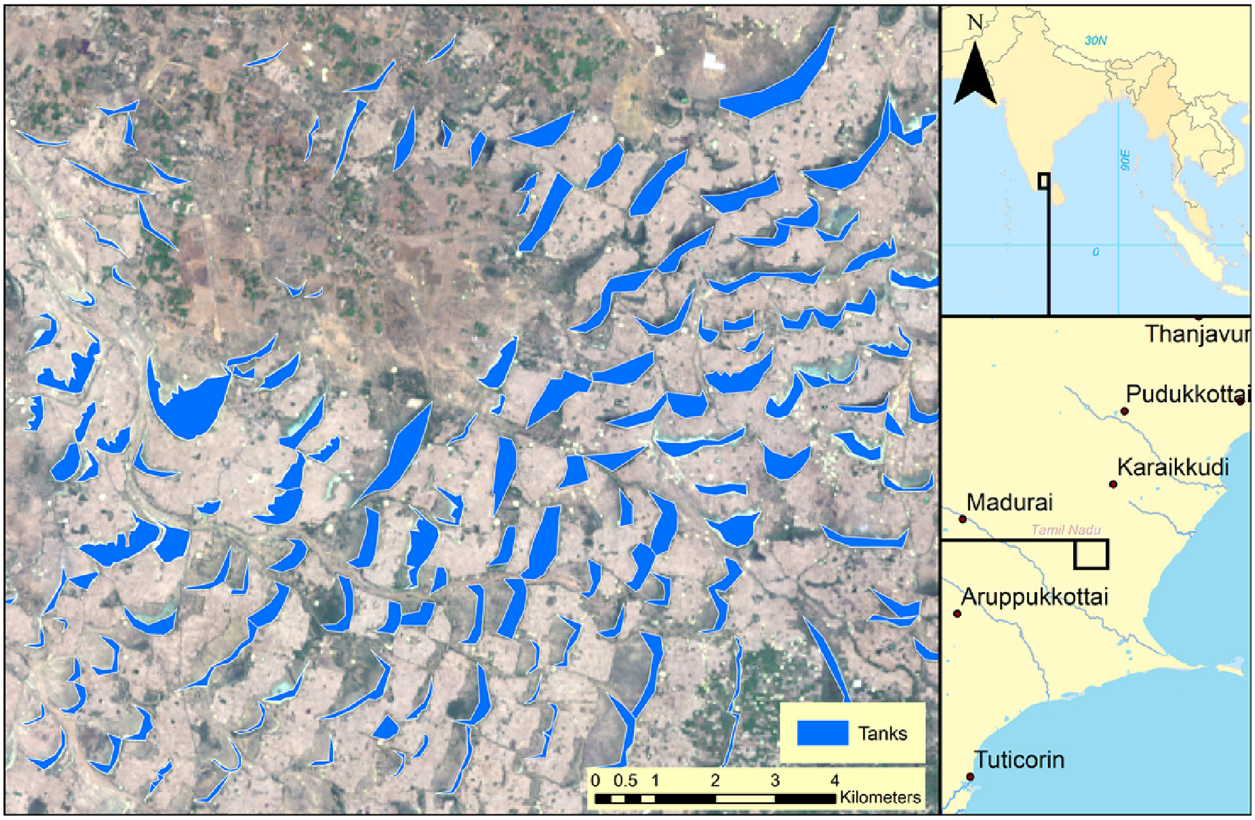

Fig. 1. Rainwater harvesting tanks across the Tamil Nadu landscape.

income stability in the face of high inter-annual variation in precipitation. Rice is a staple crop in the state, accounting for approximately 33% of planted area, 52% of planted area under irrigation, and 75% of grain consumption (Amarasinghe, Singh, Sakthivadivel, & Palanisami, 2009; DES., 2011). Along with sugar cane, rice production is the leading beneficiary of tank irrigation due to high input water requirements. However, irrigation also produces yield improvements when applied to less water-intensive crops such as millet, sorghum, and groundnut. Beyond irrigation, well-functioning tanks support multiple uses that generate economic benefits (Palanisami & Meinzen-Dick, 2001). Tanks augment livestock production as a location for watering and grazing. As the tanks fill with monsoon runoff, they also accumulate silt. In the dry season the silt can be excavated and applied to agricultural fields to improve fertility and water-holding capacity, used for repairs to the tank bund, and used as input to commercial brick-making. Other economic benefits derive from tree and fodder production, fish and duck rearing, and the manufacture of concrete blocks (Anuradha, Ambujam, Karunakaran, & Rajeswari, 2009).

A major advantage of tank irrigation as compared to other forms of irrigation is the multidimensional aspect of benefits. Among the primary environmental benefits are the regulating ecosystem services of groundwater recharge and flood control. Infiltration from tank storage supports well irrigation by increasing groundwater levels in the command area, typically in the range of 3–7 m following restoration of a degraded tank (Palanisami, Amarasinghe, & Sakthivadivel, 2009). In coastal areas, this recharge serves as a buffer against saltwater intrusion. Given that total groundwater extraction in Tamil Nadu exceeds 85% of total recharge (Amarasinghe, Palanisami et al., 2009), added groundwater inflows from tanks can be locally important. During periods of high rainfall, the storage capacity of tanks and tank cascades protect downstream agricultural areas and communities from flood damage.

Nearly a million rural households in Tamil Nadu rely on tanks for their livelihoods, the majority of which are small and marginal farmers (Amarasinghe, Palanisami.et al., 2009). Shared access to tank water is a contributor to social equity and community stability, and the deterioration of tanks has led to rising inequality and poverty (Kajisa et al., 2007). Functional tanks provide water for domestic uses, improve food security, and benefit a diverse group of stakeholders. As the water provisioning capacity of tanks has declined, many farmers have abandoned tank agriculture due to labor costs and lower profits (Sato, 2013). Indeed, lack of access to irrigation water has strongly influenced both short and long-term migration from dry lands in India (Shah, 2010), and contributes to ongoing statewide trends in rural-urban migration (Amarasinghe, Singh et al., 2009). Meanwhile, the rehabilitation of tanks has been associated with a reversal of outmigration, and disproportionately benefits marginal farmers, women, and the landless (Anuradha & Ambujam, 2012; Reddy & Behera, 2009). Accordingly, tank restoration has become a focus of NGOs in the development sector as a strategy to alleviate poverty. The restoration process typically includes repairs to the bund, sluice gates, and weirs, removal of silt and vegetation from the tank bed and feeder channels, and (re)establishment of a water user association.

2.2. Threats

Despite the benefits provided by well-functioning tank systems, many have fallen into disrepair. Tanks are a common resource, with governance and maintenance requiring broad participation from the surrounding community. However, tank usage has steadily declined over the past half century, largely due to a significant expansion of private groundwater extraction that disincentivized tank maintenance (Gunnell & Krishnamurthy, 2003; Mosse & Sivan, 2003). The reduced maintenance has resulted in structural degradation of the tanks, excessive siltation, and reduced capacity to provide water. The trend has been amplified by government policies that provide free electricity for well pumping, and subsidize the cost of rice to combat food insecurity (Fan, Hazell, & Thorat, 2000). Trends in livelihood diversification toward non-farm income sources also contribute to a reduced reliance on tanks (Amarasinghe, Singh et al., 2009). Collectively, these developments have created a positive feedback loop, reducing tank maintenance and increasing dependence on well irrigation.

Tanks also face encroachment on several fronts. Although the inundation area of the tanks is considered collective property, landless farmers often farm within a tank, reducing storage capacity and area for livestock grazing. The mesquite plant, *Prosopis juliflora*, was introduced by the Indian government in 1870s to help meet fuel wood needs of the region (Singh & Singh, 1993). Due to a combination of drought tolerance and seed dispersal in livestock dung, *P. juliflora* has spread across Tamil Nadu, and its use as a fuel for household use and electricity generation provides an important source of income (Sato, 2013). However, *P. juliflora* also has extensive root systems that increase evaporative losses and reduce tank inflow once it has invaded tanks and feeder channels (Fig. 2a). Based on informal discussions with local farmers, the presence of *P. juliflora* in their local tank has reduced storage capacity by at least half. Peri-urban and urban tanks also face encroachment, as tanks

Fig. 2. Rainwater harvesting tank in Tamil Nadu. (a) Tank inundation area, with a sluice and invasive *Prosopis juliflora* present in the foreground; (b) irrigated agricultural plots in the command area.

and feeder channels are built over and their structures damaged or destroyed. This process can increase flood risk, as experienced in recent years in Tamil Nadu's capital city of Chennai (Gupta & Nair, 2010; Ramanathan, 2015; Srivathsan & Lakshmi, 2011).

2.3. Scale

When considering the processes associated with tank irrigation, scale is particularly important. For example, although the positive effects of the tank systems on increasing water availability have been widely touted at local scales (Gupta & Deshpande, 2004; Kumar, Patel, Ravindranath, & Singh, 2008; Shah, 2004), increased water resources development in upstream areas changes the distribution of water between upstream and downstream users (Venot, Reddy, & Umapathy, 2010). Accordingly, while tank rehabilitation may increase local water availability, availability at the watershed scale may remain constant, or even decline, as surface water runoff decreases and evaporative losses increase (Bouma, Biggs, & Bouwer, 2011; Glendenning, Van Ogtrop, Mishra, & Vervoort, 2012; Neumann, Barker, MacDonald, & Gale, 2004; Sharda, Kurothe, Sena, Pande, & Tiwari, 2006). Important tank-related processes such as encroachment, recharge, and migration may also operate at different temporal scales, creating additional challenges for measurement.

3. Conceptual foundations

Given the multitude of benefits and pressures on tank systems, the security of the water-provisioning services they provide is critical to ecological and economic well-being (Gunnell & Krishnamurthy, 2003). Water security indicators can serve as tools to evaluate current conditions, assess the effectiveness of tank rehabilitation, and prioritize future restoration investments. To accurately measure water security, the indicators must be based on a conceptual framework that incorporates the interactions between natural and human factors, and scale-dependent variations in tank-related processes and impacts. In developing a conceptual model of water security in Tamil Nadu, we integrated related frameworks of water poverty, coupled systems, and socio-hydrology.

3.1. Water security

Water security has emerged as a prominent framing for water management (Cook & Bakker, 2012). While distinctions among water security, scarcity, and integrated water resources management have at times been unclear (Lautze & Manthrithilake, 2012), water security is a useful and integrative way to describe the multi-dimensional linkages between human well-being and water access and availability. According to the United Nations, water security is:

> "… *the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability* (UN Water, 2013)."

For tank systems, we narrow the UN definition of water security to the sustained availability of and access to water as an input to agricultural production and associated human well-being. The broad themes of human health and livelihoods, provisioning uses, ecological function, and vulnerability reduction identified in the water security literature (Cook & Bakker, 2012; Global Water Partnership, 2000; Grey & Sadoff, 2007) are integral to the long-term sustainability of the system. However, the underlying water scarcity that drives questions of water security is context dependent – how the needs of the affected population are defined, the availability of water, and the spatial and temporal scales of water delivery to meet those needs (Rijsberman, 2006). In many cases, those needs and the pressures acting upon them can be classified into "syndromes" of water security, with common causal factors and potential outcomes (Srinivasan, Lambin, Gorelick, Thompson, & Rozelle, 2012). In rural Tamil Nadu, the local context is largely subsistence-level farming, poverty, and arid conditions mediated by monsoon precipitation, cutting across typologies of water security (e.g., groundwater depletion, ecological destruction, unmet subsistence needs, resource capture) within a nested coupled system. From a risk-based perspective on water security (Hall & Borgomeo, 2013), tanks enable alternative decisions and outcomes by altering the availability and access of water at the scales of farm fields, tanks, and tank cascades.

3.2. Indicators of water poverty and sustainability

Several existing indicator frameworks incorporate aspects of water security, most of which employ design standards of simplicity, transparency, and data availability (Pintér, Hardi, Martinuzzi, & Hall, 2012) to improve accessibility to policymakers and local stakeholders. The Water Poverty Index measures water stress by combining indicators of physical water availability, access, use, social & institutional capacity, and environmental integrity (Sullivan, 2002; Sullivan, Meigh, & Giacomello, 2003). It has been applied as a comparative measure across national settings and scales (Garriga & Foguet, 2010). However, the Water Poverty Index underplays interactions among social and environmental processes, omits ecosystem services (Sullivan, Meigh, & Lawrence, 2006), and may poorly distinguish "poor" and "water poor" (Komnenic, Ahlers, & Van Der Zaag, 2009).

Other water indicators incorporate system processes and component interaction via performance criteria (Sandoval-Solis, McKinney, & Loucks, 2010), or indicator construction based on the a pressure-state-response (PSR) causal chain (Chaves & Alipaz, 2007; Milman & Short, 2008; Pérez-Foguet & Garriga, 2011). Despite limitations in data availability and structural design, these indicators of water poverty and water sustainability describe how system dynamics and causal relationships can structure the assessment of water poverty. The Water Security Status Indicators assessment method includes end users working at a local scale, and uses multivariate inputs to generate concrete outputs to aid in the water decision-making process (Norman, Dunn, Bakker, Allen, & DeAlbuquerque, 2013). It allows for simultaneous analysis of multiple indicators, though their efficacy depends upon the quality of the selected indicators.

3.3. Coupled systems frameworks

Indicator models have tended to focus on a single scale of analysis, such as national water budgets or watershed hydrology (Cook & Bakker, 2012). The multi-scale processes, social outcomes, and spatiotemporal lags between cause and effect in tank systems can be understood through coupled human and natural systems (CHANS) and socio-hydrology frameworks. CHANS research investigates the bidirectional feedback mechanisms and interactions that link natural and human systems across space and scale (Liu et al., 2007). For example, expansion of groundwater extraction is strengthening feedback mechanisms between tank management and dependence on wells.

Water security can also be assessed through the ecosystem service model (Carpenter et al., 2006; Potschin & Haines-Young, 2011; Raudsepp-Hearne et al., 2010), in which tanks enable a series of ecosystem services and benefits. The management of these services occurs in the context of multi-scale preferences, policy, and market forces, thereby linking the water provisioning system to human well-being. Similarly, socio-hydrology considers "the co-evolution of humans and water on the landscape" (Sivapalan, Savenije, & Blöschl, 2012), with co-evolutionary defined as a system exhibiting emergent behavior created by feedbacks between processes (Kallis, 2007; Winder, McIntosh, & Jeffrey, 2005). The socio-hydrology perspective embodies a shift in analytical focus in hydrologic science from isolated collections of stocks and flows, to the processes linking social and ecological dynamics in a region (Jackson, Jobbágy, & Nosetto, 2009; Rodriguez-Iturbe, 2000). Research in this area addresses water and human activity at a range of spatial and temporal scales (Sivapalan et al., 2014), with a recognition that human-water systems contain nonlinearities, where slow and fast processes interact to create complex system dynamics and often produce unexpected outcomes (Carpenter & Turner, 2000; Crépin, 2007; Sivapalan et al., 2012).

There is still much to be understood about the interaction of cross-scale mechanisms through which broad scale pressures generate local water insecurity in Tamil Nadu. Based on the frameworks of water poverty, coupled systems, and socio-hydrology, we acknowledge the importance of incorporating complex human-environmental linkages, non-linear processes, and local context in our model of water security. However, we also recognize the inherent trade-offs between developing relatively simple, static indicators that are unable to capture the effects of individual and group actions in different environmental and social contexts, and the construction of complex process models that are often expensive and require substantial data inputs. In our exploration of the system, we instead sought to incorporate both approaches – to develop an indicator set informed by our knowledge of system dynamics. Through the careful mapping of key system components, properties, and processes, we can gain further insight into the key determinants of water security, identify leading and trailing indicators, and guide future data collection efforts.

4. Modeling framework

To characterize how the water security of farmers is linked to broader scale driving forces and localized outcomes, we employed the enhanced driving forces-pressure-state-impact-response (eDPSIR) framework (Niemeijer & de Groot, 2008a; 2008b). The eDPSIR builds upon the pressure-state-response causal chain framework and its derivatives to represent real-world interactions via causal linkages among system components, incorporating feedback mechanisms vital to understanding system stability (Olsson, Folke, & Berkes, 2004). Previous applications of the DPSIR framework include assessments of ecosystem services (Kelble et al., 2013; Van Oudenhoven et al., 2012), and climate change vulnerability (Bär, Rouholahnejad, Rahman, Abbaspour, & Lehmann, 2015). While DPSIR models have been criticized as anthropocentric and lacking in social dynamics (Binder, Hinkel, Bots, & Pahl-Wostl, 2013), its systems perspective can be generalized to produce a useful formalization of system structures, actors, and interactions that can guide water governance (Wiek & Larson, 2012). A causal network created with the eDPSIR process identifies not only the key components and relationships, but also the direction (cause/effect) of the relationships, thereby aiding indicator selection.

Our process for creating the eDPSIR causal network was highly iterative. At each step, we integrated knowledge from a review of tank literature, field visits and *in situ* hydrologic data collection, discussions with local farmers, and results of a 2015 workshop involving an international group of water researchers and tank rehabilitation experts from the DHAN Foundation. During this process, we attempted to integrate different frameworks (e.g., socio-hydrology, coupled systems, ecosystem services) into potential causal pathways affecting water security. For example, one simple causal chain might focus on biophysical processes, beginning with shifts in monsoon precipitation, thereby affecting tank storage volume, available irrigation water, and agricultural productivity. By contrast, a different causal chain might begin with national food security policies that subsidize rice production, resultant electricity subsidies, and the expansion of well irrigation.

We evaluated these and many other potential pathways of causation that might affect (or be affected by) localized agricultural water security. Where causal pathways overlapped, we combined them into a larger causal network. To tailor the eDPSIR to water security in the context of tanks, we included components that are clearly tied to biophysical phenomena (e.g., groundwater levels) or social outcomes (e.g., agricultural income). However, we also integrated emergent, aggregated components, such as water availability and access, that inform decision-making at household and administrative scales. The resulting conceptual model, while complex in its components, linkages, and feedback processes, captures our current understanding of the determinants of water security within this coupled system.

Fig. 3 presents this causal network, explicitly linking water provisioning and smallholder agriculture. Farmer water security is central to the project, and therefore central to network, as it drives local land use decisions and economic outcomes in rural Tamil Nadu. Although the network includes reciprocal linkages and feedbacks fundamental to a CHANS, the causality generally initiates from broad-scale driving forces, which then generate more localized pressures. These pressures then act upon state variables, which impact the system and generate response. Our causal network explicitly separates the natural (or biophysical) components from the human (or socioeconomic) components, emphasizing the primary human-natural causal linkages.

4.1. Structure and components

The primary environmental driving force of the tank system is the monsoon climate, and the associated variability in precipitation and temperature that is projected to increase this century (Kumar et al., 2010). The primary human driving forces are: (1) market prices that influence local land use decisions, (2) legacy effects of cultural norms that shape local equity and management (Mosse & Sivan, 2003), and (3) government electricity subsidies to increase agricultural production, alleviate poverty, and improve food security (Fan et al., 2000). These human and environmental driving forces directly affect land use and management of the agro-water system, and generate pressures on water security.

Biophysical pressures in the causal network include precipitation (timing, duration, intensity) and surface-groundwater interactions that affect agriculture and environmental function (Kumar et al., 2008), and tank storage capacity, which is a function of size and maintenance (Van Meter et al., 2014). On the social side, government electricity subsidies incentivize the pumping of groundwater wells, which in turn alters the local water cycle (Janakarajan & Moench, 2006). Localized water scarcity affects the land use and land cover (LULC) through farmer crop decisions. The LULC component also includes the spread of *P. juliflora* in and around tanks, and planting in the tank bed by landless farmers. Tank management represents the ability of local villagers and water user organizations to manage tank capacity, perform maintenance, and control encroachment of agriculture, vegetation, and land development in the tank and feeder channels.

The primary state components are determinants of water access and availability. Availability is a function of tank storage and groundwater levels, and fluctuates over time according to use, precipitation, and evaporation. Peak surface water availability is bounded by tank functionality at the individual tank scale and tank density at the landscape scale. Groundwater availability is bounded by groundwater reserves that are spatially and temporally variable. Water access is mediated by social inequality, a result of the legacy of cultural norms and household income. Local inequality is inversely related to the efficacy of tank management (Kajisa et al., 2007) and influences access to tank water and the economic capacity to drill a well (Mosse & Sivan, 2003). Water security in the model is an emergent property at the village scale, and is central to farmer land use decisions according to their water availability and access. The ability of farmers to secure water is the ultimate determinant of agricultural productivity, and fundamentally affects the trajectory of the coupled system.

Changes in state components produce impacts to ecosystem services generated by tanks, including brick manufacture, livestock watering, and charcoal production (Palanisami & Meinzen-Dick, 2001; Van Meter et al., 2014). Agricultural productivity is a result of land use decisions and water security during the growing season. Agricultural income is a function of productivity and market prices, and combines with other income sources (e.g., brickmaking, charcoal sales, remittances from family) to generate household income. Finally, impacts might evoke a response from government agencies dedicated to food security or poverty alleviation (Umali-Deininger & Deininger, 2001) or from non-governmental agencies operating at various scales and purpose, creating feedback mechanisms that close the causal loop from human actions to environmental health. The feedback loops are potential pathways of adaptation, guiding the system along alternative trajectories or reinforcing current trends.

4.2. Indicator selection

What should be measured if the current status and future changes in water security are to be understood? The causal network

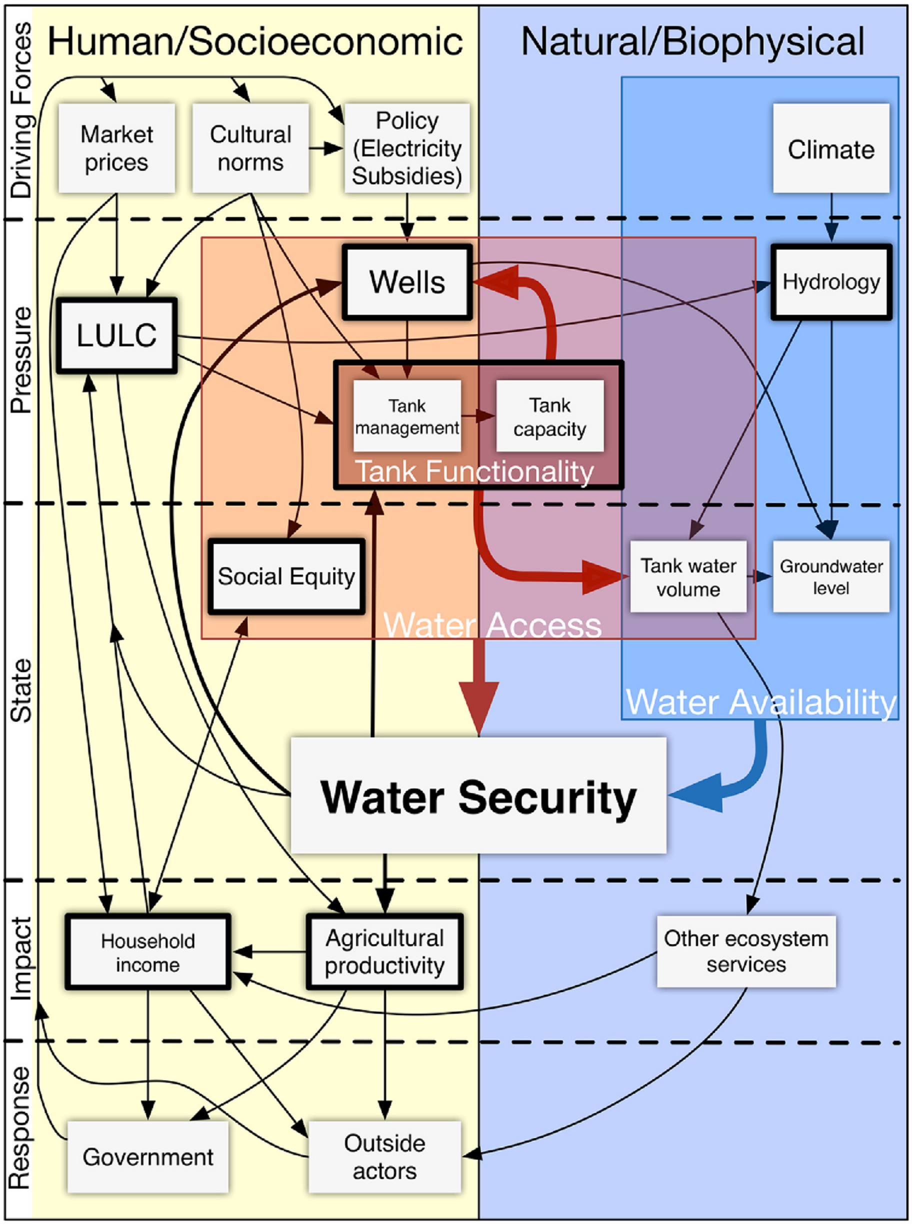

Fig. 3. Causal network for water security. The most influential components (outlined in bold) have the greatest number of incoming and outgoing arcs.

is a valuable tool in addressing this question. The network nodes represent the leading determinants and outcomes of water security, and the scales at which they operate. Focusing indicator selection on the root, central and end-of-chain nodes will produce indicators that are most influential in causal processes (Niemeijer & de Groot, 2008b). Each node could be represented by multiple finer-scale variables, each with its own spatiotemporal scale and causal linkages.

Applying this rationale, Table 2 identifies the key components (nodes) and associated sets of candidate indicators for measuring water security in the context of rainwater harvesting tanks in Tamil Nadu. The causal network provides a robust and transparent methodological foundation for indicator selection. This increases the likelihood that the resultant indicators will capture the most important aspects of water security, are sensitive to changes in causal processes, and match the geographic and temporal scales of the underlying processes.

4.3. Index development

While a suite of indicators can provide insight into the current state of the system, it is sometimes desirable to combine indicators in a composite index to reduce complexity, compare places, and communicate with stakeholders. Accordingly, the causal network is well suited to guide decisions involving indicator weighting and aggregation. The assignment of weights should ideally reflect the relative importance of indicators (Garriga & Foguet, 2010). Equal weighting is most often exercised approach for water indicators when the stated goal is simplicity, transparency, and/or avoidance of bias (Pandey, Shrestha, Chapagain, & Kazama, 2011), but is often implemented because the index designers lack a rationale for differential weights (Chaves & Alipaz, 2007; Garriga & Foguet, 2010; Sullivan et al., 2003). Causal networks offer both transparency and a rationale for differential weights, by using the structure of the network to assess the relative importance of system components. Network nodes with a greater number of incoming and outgoing arcs are particularly important for describing the system (Niemeijer & de Groot, 2008b), and indicators for these nodes should be weighted more heavily. Applying this criterion to Fig. 3, tank management has a greater influence on water security than tank capacity, and thus should be weighted more heavily in an index. While this simplified view of the system only uses outgoing arcs and assumes all causal linkages are equally influential on water security, the network could be refined to also reflect the relative strength of causal links.

The aggregation method for an index should reflect the relationship between indicators. The cause-effect relationships embedded in the causal network provide insight about these relationships in at least two ways. First, the network can help define the structural arrangement of indicators within the index. A hierarchical index structure based on Fig. 3 might include pillars identified alternatively as (1) biophysical and socioeconomic, (2) pressure, state, and response, or (3) the components listed in Table 2. Second, the causal network informs about the suitability of different aggregation methods, such as additive, multiplicative, and multi-criteria approaches (Nardo et al., 2008). Compensability is the index characteristic in which poor performance in one indicator can be offset by strong performance in another. For example, farmers may be able to compensate for a reduction in agricultural production by diversifying their income through non-farm labor. Indicators for these components share a direct path in the causal network, and can be aggregated with additive methods such as the arithmetic mean. A causal relationship that is mediated by other components in the causal network (e.g., land use and tank storage capacity) signifies partial compensability. Indicators for these components can be aggregated using multiplicative approaches such as the geometric mean.

Table 2
Water security components and indicators for rainwater harvesting tanks.

Component	Candidate indicators
Land use/land cover	Planted area Tank inundation area *P. juliflora* extent Drainage area encroachment
Groundwater wells	Density Type (open, bore, tube) Volume extracted Electricity infrastructure Depth to water table Salinity
Hydrology	Precipitation (amount, timing, intensity) Evaporative loss Groundwater recharge Groundwater reserves
Tank functionality	Storage capacity Diversity of uses Structural integrity (bund, channels, sluices, weirs) Water user associations (configuration, effectiveness) Cascade (configuration, tank positioning)
Social equity	Demographics (land tenure, water access) Health/nutrition Migration Number of farmers (irrigated, rain fed)
Income	Crop prices Income (total, non-farm) Income stability Income inequality
Agricultural production	Yield Crop type Irrigated area Plantings (number, timing) Farm size Livestock Labor cost

4.4. Measurability

Data availability for the candidate indicators identified in Table 2 largely depends on the scale of analysis. At broad administrative scales (e.g., taluk, district, state), indicators of agricultural production, wells, and income are available from government crop and groundwater reports and the decennial Indian census. Regional-scale land cover information can be derived from remote sensing analysis, such as delineating tank boundaries and estimating storage capacity (Ran & Lu, 2012; Rodrigues, Sano, Steenhuis, & Passo, 2012; Selvakumar, Rajasimman, & Gunasekaran, 2014). Broad-scale data cannot reveal tank scale dynamics, but can be used to measure a subset of the candidate indicators and construct a water security index. The resulting indicators can be used to measure progress, identify potential trouble spots, and guide policy and management priorities.

Measuring indicators of water security at finer scales (e.g., tank, village, cascade) requires primary data collection. Indicators of tank storage, groundwater recharge, and evapotranspiration can be developed through field instrumentation and modeling (Van Meter, Basu, McLaughlin, & Steiff, 2015). Local-scale encroachment by invasive species, peri-urban development, and landless farmers could be acquired through the collection and analysis of high-resolution remotely sensed information. Quantification of the tank management and social equity components would require primary data collection, using approaches such as household and farmer surveys. The resulting indicators can be used to understand interactions between water security determinants, assess the performance of tank rehabilitation, and quantify local water security.

Planned and ongoing tank rehabilitation projects offer opportunities to collect and analyze many of these indicators. Since the mid 1980s, numerous large tank rehabilitation projects have been funded by organizations such as Indian State governments, the European Economic Community, Asian Development Bank, and the World Bank (Anuradha et al., 2009; Palanisami et al., 2009). The projects may involve the renovation of hundreds of tanks, intended to support rural agricultural livelihoods and reduce water and food insecurity. However, assessments of the effectiveness of rehabilitation efforts often focus on technical grounds. Critics have called for a rehabilitation assessment strategy that moves beyond a narrow emphasis on gains in irrigation efficiency and agricultural productivity, to one inclusive of the broader sociocultural and socio-ecological benefits of tanks (Reyes-García et al., 2011; Shah & Raju, 2002). Adopting this approach, a few studies have measured indicators of water use, income, and ecosystem services before and after tank renovation, and reported performance improvements (Reddy & Behera, 2009; Siderius et al., 2015).

Well-formulated indicators of water security would support assessment of a more expansive notion of rehabilitation performance, as well as help satisfy funders who increasingly require digital and geospatial outcome measures. The planning stages for tank rehabilitation already involve site evaluation and meetings with local farmers and stakeholders, and relevant indicators from Table 2 should be collected or developed during this stage. The collection of hydrological and socioeconomic data could parameterize new models, as well as provide useful baseline assessments as restoration proceeds, monsoon timing shifts later in the season, and a government program to remove *P. juliflora* commences. The development of new hydrological time series data could also deliver basic monitoring capabilities, potentially providing advance warning of potential state changes as the coupled system approaches key thresholds (Scheffer et al., 2009).

5. Next steps

In the context of climate change, distributed rainwater harvesting, and smallholder agriculture, water security is central to human well-being in rural Tamil Nadu. The expansion of well irrigation has provided much needed water to local farmers and increased agricultural production (Sato & Duraiyappan, 2011). However, groundwater reserves are finite, and their ability to continually support increased withdrawals is limited. While the causal network is but one view of the system, it deconstructs the interactions of system components that span space, scale, and the social-ecological spectrum. Future research should focus on knowledge gaps highlighted by the causal model, including component interactions, scale, and data availability.

5.1. Land use and land cover

There is a need to better understand how cropping decisions, agricultural productivity, and income vary by tank position within a cascade, and how the timing of water availability from different sources affects local farmers. However, data are sparse or nonexistent regarding the selection of crops, and the timing and number of plantings. For example, informal discussions with farmers suggest that as upstream tanks fill first, farmers can plant earlier in the season as they are assured that tank water will be available. Farmers lower in the cascade may have to wait to plant their crops until their tank begins to fill, potentially differentially affecting cropping decisions and agricultural yields. Similarly, additional research on how information, labor, and resources move among farmers, management groups, and tank cascades may provide valuable insight to the long-term viability of the agro-tank systems.

The ongoing expansion of tank rehabilitation by regional NGOs provides an opportunity to study a cross section of restored tanks, as well as shifts in social, hydrological, and ecological outcomes for tanks undergoing renovation. Remote sensing analysis can also map the spatial extent of *P. juliflora* on the landscape (Hoshino et al., 2011; Sastry, Thakker, & Jadhav, 2003), as it encroaches into tanks and reduces water storage capacity. When farms are abandoned, *P. juliflora* often spreads to empty plots and is very difficult to remove, thereby reducing available land in the command area and water availability for neighboring plots. Similarly, the growth of *P. juliflora* in the drainage area and channels that connect tanks has broader impacts on hydrology at the cascade scale. If the flow of water is impeded across the landscape and from tank to tank, villages lower in the watershed are disadvantaged. Further research is necessary to understand the spread and impact of *P. juliflora* on both environmental and social outcomes.

5.2. Hydrologic processes

Additional field studies are needed to quantify the hydrologic water balance at tank and cascade scales. Recent work indicates that infiltration and sluice discharge account for a much higher proportion of storage loss than evaporation (Van Meter et al., 2015). The specific methods and details of tank rehabilitation are important to understand *in situ*, as they may directly affect biophysical relationships, alter model coefficients, and affect water availability. A combination of field measurement and remote sensing analysis could generate a better understanding of rates of groundwater recharge and evapotranspiration, and the relationship between tank surface area and volume (Liebe, Van De Giesen, & Andreini, 2005; Rodrigues et al., 2012).

5.3. Tank management

At the tank scale, rehabilitated tanks increase local water availability during the monsoon season and extend it longer into the dry season. Yet, the various institutions that manage tanks and tank cascades possess potentially competing interests and operate at different scales. Prior to investment in rehabilitation, the local farmers form a water user association to manage and maintain the restored tank and its connections (e.g., feeder channels, surplus channels) within a cascade. There are also user associations at the cascade scale, comprised of members from each tank water user association. However, tank users who are not land owners are often excluded from participation (Aubriot & Prabhakar, 2011; Siderius et al., 2015). For rainfed tanks with command areas of less than 40 ha, village-scale government organizations called Panchayat Unions set priorities, control budgets, and auction the right to harvest silt, fish, or fruit. It is not well understood how mismatches in purpose, scale, and authority of management groups affect the efficacy of tank rehabilitation and the long-term sustainability of smallholder agriculture. Research regarding how these local organizations make management decisions should be integrated with quantitative process models to more holistically model the agro-tank system.

Collectively, these next steps will help isolate the root causes of water security with respect to local context. Further, it may provide insight into how traditional rainwater harvesting methods can be integrated with modern drilling technology to improve water security and human well-being.

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References

Akpinar Ferrand, E., & Cecunjanin, F. (2014). Potential of rainwater harvesting in a thirsty world: A survey of ancient and traditional rainwater harvesting applications. *Geography Compass, 8*(6), 395–413.

Amarasinghe, U. A., Palanisami, K., Singh, O., & Sakthivadivel, R. (2009). State of irrigation in Tamil Nadu: Investments and returns. In , *Proceedings of the second national workshop on strategic issues in indian irrigationStrategic analyses of the national river linking project (NRLP) of India series 5* (pp. 53–78).

Amarasinghe, U. A., Singh, O., Sakthivadivel, R., & Palanisami, K. (2009). State of irrigation in Tamil Nadu: Trends and turning points. In , *Proceedings of the second national workshop on strategic issues in indian irrigationStrategic analyses of the national river linking project (NRLP) of India series 5* (pp. 275–304). New Delhi: International Water Management Institute (IWMI).

Anuradha, B., & Ambujam, N. (2012). Impact of tank rehabilitation on improved efficiency of storage structures. *International Journal of Engineering Research and Applications (IJERA), 2*, 1941–1943.

Anuradha, B., Ambujam, N., Karunakaran, K., & Rajeswari, B. (2009). Impact of tank rehabilitation—an analytical study of peri-urban tank of Tamil Nadu. *Water and Energy International, 66*(4), 17–23.

Ariza, P., Galán, E., Serrano, T., & Reyes-García, V. (2007). Water tanks as ecosystems. Local ecosystemic perception for integral management of water tanks in Tamil Nadu, South India. *Periferia: revista de recerca i formació en antropologia, 7*.

Aubriot, O., & Prabhakar, I. P. (2011). Water institutions and the "Revival" of tanks in South India: What is at stake locally? *Water Alternatives, 4*(3), 325–343.

Bär, R., Rouholahnejad, E., Rahman, K., Abbaspour, K., & Lehmann, A. (2015). Climate change and agricultural water resources: A vulnerability assessment of the black sea catchment. *Environmental Science & Policy, 46*, 57–69.

Biazin, B., Sterk, G., Temesgen, M., Abdulkedir, A., & Stroosnijder, L. (2012). Rainwater harvesting and management in rainfed agricultural systems in sub-Saharan Africa—a review. *Physics and Chemistry of the Earth, Parts A/B/C, 47*, 139–151.

Binder, C. R., Hinkel, J., Bots, P. W., & Pahl-Wostl, C. (2013). Comparison of frameworks for analyzing social-ecological systems. *Ecology and Society, 18*(4), 26.

Bouma, J. A., Biggs, T. W., & Bouwer, L. M. (2011). The downstream externalities of harvesting rainwater in semi-arid watersheds: An Indian case study. *Agricultural Water Management, 98*(7), 1162–1170.

Carpenter, S. R., De Fries, R., Dietz, T., Mooney, H. A., Polasky, S., Reid, W. V., et al. (2006). *Millennium ecosystem assessment: Research needs*.

Carpenter, S. R., & Turner, M. G. (2000). Hares and tortoises: Interactions of fast and slow variablesin ecosystems. *Ecosystems, 3*(6), 495–497.

Chaves, H. M., & Alipaz, S. (2007). An integrated indicator based on basin hydrology, environment, life, and policy: The watershed sustainability index. *Water Resources Management, 21*(5), 883–895.

Cook, C., & Bakker, K. (2012). Water security: Debating an emerging paradigm. *Global Environmental Change, 22*(1), 94–102.

Crépin, A.-S. (2007). Using fast and slow processes to manage resources with thresholds. *Environmental and Resource Economics, 36*(2), 191–213.

DES. (2011). Season and crop report, Tamilnadu 2009-2010. In *Tamil Nadu Department of Economics and Statistics, Chennai*.

Fan, S., Hazell, P., & Thorat, S. (2000). Government spending, growth and poverty in rural India. *American Journal of Agricultural Economics, 82*(4), 1038–1051.

Garriga, R. G., & Foguet, A. P. (2010). Improved method to calculate a water poverty index at local scale. *Journal of Environmental Engineering, 136*(11), 1287–1298.

Geekiyanage, N., & Pushpakumara, D. (2013). Ecology of ancient tank cascade systems in island Sri Lanka. *Journal of Marine and Island Cultures, 2*(2), 93–101.

Glendenning, C., Van Ogtrop, F., Mishra, A., & Vervoort, R. (2012). Balancing watershed and local scale impacts of rain water harvesting in India—A review. *Agricultural Water Management, 107*, 1–13.

Global Water Partnership. (2000). *Toward water security: A framework for action* (Stockholm).

Grey, D., & Sadoff, C. W. (2007). Sink or swim? Water security for growth and development. *Water Policy, 9*(6), 545.

Gunnell, Y., & Krishnamurthy, A. (2003). Past and present status of runoff harvesting systems in dryland peninsular India: A critical review. *AMBIO: A Journal of the Human Environment, 32*(4), 320–324.

Gupta, S., & Deshpande, R. (2004). Water for India in 2050: First-order assessment of available options. *Current Science, 86*(9), 1216–1224.

Gupta, A. K., & Nair, S. S. (2010). Flood risk and context of land-uses: Chennai city case. *Journal of Geography and Regional Planning, 3*(12), 365–372.

Hall, J., & Borgomeo, E. (2013). Risk-based principles for defining and managing water security. *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, 371*(2002), 20120407.

Hoshino, B., Yonemori, M., Manayeva, K., Karamalla, A., Yoda, K., Suliman, M., et al. (2011). Remote sensing methods for the evaluation of the mesquite tree (Prosopis juliflora) environmental adaptation to semi-arid Africa. In *Geoscience and remote sensing symposium (IGARSS), 2011 IEEE international* (pp. 1910–1913). IEEE.

Hussain, I., Abu-Rizaiza, O. S., Habib, M. A., & Ashfaq, M. (2008). Revitalizing a traditional dryland water supply system: The karezes in Afghanistan, Iran, Pakistan and the kingdom of Saudi Arabia. *Water International, 33*(3), 333–349.

Jackson, R. B., Jobbágy, E. G., & Nosetto, M. D. (2009). Ecohydrology in a human-dominated landscape. *Ecohydrology, 2*(3), 383–389.

Janakarajan, S., & Moench, M. (2006). Are wells a potential threat to farmers' well-being? Case of deteriorating groundwater irrigation in Tamil Nadu. *Economic and Political Weekly*, 3977–3987.

Kajisa, K., Palanisami, K., & Sakurai, T. (2007). Effects on poverty and equity of the decline in collective tank irrigation management in Tamil Nadu, India. *Agricultural Economics, 36*(3), 347–362.

Kallis, G. (2007). When is it coevolution? *Ecological Economics, 62*(1), 1–6.

Kelble, C. R., Loomis, D. K., Lovelace, S., Nuttle, W. K., Ortner, P. B., Fletcher, P., et al. (2013). The EBM-DPSER conceptual model: Integrating ecosystem services into the DPSIR framework. *PloS one, 8*(8), e70766.

Komnenic, V., Ahlers, R., & Van Der Zaag, P. (2009). Assessing the usefulness of the water poverty index by applying it to a special case: Can one be water poor with high levels of access? *Physics and Chemistry of the Earth, Parts A/B/C, 34*(4), 219–224.

Krishna, K. (2010). *Agroecosystems of South India: Nutrient dynamics. Ecology and productivity*. Boca Raton, Florida, USA: Universal-Publishers.

Kumar, K. K., Kamala, K., Rajagopalan, B., Hoerling, M. P., Eischeid, J. K., Patwardhan, S. K., et al. (2010). The once and future pulse of Indian monsoonal climate. *Climate Dynamics, 36*(11), 2159–2170.

Kumar, M. D., Patel, A., Ravindranath, R., & Singh, O. (2008). Chasing a mirage: Water harvesting and artificial recharge in naturally water-scarce regions. *Economic and Political Weekly*, 61–71.

Lautze, J., & Manthrithilake, H. (2012). Water security: Old concepts, new package, what value?. In *Natural resources forum* (Vol. 36, pp. 76–87) Wiley Online Library.

Liebe, J., Van De Giesen, N., & Andreini, M. (2005). Estimation of small reservoir storage capacities in a semi-arid environment: A case study in the upper East region of Ghana. *Physics and Chemistry of the Earth, Parts A/B/C, 30*(6), 448–454.

Liu, J., Dietz, T., Carpenter, S. R., Folke, C., Alberti, M., Redman, C. L., et al. (2007). Coupled human and natural systems. *AMBIO: A Journal of the Human Environment, 36*(8), 639–649.

Milman, A., & Short, A. (2008). Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change, 18*(4), 758–767.

Molle, F., Shah, T., & Barker, R. (2003). The groundswell of pumps: Multilevel impacts of a silent revolution. In *ICID-asia meeting, Taiwan*.

Mosse, D., & Sivan, M. (2003). *The rule of water: Statecraft, ecology and collective action in South India*. Oxford University Press.

Nardo, M., Saisana, M., Saltelli, A., Tarantola, S., Hoffman, A., & Giovannini, E. (2008). *Handbook on constructing composite indicators: Methodology and user guide*. OECD.

Neumann, I., Barker, J., MacDonald, D., & Gale, I. (2004). *Numerical approaches for approximating technical effectiveness of artificial recharge structures*.

Niemeijer, D., & de Groot, R. S. (2008a). A conceptual framework for selecting environmental indicator sets. *Ecological Indicators, 8*(1), 14–25.

Niemeijer, D., & de Groot, R. S. (2008b). Framing environmental indicators: Moving from causal chains to causal networks. *Environment, Development and Sustainability, 10*(1), 89–106.

Norman, E. S., Dunn, G., Bakker, K., Allen, D. M., & De Albuquerque, R. C. (2013). Water security assessment: Integrating governance and freshwater indicators. *Water Resources Management, 27*(2), 535–551.

Olsson, P., Folke, C., & Berkes, F. (2004). Adaptive comanagement for building resilience in social—ecological systems. *Environmental management, 34*(1), 75–90.

Pal, I., & Al-Tabbaa, A. (2010). Regional changes in extreme monsoon rainfall deficit and excess in India. *Dynamics of Atmospheres and Oceans, 49*(2), 206–214.

Palanisami, K., Amarasinghe, U. A., & Sakthivadivel, R. (2009). Policy interfacing and irrigation development in Tamil Nadu. In , *Proceedings of the second national workshop on strategic issues in indian irrigationStrategic analyses of the national river linking project (NRLP) of India series 5* (pp. 83–94). New Delhi: International Water Management Institute (IWMI).

Palanisami, K., & Meinzen-Dick, R. (2001). Tank performance and multiple uses in Tamil Nadu, South India. *Irrigation and Drainage Systems, 15*(2), 173–195.

Pandey, V. P., Shrestha, S., Chapagain, S. K., & Kazama, F. (2011). A framework for measuring groundwater sustainability. *Environmental Science & Policy, 14*(4), 396–407.

Pérez-Foguet, A., & Garriga, R. G. (2011). Analyzing water poverty in basins. *Water Resources Management, 25*(14), 3595–3612.

Pintér, L., Hardi, P., Martinuzzi, A., & Hall, J. (2012). Bellagio STAMP: Principles for sustainability assessment and measurement. *Ecological Indicators, 17*, 20–28.

Potschin, M. B., & Haines-Young, R. H. (2011). Ecosystem services Exploring a geographical perspective. *Progress in Physical Geography, 35*(5), 575–594.

Ramanathan, S. (2015). *Urban planning in denial: Why Chennai gets unbearably flooded and what can be the solution* (Vol. 2016). The News Minute.

Ran, L., & Lu, X. (2012). Delineation of reservoirs using remote sensing and their storage estimate: An example of the yellow river basin, China. *Hydrological*

Processes, 26(8), 1215–1229.

Raudsepp-Hearne, C., Peterson, G. D., Tengö, M., Bennett, E. M., Holland, T., Benessaiah, K., et al. (2010). Untangling the environmentalist's paradox: Why is human well-being increasing as ecosystem services degrade? *BioScience, 60*(8), 576–589.

Reddy, V. R., & Behera, B. (2009). The economic and ecological impacts of tank restoration in South India. *European Journal of Development Research, 21*(1), 112–136.

Reyes-García, V., Aubriot, O., Ariza-Montobbio, P., Galán-Del-Castillo, E., Serrano-Tovar, T., & Martinez-Alier, J. (2011). Local perception of the multifunctionality of water tanks in two villages of Tamil Nadu, South India. *Society and Natural Resources, 24*(5), 485–499.

Rijsberman, F. R. (2006). Water scarcity: Fact or fiction? *Agricultural Water Management, 80*(1), 5–22.

Rodrigues, L. N., Sano, E. E., Steenhuis, T. S., & Passo, D. P. (2012). Estimation of small reservoir storage capacities with remote sensing in the Brazilian Savannah Region. *Water Resources Management, 26*(4), 873–882.

Rodriguez-Iturbe, I. (2000). Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research, 36*(1), 3–9.

Sandoval-Solis, S., McKinney, D., & Loucks, D. (2010). Sustainability index for water resources planning and management. *Journal of Water Resources Planning and Management*.

Sastry, K., Thakker, P., & Jadhav, R. (2003). Biodiversity threat through exotic species monitoring and management using remotely sensed data and GIS techniques—A case study of Banni (Kachchh) Gujarat, India. In *6th annual international conference on MAP India*.

Sato, T. (2013). Beyond water-intensive agriculture: Expansion of Prosopis juliflora and its growing economic use in Tamil Nadu, India. *Land Use Policy, 35*, 283–292.

Sato, T., & Duraiyappan, P. R. (2011). The effects of expansion of private wells on rural livelihood in tank intensive watersheds: A case study in upper gundar river basin, Tamil Nadu. *Southeast Asian Studies, 49*(1).

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., et al. (2009). Early-warning signals for critical transitions. *Nature, 461*(7260), 53–59.

Selvakumar, R., Rajasimman, U. A. B., & Gunasekaran, S. (2014). Restoration of cascading tank system using geoinformatics technology. *Asian Journal of Applied Sciences, 7*, 433–440.

Shah, T. (2004). Water and welfare: Critical issues in India's water future. *Economic and Political Weekly*, 1211–1213.

Shah, A. (2010). Land degradation and migration in a dry land region in India: Extent, nature and determinants. *Environment and Development Economics, 15*(02), 173–196.

Shah, T., & Raju, K. V. (2002). Rethinking rehabilitation: Socio-ecology of tanks in Rajasthan, north-west India. *Water Policy, 3*(6), 521–536.

Sharda, V., Kurothe, R., Sena, D., Pande, V., & Tiwari, S. (2006). Estimation of groundwater recharge from water storage structures in a semi-arid climate of India. *Journal of Hydrology, 329*(1), 224–243.

Siderius, C., Boonstra, H., Munaswamy, V., Ramana, C., Kabat, P., van Ierland, E., et al. (2015). Climate-smart tank irrigation: A multi-year analysis of improved conjunctive water use under high rainfall variability. *Agricultural Water Management, 148*, 52–62.

Singh, G., & Singh, N. (1993). *Mesquite for the revegetation of salt landa*.

Sivapalan, M., Konar, M., Srinivasan, V., Chhatre, A., Wutich, A., Scott, C., et al. (2014). Socio-hydrology: Use-inspired water sustainability science for the Anthropocene. *Earth's Future, 2*(4), 225–230.

Sivapalan, M., Savenije, H. H., & Blöschl, G. (2012). Socio-hydrology: A new science of people and water. *Hydrological Processes, 26*(8), 1270–1276.

Srinivasan, V., Lambin, E., Gorelick, S., Thompson, B., & Rozelle, S. (2012). The nature and causes of the global water crisis: Syndromes from a meta-analysis of coupled human-water studies. *Water Resources Research, 48*(10).

Srivathsan, A., & Lakshmi, K. (2011). *Chennai's vanishing waterbodies* (Vol. 2016). The Hindu.

Sullivan, C. (2002). Calculating a water poverty index. *World Development, 30*(7), 1195–1210.

Sullivan, C. A., Meigh, J. R., & Giacomello, A. M. (2003). The water poverty index: Development and application at the community scale. In *Natural resources forum* (Vol. 27, pp. 189–199). Wiley Online Library.

Sullivan, C., Meigh, J., & Lawrence, P. (2006). Application of the water poverty index at different scales: A cautionary Tale: In memory of jeremy meigh who gave his life's work to the improvement of peoples lives. *Water International, 31*(3), 412–426.

Umali-Deininger, D. L., & Deininger, K. W. (2001). Towards greater food security for India's poor: Balancing government intervention and private competition. *Agricultural Economics, 25*, 321–335.

Van Meter, K., Basu, N., McLaughlin, D., & Steiff, M. (2015). The socio-ecohydrology of rainwater harvesting in India: Understanding water storage and release dynamics at tank and catchment scales. *Hydrology and Earth System Sciences Discussions, 12*(11), 12121–12165.

Van Meter, K., Basu, N., Tate, E., & Wyckoff, J. (2014). Monsoon Harvests: The Living Legacies of Rainwater Harvesting Systems in South India. *Environmental Science & Technology, 48*(8), 4217–4225.

Van Oudenhoven, A. P., Petz, K., Alkemade, R., Hein, L., & de Groot, R. S. (2012). Framework for systematic indicator selection to assess effects of land management on ecosystem services. *Ecological Indicators, 21*, 110–122.

Venot, J.-P., Reddy, V. R., & Umapathy, D. (2010). Coping with drought in irrigated South India: farmers' adjustments in nagarjuna sagar. *Agricultural Water Management, 97*(10), 1434–1442.

Vohland, K., & Barry, B. (2009). A review of in situ rainwater harvesting (RWH) practices modifying landscape functions in African drylands. *Agriculture, Ecosystems & Environment, 131*(3), 119–127.

U. N. Water. (2013). *Water security & the global water agenda: A UN-water analytical brief*. Hamilton, Ontario: United Nations University Institute for Water, Environment & Health.

Wiek, A., & Larson, K. L. (2012). Water, people, and sustainability—a systems framework for analyzing and assessing water governance regimes. *Water Resources Management, 26*(11), 3153–3171.

Winder, N., McIntosh, B. S., & Jeffrey, P. (2005). The origin, diagnostic attributes and practical application of co-evolutionary theory. *Ecological Economics, 54*(4), 347–361.