




Water management using traditional tank cascade systems: a case study of semi-arid region of Southern India

Aman Srivastava¹  · Pennan Chinnasamy^{1,2}

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Abstract

Most arid and semi-arid regions of the Southern-Indian peninsula experience frequent drought. To combat this, historically many water recharge structures, such as tank cascade systems, have been constructed. However, in recent years, performance of these tanks, especially for irrigation and groundwater recharge, is limited due to impacts of external factors that are not scientifically understood. This study, for the first time, aimed to explore spatio-temporal variation of water mass balance components and their impact on the Vandiyur tank cascade system (VTCS) in the city of Madurai, India. Study estimated water mass balance components for rural, peri-urban, and urban catchments across VTCS. Catchment-specific algorithms and water budget equation were used to estimate the volume of hydrological parameters. Additionally, land use/land cover maps were developed to understand the significance of using a water balance approach in understanding the behavior of hydrological components governing the water budget of a catchment. Results indicated a rapid increase in the urban area, up to 300%, in peri-urban and urban regions. Urbanization was considered the primary cause of high catchment runoff (40–60% of rainfall). Due to this, seasonal water availability within each tank across catchment was observed inconsistent (0–15%), wherein summer recorded approximately the least tank storage (0–8%). In general, study provided an approach for a practical, water-focused application demonstrating how the principles of mass balance can help to foster robust water accounting, monitoring, and management. It further emphasized the use of a water balance approach in identifying vulnerable catchments for appropriate tank-rehabilitation-based interventions.

Keywords Sustainable water management · Water budget · Hydrology · Groundwater · Tank cascade systems · Tank irrigation

1 Introduction

The watershed or catchment productivity in an arid or semi-arid region, characterized by hot climate, scanty water availability, and erratic rainfall patterns, is crucial for sustaining the survival and development of living beings [24]. These regions are mostly rain-dependent and thus are vulnerable to the issues of water scarcity [28]. In developing countries, where the agricultural sector remains to be the combatant preliminary occupation for sustaining

livelihood, water resources management continues to play a key role in economic growth and developmental activities [27]. In recent years, the rising issues due to climate change, apart from rapid urbanization and advancement in technologies for surface and groundwater extraction, have significantly increased water stress [1, 60]. As a result of the hasty change in the land use land cover pattern, extreme events such as floods and droughts, in recent years, are becoming frequent and cyclic, especially in those regions where the rate of urbanization is

✉ Aman Srivastava, amansrivastava1397@gmail.com | ¹Centre for Technology Alternatives for Rural Areas (CTARA), Indian Institute of Technology Bombay, Mumbai, India. ²Rural Data Research and Analysis (RuDRA) Lab, Indian Institute of Technology Bombay, Mumbai, India.



significantly high [64]. At the same time, anthropogenic activities such as deforestation, streamflow regulations, and untenable agricultural practices are further causing chronic water shortage at the sub-catchment level [11, 12]. In these regions, the hydrological components such as evapotranspiration and surface runoff remain comparatively higher leading to large spatio-temporal variability of the water resources [50]. Inconsistencies in the water availability across seasons not only impact ecological balance in the watershed, but at the same time, makes it critical for diverse life forms of the watershed such as humans, animals, forests, and agriculture. Subsequently, it impacts socio-economic conditions which are integral to the water resources management [49]. Due to these factors, rural communities, located in the dry-arid watersheds, are pushed to shift from subsistence agriculture to sub-optimal livelihood alternatives [26]. Under these shifts, achieving sustainable development goals with the limited and unexplored natural resources in the arid and semi-arid watersheds is challenging [16]. Besides the management issues, there is a lack of data on water demand and supply in rural or remote watersheds. The absence of such information consequently falls out in the form of unsustainable practices, unpredictable plannings, and underprovided development initiatives for water management. As a result of this, the watersheds, in general, undergo further degradation largely due to off-balance between water availability and water requirements [16].

Similar challenges have been witnessed by the tank cascade systems in Southern India, which has been mostly employed for tank-based irrigation. A tank cascade is a network of surface water holding structures, built more than 2000 years ago by local rulers and maintained since then for centuries by the local communities [47]. A chain of tanks in a cascade forms a micro-watershed wherein an individual tank has its own catchment, tank bed area, and command area. These tanks are often observed inter-linked by a common stream flowing under gravity from the upstream tank thereby feeding the downstream tank. The underlying principle behind tank operation is the reuse and recycling of water from a series of small- to large-scale tanks. The catchment or watershed captures and conserves rainwater runoff, which would otherwise flow down as streams and mostly dissipated as evaporation [5, 17]. These traditional tanks, based on their functionality and in the modern context, have provided an effective alternative to combat climate change challenges in terms of moderating floods and droughts. Arid and semi-arid regions of Southern India, characterized by undulating topography, were identified as a suitable location for establishing the massive network of the cascading tanks by the ancestors [17, 47]. The sustainability of the tank functionality has been reflected in sustaining

the hydro-ecological and socio-environmental services by tank irrigation technology for over two millennia against spatial and temporal disparities in the typically dry climate of South India. Few of the major functionalities of the cascading tanks that have the potential to combat future climate change included, but not limited to, are (1) ensuring the continuous cultivation of paddy during both monsoon and non-monsoon (dry) seasons, (2) providing a seasonal water supply for domestic and livestock consumption, and (3) protecting the surrounding flora (including vegetation and forest), and fauna (considering the biodiversity) by positively influencing the micro-climatic conditions [40, 47]. Therefore, it becomes paramount to shift focus from devising new and costly technologies for flood and drought mitigation to further enhancing the potential of the already existing traditional tank cascade technology.

The centuries-old cascading tanks are becoming less prevalent in modern times due to lack of maintenance by the administration and civil society. Since the colonial period, the unwarranted intrusions by the state, apart from rapidly changing socio-economic dimensions at the village level, have severely degenerated tank systems. Post-independence (1947), tank irrigated area declined substantially from 3.6 million hectares (17%) in 1950 to 1.7 million hectares (2.5%) in 2014 (~212% decrease). The steep decline in tank irrigated area has been observed highly correlated with the depleting depth to the water level in wells in the surrounding region [40]. Case studies on tank cascade system have further demonstrated the need for conducting evidence-based field investigations on a functional tank cascade system in order to determine and validate the impacts of the external factors on the tank's performance and water balance components in the tank's watershed. Previous studies on water balance components of tank cascade system, such as by Van Meter et al. [59] in South India and Chowdhury and Behera [13] in West Bengal, showcased that the declining tank capacity and its potential are not only degrading tank irrigation but negatively impacting groundwater recharge to a considerable extent. For example, in relatively dry and drought-prone regions of South India, tanks have been contributing to the well recharge by 40% and decreasing surface runoff by 75%; however, the continued deterioration of tanks has increased vulnerabilities toward well-irrigation. In addition, an increased number of wells in the command area of tanks have further deteriorated the groundwater to unsustainable levels. Yet another study by Narayanamoorthy and Suresh [31] added that the ignorance toward tank management and operation and external stressors such as rapid urbanization and encroachment of tank catchment have caused surface runoff to increase and divert from reaching to tank water spread area. As a result of the aforementioned impacts, the water balance

and hydrological stability, in and around cascading tanks, are impeding. Furthermore, socio-environmental benefits from tanks, such as retarding negative impacts of floods and droughts, community-led management and maintenance of tanks, and enriching biodiversity in the vicinity of the cascading tanks, are collapsing, thereby creating a considerable imbalance in the hydro-ecological stability [24, 35, 48]. To combat the rising issues of the mismanagement of water resources in micro-watersheds (tank systems in particular), there is an urgency to impose the conception of water budgeting prior to introducing planning interventions and drafting location-specific policies. It is imperative to measure diverse water budget components of the hydrological cycle such as evaporation, evapotranspiration, surface-water storage, groundwater infiltration, and surface runoff [52]. The precise estimation of the hydrological parameter provides pilot information to systematically study the science of hydrology [37]. Calculating the water use from key sectors like agriculture, domestic, livestock, and activities supporting primary livelihoods provide information on the water requirements and water demand. The relative analysis between water availability and water requirements of a watershed designates its water balance (deficits or surpluses) [30, 61]. However, the variabilities in the hydrological parameters make the estimation of water balance components cumbersome [36]. Since the last decade, these approaches are becoming essential for the studies on water budgeting. At the same time, it is also enabling the water resource managers, policy-makers, engineers, and decision-makers to take an appropriate decision on water conservation plans and designs [3].

Several studies across India have applied the concept of water balance for quantifying the watershed-specific hydrological behavior while investigating diverse issues of water scarcity and mismanagement. For example, Wakode et al. [62], used the water balance equation to estimate the natural recharge against precipitation by quantifying evapotranspiration and surface runoff in the city of Hyderabad and found the depleting groundwater-recharge due to impermeabilization. Sharma et al. [48], validated the simulated values of rainfall and runoff using a water balance equation and further proposed strategic improvements in the water supply in the city of Shimla. Machiwal et al. [24] estimated inflow and outflow components of a small reservoir in the arid region of Kuchchh using a water balance model and highlighted the issue of depleting agricultural productivity due to high water loss through percolation and evaporation. Murty et al. [29] evaluated the water balance for the Ken basin of Central India and investigated the reason for higher water losses. They identified that, of the total precipitation received, 23% flows out as surface runoff, 73% as evapotranspiration

while 4% as groundwater flow. Yet in another study by Nayak et al. [32], a water balance analysis revealed higher groundwater exploitation due to excessive cultivation of paddy. Their study further proposed for 25% decrement in paddy cultivation to achieve groundwater sustainability. The use of the water balance method for the Thuringalur watershed in Tamil Nadu by Santhanam and Abraham [42] provided scope to convert 46% underutilized land for additional groundwater recharge. Seasonal water budget assessment by Setti et al. [46] in Kalahandi, Rayagada, and Koraput districts of Odisha and Vizianagaram and Srikakulam districts of Andhra Pradesh showed the need for water harvesting structures. The proposal was made so because 70% of the annual rainfall and 74% of the annual runoff occurs during the monsoon season. On the evaluation of the annual water balance components at the Sina basin in the Maharashtra state by Nandi and Reddy [30], the reason for the frequent drought was analyzed. Their study showed that annual evapotranspiration (~ 572 mm) was comparatively higher (80% of rainfall) among all hydrological parameters. Similar aforesaid findings have also been reflected in other study areas, globally, for example [10, 20, 23, 25, 63]. On the aforementioned note, the present study takes into account the water balance components as a case study in the city of Madurai, India.

Madurai city study area, characterized as semi-arid, is located in the South of Tamil Nadu state, India. It is having more than 46 major tanks in its surroundings and about 2500 small tanks, constructed mostly during the Sangam period (sixth-century BCE to third-century CE) across water courses and small streams which contribute to the Vaigai river. Vaigai river basin is one of the 34 river basins in Tamil Nadu covering an area of about 7000 square kilometers and it is surrounded by Cauvery and Pambar Kottakaraiyar basin on the North, Gundar River basin on the South, West by Periyar basin, and East by the Bay of Bengal. The surplus channels are more important in tank irrigation systems as they are the links of a chain, which function as the most efficient water harvesting structures. The non-perennial Vaigai river and its water holding tanks and channels that supported the urban and agricultural needs in the arid region for centuries is now damaged due to sand mining, encroachments, and real estate pressures. Most of the water that flows to it from the Periyar dam in Kerala is stopped at the Vaigai dam to serve the urban and agricultural needs of Madurai and its environments. The river dries most of the year and also has become a dumping ground for urban waste. Despite having an abundance of water availability through tanks and river streams and courses, the Madurai district, due to unreliable water supply from these system tanks and dams, is facing a high water shortage [41, 53]. In the last five decades, the district witnessed

13 events of drought. In fact, the cases of drought have turned frequent, occurring every 3–7 years [54]. In addition, the city is undergoing hasty growth since 1967. The population increased from about 7 lakhs in 1970 to 17.3 lakhs in 2019. Since the beginning of the 1990s, the district underwent rapid urbanization, thereby experiencing a remarkable change in land use land cover (LULC) pattern, as a result of which, the tanks and Vaigai river were affected. Under these circumstances, it is imperative to consider the physical characteristics of interconnected catchments such as the case of tank cascade system with an intention to understand the problems and to suggest site-specific conservation measures. Attempts have been taken since the 1980s under diverse rehabilitation programs launched by the State and Central Government to revive tanks across India [40]. Despite this, there are no studies as of now, conducted in Madurai city with the primary objective of establishing a correlation between water balance, water scarcity, and water management aspects in unison. Hence, there is a need for a comprehensive study of the water resources system across urban–rural catchments in Madurai city concerning the prospects of seasonal water balance given the potential of tank systems.

The primary objectives of this study are first, to estimate water mass balance components for the rural, peri-urban, and urban catchments of the city of Madurai, and second, to explore the spatio-temporal variation of water mass balance components and its impact on the available water resources. The broader intent is to quantify the inflow and outflow hydrological components from the respective catchments having varying developmental settings. The secondary objectives of this study are to develop a LULC map showing different land classifications thereby establishing the relation between land-use and water demand; to understand the significance of using a water balance approach in understanding the behavior of hydrological components governing the water budget of a catchment; and to identify the vulnerable catchments which are critical with regard to water availability and determining appropriate solutions to combat scarcity conditions.

2 Methods

2.1 Study site

Madurai city is part of the Madurai corporation and represents the administrative headquarter of the Madurai district in the Indian state of Tamil Nadu (Fig. 1a). The district is part of the Vaigai river basin, wherein the river approximately bisects the district into two halves. The

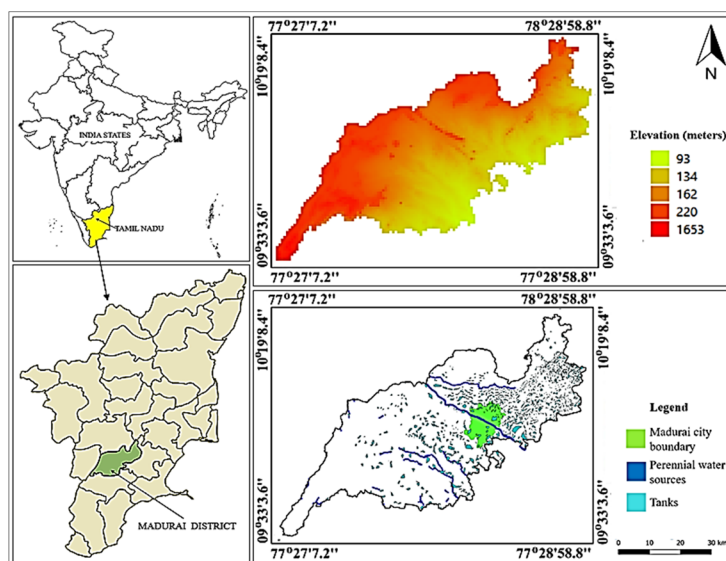
archaeological findings suggest that the district is more than two millennia old and continuously inhabited. Madurai city, which is also known as the cultural capital of the state, is located between 9.93°N and 78.12°E with an average elevation of 101 m above mean sea level. As there are no hills in the region, the city experiences roughly steady-state meteorological conditions. However, as the Tamil Nadu state is located in the semi-arid climatic zone, Madurai also experiences a dry-summer subtropical climate [7–9]. The temperature ranges from 15 °C to 41 °C, while the relative humidity ranges from 45 to 85%. The geological formations range from Archean to recent and include the Khondalite, Charnockite, and Garnitiferous Granulite Biotite Gneisses, and Fissile Hornblende Biotite Gneisses group of rocks. The groundwater occurs from semi-confined to confined aquifer conditions in deeper fractures and is interconnected by fractures [56, 57].

The study site, Vandiyur Tank Cascade System (VTCS) is located upstream (North) of the Vaigai river in Madurai city, and it extends from a village named Vandiyur located in Madurai-urban on the left bank of the Vaigai river to the Kulamangalam village in the Madurai-rural region. The study site has been categorized into six catchments (C) where each one is representative of at least a system tank (T) of VTCS, wells (W), and agricultural land apart from the human settlement (Fig. 1b). These catchments are further classified into three types based on their developmental settings. First, the villages Kulamangalam (C1) and Veerapandi (C2) are classified under Madurai-rural each having the tanks T1 and T2. Second, Thiruppalai (C3) and Siruvour (C4) are classified under Madurai-peri-urban each having the tanks T3 and T4. Third, Kosakulam–Parsurampatti–Kodikulam (KPK—C5) and Vandiyur (C6) are classified under Madurai-urban each having the tanks T5, T6, T7 and T8. There is a gentle slope from C1 to C6 due to which, gravity flow is observed from T1 to T8 in VTCS, wherein the surplus runoff from one tank recharges the next tank at the downstream, and thus, the catchments are interconnected (Fig. 1c).

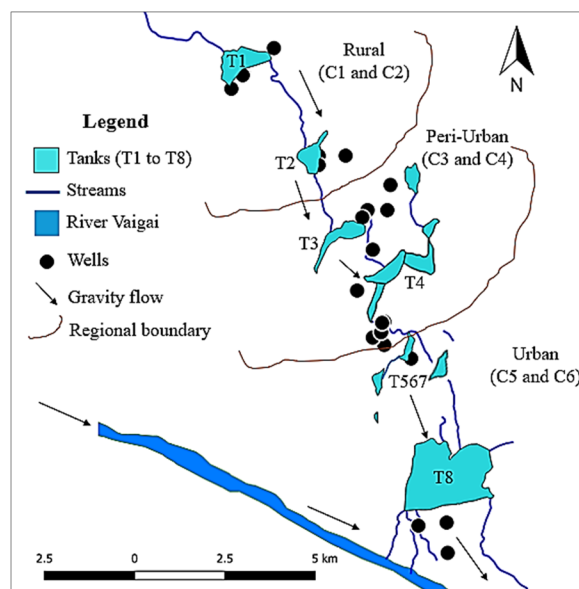
2.2 Fieldwork and data collection

Given the data collection methods using quantitative and qualitative research approaches, the present study first estimated the hydrological components such as rainfall, evaporation, and evapotranspiration based on the magnitudes and rates obtained from the hydrologic data, while runoff was obtained using the curve number technique. Using the water balance equation, the magnitude of the groundwater percolation was obtained. For comparative analysis, all the hydrological parameters were expressed in the percentage volume of rainfall and were compared in

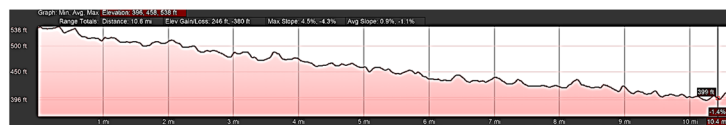
Fig. 1 Study site showing the location and elevation of Madurai city and Vandiyur tank cascade system (VTCS) (Source: Google Earth Pro)



(a) Location of study site in Madurai district, Tamil Nadu, India. Inset shows the location of Madurai in India and the Digital Elevation Model (DEM) of Madurai



(b). Location of tanks (T1 to T8) and wells (W1 to W22) in catchments (C1 to C6)



(c). Google Earth elevation graph from Kulamangalam village (North) to Vaigai river (South)

order to highlight the hydrologic trends across the catchment. Reconnaissance surveys, followed by a detailed field survey and experimentations, were conducted across the catchments from December 2018 to January 2020, wherein depth to the water level in each tank of the VTCS was measured to arrive at the current storage capacity of

the tanks. The actual volume of each component has been estimated across four seasons ($t=4$), viz. winter (January and February), summer (March to May), S–W monsoon (June to September), and N–E monsoon (October to December) and four types of land-use ($x=4$), in the units of a thousand cubic meters (TCM). For the present study,

the number of days in each season (d_{season}) was considered 59, 92, 122, and 92 days, respectively, and the study period was considered between 2002 and 2018.

The primary data were used in this study for understanding the nuances of the secondary data, given the behavior of water balance components and articulating rehabilitation of VTCS through site-specific interventions. The purpose of bringing qualitative investigations in this study was to acquire field insights (primary data), to fill the secondary data gaps, to understand the historical significance of tank water and irrigation, and for gathering people's perception toward water management schemes. In this regard, the Centre for Urban Water Resources (CURE) and DHAN Vayalagam Tank Foundation (DVTF) in association with the Hindustan Computers Limited Foundation (HCLF) in Madurai have been conducting personal interviews, transect walk across tank water spread areas, creating social and resource maps, and other tools of Participatory Rural Appraisal (PRA). These activities were and are being conducted with diverse stakeholders of VTCS which included Water User Associations (WUAs), Gram Panchayats (village-level governance body in India), Public Works Department (PWD), Municipal Corporation, Self-Help Groups (SHGs), and Vandiyur Lake Revival Associations such as Walkers Club and Gomathipuram Associations. The major findings from personal communication with the concerned official (Elamuhil, personal communication, December 28–31, 2019) have been incorporated in the present study.

2.2.1 Rainfall (P)

The monthly P data of Madurai for the period between 2002 and 2018 were obtained from the India Meteorological Department [18]. The P data were further categorized into respective seasons (P_{season}). The percentage departure in the P was estimated by comparing normal annual P (between 1969 and 2018) with the actual P data (between 2002 and 2018). The magnitude of P_{season} received in each catchment was multiplied with its catchment area (A_c) to obtain the volume of P , as shown in Eq. 6.

2.2.2 Land use land cover (LULC)

The LULC map of the study site was prepared using Remote Sensing (RS)-based satellite data from Google Earth Pro for the year 2002 and 2018. A supervised classification technique was used in order to obtain various land uses across catchments. As the role of the land-use types in the vicinity of VTCS was crucial to determine correlations of the degrading tanks with developmental settings, field investigations were carried out in 2019 to locate the key land-use types in the study area. The major land-use

identified included agriculture (inclusive of culturable command area and vegetation), wasteland/pasture (barren land), human settlement (built-up), and surface water bodies (tanks, rivers, and streams). The role of the vegetation in terms of green covers, such as forests, has the potential to influence the groundwater recharge [13] in the VTCS region. However, as there was a lack of availability of data on forest cover in specific and green cover in general, this study classified them under agricultural land-use type while conducting supervised classification. The surface area was recorded for each land-use type ($A_{\text{land-use}}$) and validated during the reconnaissance survey using Global Positioning System (GPS) Essential tool. The change in the LULC for the study period was analyzed statistically for identifying the impacts of urbanization and agricultural cover over the functionalities of the VTCS. Based on the catchment-wise LULC classifications, changes in the volumes of the hydrological components such as evaporation, evapotranspiration, surface runoff, groundwater percolation, and tank storage were evaluated for rural, peri-urban, and urban catchments. The volume (in cubic meters) of each of these components was obtained by multiplying their depth (in meters) with the surface area of the respective land-uses (in square meters) in each catchment. Later, the percentage contribution of the aforementioned hydrological components was expressed in terms of rainfall to identify the dominating hydrological phenomena prevailing across each catchment. Furthermore, quantitative (survey-based) and qualitative observations (Elamuhil, personal communication, December 28–31, 2019) from the field investigation were used to establish possible linkages between changing LULC patterns and hydrological balance.

2.2.3 Surface water storage in tanks (S)

The surface area of the tank (A_{tank}) was obtained during LULC studies, and the volume estimation (S) was based on the average depth to full-tank level (FTL) of these structures. The data on the total volume of the tanks were obtained from the District Public Works Department (PWD) office, while the actual volume was obtained by site survey of tanks. In order to obtain the actual tank storage capacity, site surveys were conducted inside the tanks during the summer of 2019 when the structures were completely dry. To avoid plausible error in estimating the actual storage, a large number of points were recorded from the field using GPS Essential tool by traversing in North–South (N–S), East–West (E–W), NW–SE, and NE–SW directions inside the tank water spread boundary. These points were imported to Google Earth Pro for visualization of the actual tank storage boundary, and mean sea level (MSL) was obtained for each

recorded point. While keeping the FTL of each tank as the maximum depth of storage, wherein the FTL was considered as the reference depth for estimating tank storage capacity, its MSL was obtained. The MSL of FTL was compared with the MSL of the recorded points. The difference between the two provided an actual depth (in meters) of storage in and around the recorded points wherein each recorded point was centered in the spatially created small rectangular surface area (in square meters) of the tank. The average depths obtained for each of these recorded points were further multiplied with their corresponding surface area of the tank for estimating the storage capacity (in cubic meters). Finally, storage capacities in and around each of the recorded points were summed up to determine the total storage capacity of the tank (in the units of thousand cubic meters). To record and analyze the seasonal tank storage capacity (S_{season}) and seasonal fluctuations in the tank water level, measurements of the depth to the water level in the tanks were taken across winter, summer, S–W monsoon, and N–E monsoon seasons in 2019. To ascertain the estimates of the level of the water in the tank for the last couple of decades (since 2002), qualitative investigations were conducted (Elamuhil, personal communication, December 28–31, 2019). The responses on the availability of the water in the tank across each season were quantified as a percentage of ‘water availability’, and the total volume of S was calculated using Eq. 6.

2.2.4 Evaporation (E) and evapotranspiration (ET)

The seasonal rates of E (E_{season}) and ET (ET_{season}) for each catchment of the study site were obtained from Allen et al. [2], and Smith et al. [51]. The E was considered to occur from the area of water bodies (A_{tank}), while the ET was considered to occur from the agricultural and wasteland/pasture land areas ($A_{\text{green cover}}$). The volume of E and ET was obtained by multiplying their corresponding rates with the surface area of their potential LULC type, percentage water availability (in tanks; for E estimation), and d_{season} , as shown in Eqs. (1) and (2).

$$E = \sum_1^t ((E_{\text{season}}) \times (A_{\text{tank}}) \times (\% \text{WaterAvailability}) \times (d_{\text{season}})) \quad (1)$$

$$ET = \sum_1^t ((ET_{\text{season}}) \times (A_{\text{green cover}}) \times (d_{\text{season}})) \quad (2)$$

2.2.5 Catchment runoff (R)

The Soil Conservation Services-Curve Number (SCS-CN) equation for the Indian conditions was used in the estimation of R from the study site [4, 6]. In the determination of CN, the hydrological soil classification Group-C (moderately high R potential) and antecedent moisture condition type-II (AMC-II) were adopted based on the conditions of the study site, and as per Rajesh et al. [38] and Sashikumar et al. [44]. The weighted curve number for AMC-II (represented as CN_{II}) was identified for all LULC classification using the values shown in Table 1. The parameter S_r , representing potential maximum retention, was obtained using Eq. 3. The depth of runoff (R_{depth}) was calculated using Eq. 4 which is valid against all monthly $P > 0.3S_r$. The total volume of R was estimated by multiplying it with each catchment area ($A_{\text{land-use}}$), as shown in Eq. (6)

$$S_r = \frac{25400}{CN_{II}} - 254 = 254 \left(\frac{100}{CN_{II}} - 1 \right) \quad (3)$$

$$R_{\text{depth}} = \frac{(P - 0.3S_r)^2}{P + 0.7S_r} \text{ for } P > 0.3S_r \quad (4)$$

2.2.6 Groundwater (G) flow

The determination of G was based on the water budget equation expressed in terms of hydrological parameters, as shown in Eq. (5). Due to the non-availability of the latest groundwater data in the public domain, the present study did not use any secondary data sources to obtain groundwater magnitudes, instead identified magnitudes of other hydrological components from secondary sources (such as for P , E , and ET), analytical methods (such as SCS-CN method for estimating R), and field investigations (such as for S) and later substituted them in water budget equation to indirectly arrive at the magnitude of the G (unknown variable in Eq. 5 and further elaborated in

Table 1 Runoff curve numbers (CN_{II}) under AMC-II conditions for hydrologic soil cover complexes for interconnected catchment (C1 to C6) in Madurai city [33, 52]

Region	CN_{II} for hydrologic soil Group-C in various land uses			
	Built-up	Agricultural	Tank	Waste-land/pasture
Rural (C1 and C2)	77	59	100	49
Peri-urban (C3 and C4)	82	63	100	61
Urban (C5 and C6)	86	67	100	72

Eq. 6) for each catchment across four seasons, viz. winter, summer, S–W monsoon, and N–E monsoon. Based on the qualitative investigations (Elamuhil, personal communication, December 28–31, 2019), narratives were developed regarding the groundwater usage pattern and well-irrigation scenarios that prevailed between 2002 and 2018 across VTCS. The narratives, in this study, have been used to validate the findings on seasonal groundwater storage as obtained from the water budget equation so as to arrive at the holistic measures for improving groundwater management across each catchment.

$$G = P - R - E - ET - S \quad (5)$$

$$G = \sum_1^t ((P_{\text{season}}) \times (A_c)) - \sum_1^x (R_{\text{depth}} \times A_{\text{land-use}}) - \sum_1^t ((E_{\text{season}}) \times (A_{\text{tank}}) \times (\% \text{WaterAvailability}) \times (d_{\text{season}})) - \sum_1^t ((ET_{\text{season}}) \times (A_{\text{green cover}}) \times (d_{\text{season}})) - \sum_1^t ((S_{\text{season}}) \times (A_{\text{tank}}) \times (\% \text{WaterAvailability})) \quad (6)$$

3 Results and discussion

3.1 Rainfall (P) analysis

From the field survey, it was found that the availability of water in the system tanks across the seasons was uncertain and mostly dependent on P , and hence, historic P analysis was done. The normal annual P was estimated to be 931 mm. N–E monsoon was the primary source of P in the city of Madurai which contributed 45% of the annual normal P followed by S–W monsoon contributing 36% (Table 2). The annual percentage departure of the P was calculated with reference to normal annual P . Results indicated that there was an overall reduction in the N–E monsoon by 11.2%, while the S–W monsoon recorded a decrease of 10.6%. Of the total 17 years of the study

period, the district recorded the annual percentage deficiency in P for 12 times, as evident from Fig. 2. The average percentage deficiency between 2002 and 2018 had been estimated to be 28%, while the percentage surplus in the P was observed five times with high fluctuations. The current decade (since 2012) was observed critical, concerning the percentage departure of the P , which was recorded as high as 45% (maximum) in the past seven years.

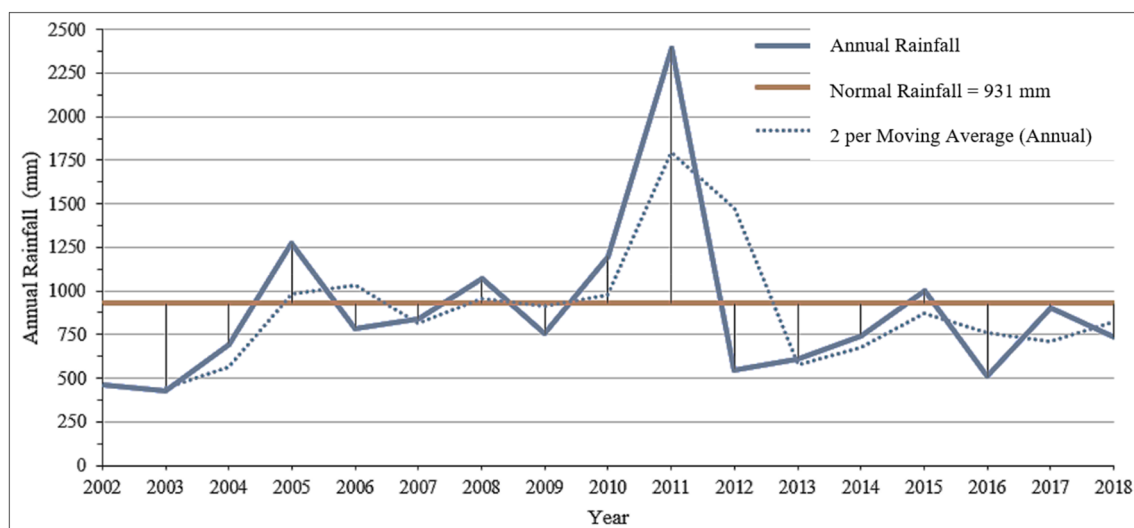
3.2 Land use land cover (LULC) change analysis

Results from areal imagery analysis showed a rapid increase in the built-up (urbanized) area, up to 300%,

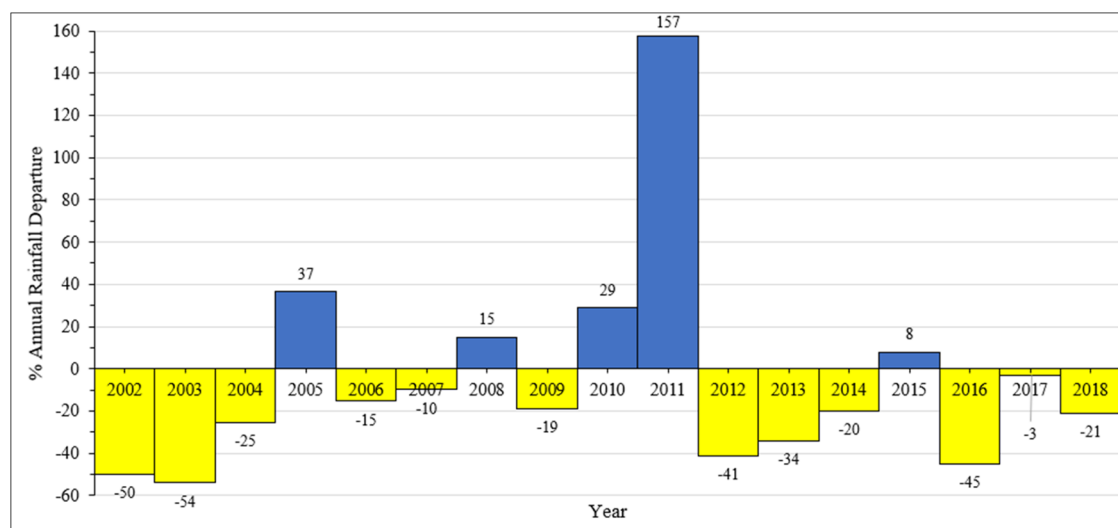
between 2002 and 2018 in peri-urban and urban Madurai (Fig. 3), while the impact of urbanization in rural areas was observed as < 200%. The cover of the urbanized area was recorded highest in urban C6 (474 hectares (ha)) followed by peri-urban C4 (167 ha) (Fig. 4a). The urbanized cover was found less than 5% of the entire rural catchments (C1 and C2). Results and past literature also indicated substantial degradation of the VTCS as a result of the unplanned urban expansion [3, 22, 39]. For example, the T8 reduced in size, as the tank once having a water spread area of 279.2 ha during the 1990s, irrigating a culturable command area of more than 404.7 ha withholding a storage capacity of 107 million cubic feet had shrunk to 71 million cubic feet by 2018 [14]. In fact, there are currently 36.4 ha of the culturable command area left for irrigation under T8 with a reduced water spread of ~ 231.5 ha [14]. The conversion of

Table 2 Seasonal analysis of rainfall in Madurai city (Source: [15])

Season	Months	Days	Actual rainfall (mm)	% Actual rainfall	Normal rainfall (mm)	% Normal rainfall
Winter	Jan, Feb	59	28.09	3.19	28.13	3.02
Summer	Mar, Apr, May	92	176.84	20.10	145.27	15.60
S–W monsoon	Jun, Jul, Aug, Sept	122	301.88	34.31	337.69	36.27
N–E monsoon	Oct, Nov, Dec	92	373.02	42.40	419.95	45.11
Total	Year	365	879.83	100.00	931.04	100.00



(a) Average actual rainfall (2002–2018) against the normal rainfall (1969–2018)



(b) Percentage departure of average actual rainfall

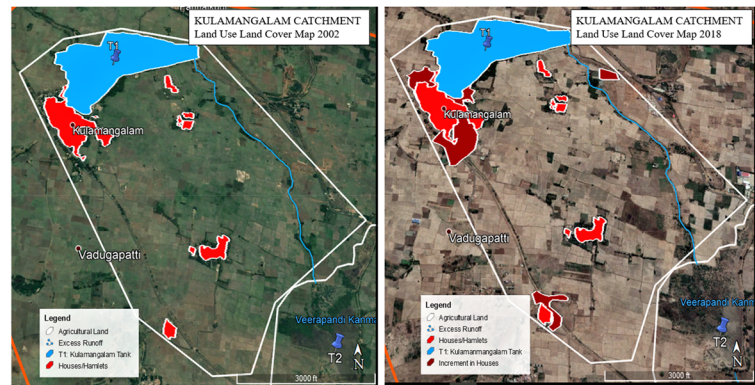
Fig. 2 Rainfall trend in Madurai city, Tamil Nadu, India

the command area into human settlement via encroachments was considered the primary reason behind the declining water spread area. In general, an increasing trend was observed in the urbanization from rural (least) to peri-urban and further to urban catchments across the study site.

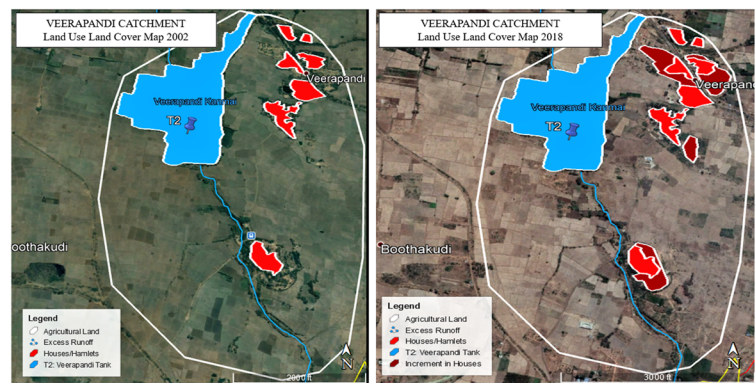
Another LULC classification considered for the present study was the agricultural cover. Agriculture was one of the primary livelihood practices in rural catchments (C1 and C2). As evident from Fig. 4b, apart from rural, C6 was the only urban catchment practicing agriculture, while the agricultural practices in C3, C4, and C5 were abandoned. In the case of later, both field investigation and

past studies found that these abandoned lands of agriculture were undergoing rapid encroachment due to the expansion of the Madurai city from urban to peri-urban belts [19, 22, 45]. Tanks served as a primary source of irrigation in C1, C2, and C6, apart from seasonal P and canal water supply from the Periyar and Sathaiyar dam located at the upstream of C1. In general, a decrease in the agricultural land cover was observed between 2002 and 2018 by approximately 56 ha across the study site. The general trend of agricultural land cover observed decreasing from urban (highest) to peri-urban to further rural catchments.

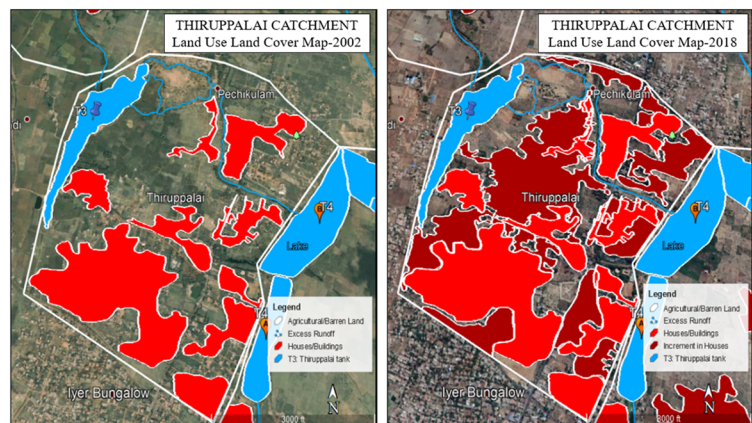
Fig. 3 Analysis of land use land cover (LULC) pattern between 2002 and 2018 for Vandiyur tank cascade system (VTCS) in Madurai city (Source: Google Earth Pro)



(a) Kulamangalam catchment (*C1-rural*) having tank *T1* located at the most upstream of VTCS; Surplus runoff from *T1* and *C1* recharges downstream tank *T2* situated in Veerapandi catchment (*C2-rural*)



(b) Veerapandi catchment (*C2-rural*) having tank *T2*, located at the downstream of Kulamangalam catchment (*C1-rural*), recharges tank *T3* situated in Thiruppalai catchment (*C3-peri-urban*)

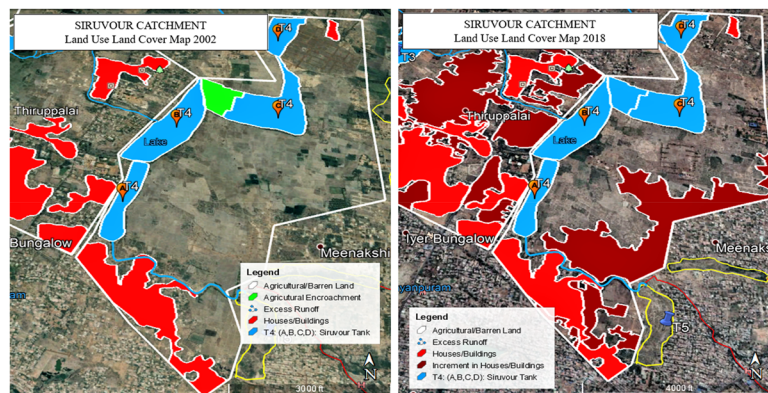


(c) Thiruppalai catchment (*C3-peri-urban*) having tank *T3*, located at the downstream of Veerapandi catchment (*C2-rural*), recharges tank *T4* situated in Siruvour catchment (*C4-peri-urban*)

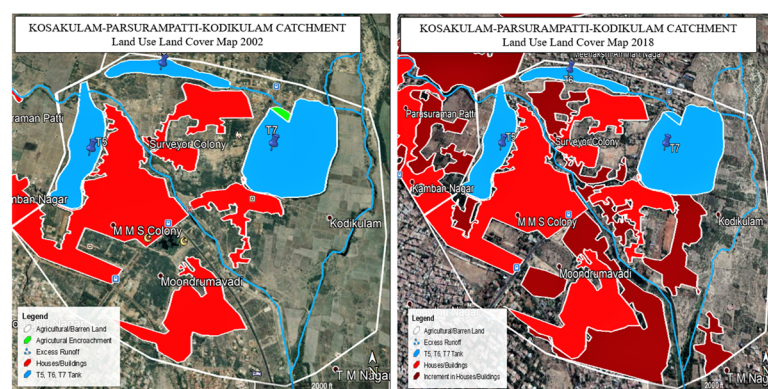
The percentage change in the LULC across six interconnected catchments in Madurai city is summarized in Fig. 5. The highest percentage increment in urbanized cover was recorded to be more than 330% in *C4* followed by *C3* with more than 210% (both peri-urban catchments). The reason behind the rapid urbanization in the peri-urban region

was attributed to its location and feasibility for expansion. Both *C5* and *C6* were close to their urbanization saturation, concerning the land area availability. Therefore, the expansion of the city was happening through *C3* and *C4* which was located next (at the upstream) to the Vandiyur. Also, the agricultural activities were declining due to

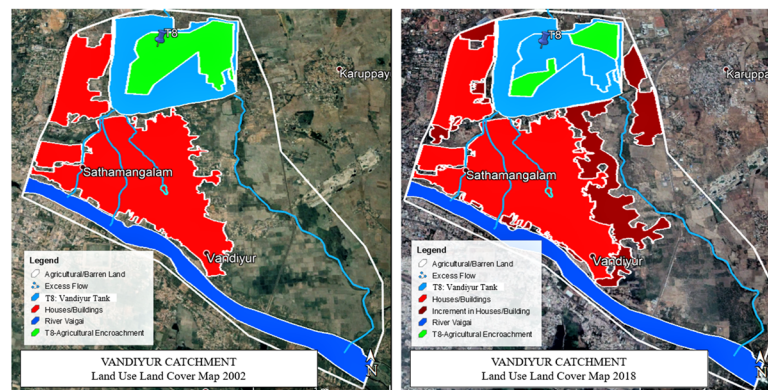
Fig. 3 (continued)



(d) Siruvour catchment (*C4*-peri-urban) having tank *T4*, located at the downstream of Thiruppalai catchment (*C3*-peri-urban), recharges tank *T567* situated in Kosakulam-Parsurampatti-Kodikulam (KPK) catchment (*C5*- urban)



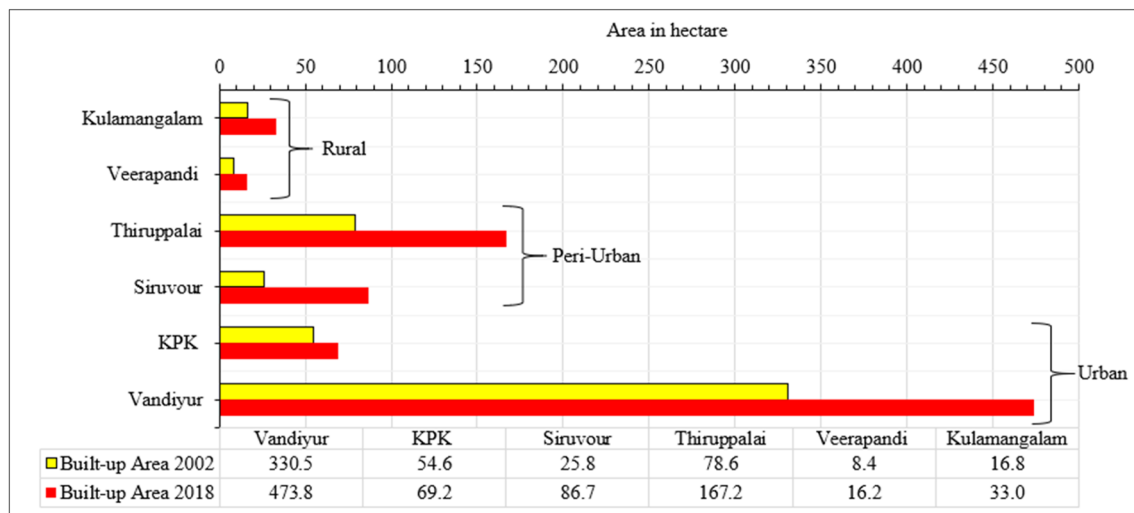
(e) Kosakulam-Parsurampatti-Kodikulam (KPK) catchment (*C5*- urban) having tank *T567*, located at the downstream of Siruvour catchment (*C4*-peri-urban), recharges tank *T8* situated in Vandiyur catchment (*C6*- urban)



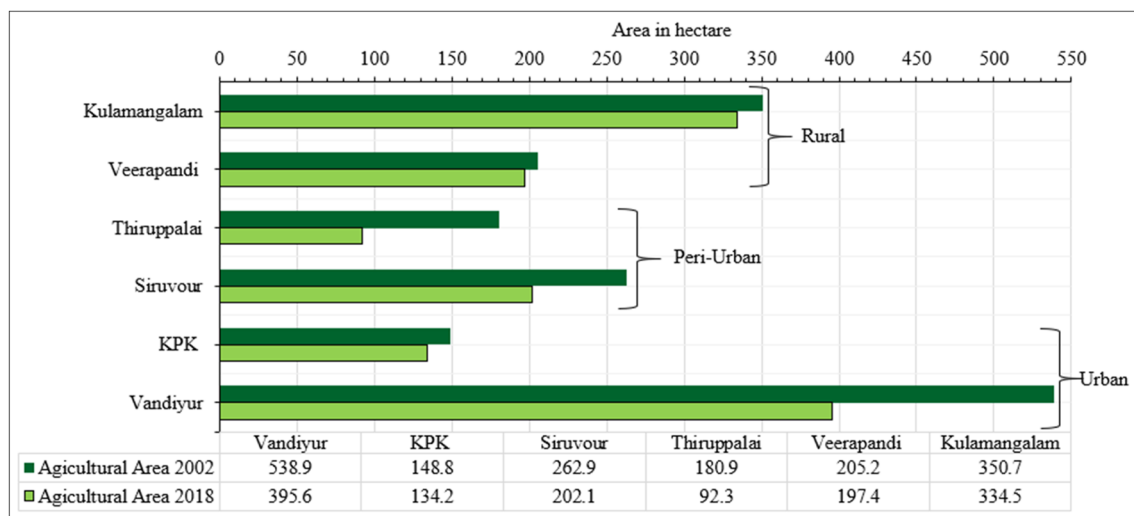
(f) Vandiyur catchment (*C6*- urban) having tank *T8*, located at the downstream of Kosakulam-Parsurampatti-Kodikulam (KPK) catchment (*C5*- urban) and the most downstream of VTCS, recharges the Vagai river

its rainfed based nature and poor potential of irrigation sources (primarily tanks) characterized by unreliable water supply from the silted (unmanaged) tanks. As a result, the rapid conversion of the agricultural land into non-agricultural land became prevalent. The highest decrement in the percentage cover of the non-urbanized region was

recorded in *C3* (49%), whereas *C6* ranked second with a 27% decrement followed by *C4* with a 23% decrement in the non-urbanized region. This newly available land was accommodating the expansion of the urbanizing cover of the city.



(a). Comparative analysis of built-up (urbanized cover) between 2002 and 2018 across interconnected catchment in Madurai city



(b). Comparative analysis of agricultural area (non-urbanized cover) between 2002 and 2018 across interconnected catchments in Madurai City

Fig. 4 LULC analysis of the Vandiyur tank cascade system (VTCS) in Madurai city

Results further indicated that the rural catchments were the least affected due to urbanization primarily for two reasons. Firstly, the villagers were actively participating in tank-fed based agricultural development programs. Villages have formed their WUAs headed by Sarpanch (or *Talaivar*). The second reason could be that the villages were located far from the urban region and hence not much influenced by the impact of urbanization. Overall, since 2002, the non-urbanized cover reduced in all the

catchments by 20%, and the urbanized cover increased in the range of 150% to 330%. Saravanabavan et al. [43] also identified the built-up cover (43% of entire Madurai city) to be the most dominating land-use, followed by fallow land (20%), cropland (14%), and tank water spread area (13%). Another study by Kundu et al. [21] indicated the decline in the non-urbanized area in Madurai city by 24%, whereas the built-up area increased by more than 200% between 2001 and 2018.

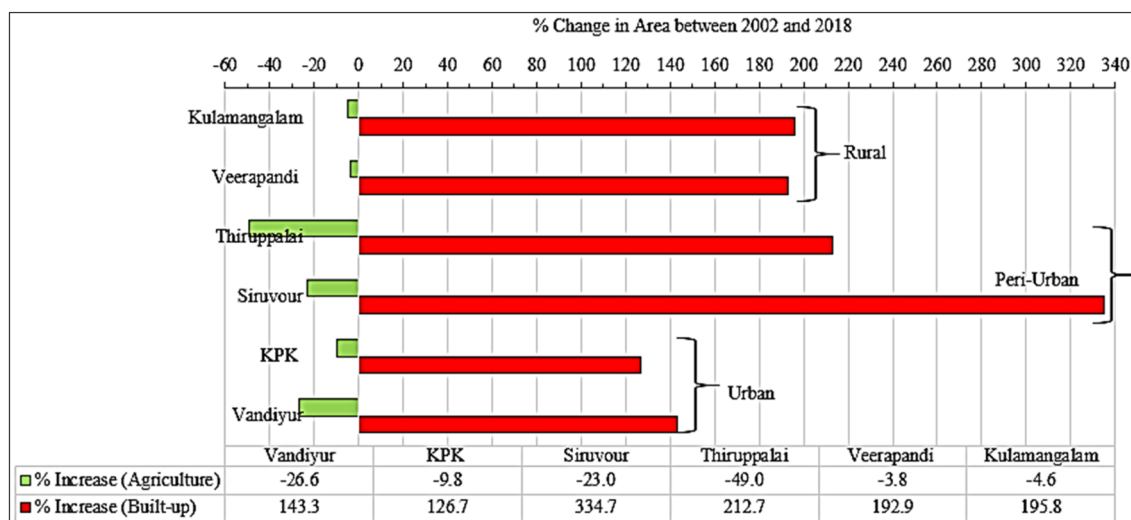


Fig. 5 Comparative analysis of built-up and agriculture land-use between 2002 and 2018 in Madurai city

3.3 Catchment-wise analysis of hydrological components

The catchments in the study site were analyzed for five hydrological parameters, viz. R , E , ET , S , and G , across four seasons, viz. winter, summer, S–W monsoon, and N–E monsoon (Fig. 6). The $C1$, a rural landscape, was the first catchment in VTCS located at the most upstream. The predominant hydrological phenomena in this catchment observed were the consistent G across the seasons. Due to high R during monsoon seasons, both G and S remained comparatively high resulting in more water availability across the catchment. However, during winter, the S fluctuates and by the mid-summer, water dries completely from $T1$. This was one of the reasons why the primary occupation of agriculture was observed limited to monsoon seasons (maximum of two cropping seasons). Similar to $C1$ was $C2$. Both the villages were observed to be self-sufficient with regard to the access and availability of the water at least for domestic purposes; nevertheless, water storage (in terms of G and S) in $C1$ was recorded to be 150% higher than $C2$.

The $C3$, a peri-urban landscape, was experiencing a reasonably high ET . This was attributed to a large barren land (wasteland and pasture), which a decade ago was under cultivation. This entire green cover remained unmanaged and fallow since then, resulting in a large patch of weeds. In addition, $C3$ experienced water scarcity even in the S–W monsoon. The water availability in the tanks (S) remained low to nil from the mid-winter to mid-N–E monsoon. Therefore, parameters such as E remained far lower in volume as compared to rural catchments. As the rate of urbanization in $C3$ was comparatively higher, the

catchment experienced higher magnitudes of R across all seasons (except winter). Similar was the hydrological observations for $C4$, however, instead of rapid urbanization, encroachment issues remained prevalent. As per the census records, $C4$ was uninhabited, still, the built-up cover in the catchment was observed increasing resulting in lower G and higher R . Overall, S in $C4$ was found approximately 150% higher than $C3$ and ~50% to 70% of $C1$ and $C2$.

The $C5$, an urban landscape, was observed experiencing a high R . Despite being urbanized, the G was observed comparatively greater than the peri-urban catchments. This was attributed to the fact that $C5$ consisted of three tanks ($T567$) located adjacent to each other allowing more water to percolate. $C6$ was the last catchment in VTCS before surplus runoff from the tanks discharged into the Vaigai river. Although $T8$ was the biggest among all system tanks across VTCS, both S and G proportionately remained lower than $C5$ with higher magnitudes of R .

In general, R was observed to be the most influential hydrological parameter across catchments in the VTCS region. This was attributed to the geological formation of the city which ranged from ancient Archean to recent alluvium and geologically classified into sedimentary formations and hard rocks. The hard rocks included granite which had poor G potential. At the same time, these were observed located at a narrow depth of 1 to 8 m below ground level and in few regions as outcrops, thus causing shallower soil layers [58]. Under these conditions, more R would be generating due to early soil saturation. Also, rapid urbanization would further add to the R leading to low water storage. On the other hand, G and S remained more consistent and significant in rural

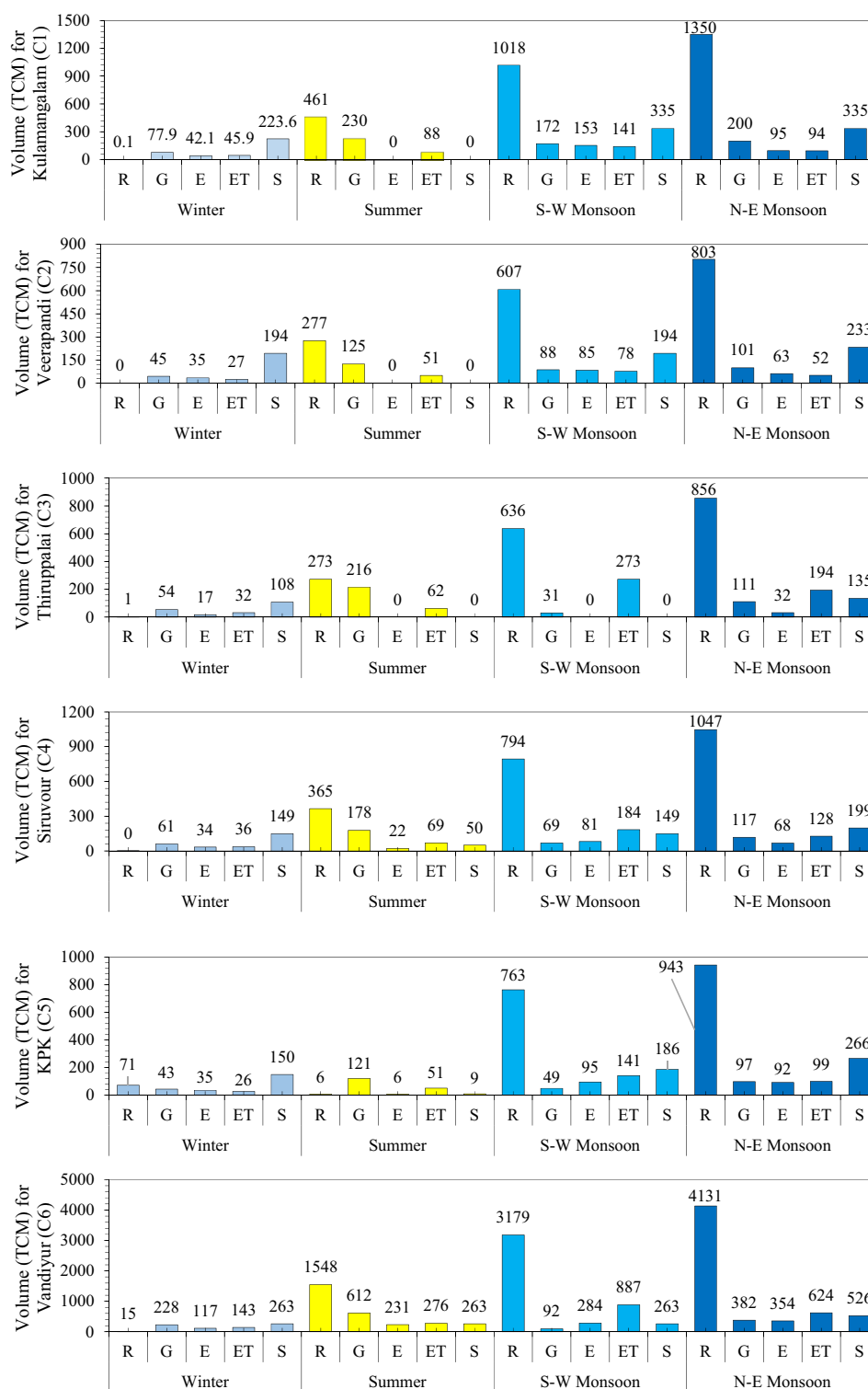


Fig. 6 Analysis of seasonal variation of hydrological parameters across rural, peri-urban, and urban catchments, in Madurai city [Note: hydrological parameters are represented as R: runoff; G:

groundwater flow; E: evaporation; ET: evapotranspiration; S: tank storage. Catchment KPK (C5) stands for Kosakulam–Parsurampatti–Kodikulam (KPK)]

catchments, while R and ET were recorded mostly higher than the G in peri-urban and urban catchments. Moreover, the magnitude of E was observed dependent on the water availability in the tanks, therefore, recorded higher during monsoon seasons and lower during summer and winter seasons (Fig. 6).

3.4 Analysis of hydrological components across catchments

The hydrological parameters of each catchment were expressed in the percentage of its corresponding P and were compared across the catchments, as shown in Fig. 7. In general, due to the highly erratic pattern of P during summer, all the hydrological parameters were identified as unstable and inconsistent for the summer season. The percentage volume of E was higher during the winter across all the catchments and observed fluctuating in the range of 30% to 60%. Followed by winter, N–E monsoon recorded E in the range of 10% to 20%. As the study estimated the E based on the water availability in the tanks (S), E was recorded lowest during summer (nearly 0%). Overall, E was estimated higher for rural areas due to more S potential within the catchment. Besides E , the percentage volume of ET was found higher for peri-urban catchment (averagely 20%) followed by urban catchments (averagely 15%) across summer, S–W monsoon, and N–E monsoon, whereas ET remained a recessive component in rural areas and estimated about 9%. The percentage volume of G was observed to be about 250% higher during non-monsoon seasons, as compared to monsoon seasons. There were two possible reasons identified during the field survey for this higher groundwater availability: (i) the tanks during N–E monsoon achieve nearly full capacity resulting in maximum percolation and thus recharged significant during winter, whereas, (ii) the infiltration during summer rainfall remained relatively higher due to unsaturated and dry soil conditions causing more percolation during initial showers. The percentage volume of the S was estimated higher during winter. This was attributed to the fact that despite the winter season receiving the lowest P among all the seasons, agricultural activities remained recessive. At the same time, the R remained closer to null due to no surplus runoff from the tanks. Since the S during winter remained higher, its percentage contribution during winter dominates over other parameters. The percentage volume of the R was averagely estimated to be 55% during summer, 63% during S–W monsoon, and 67% for N–E monsoon, while it was observed nearly null during winter. Within seasons, it showed an increasing trend from rural catchment to urban catchments (Fig. 7).

4 Discussions

4.1 Assessing VTCS and catchment performance

The results of the hydrological behavior, expressed in the percentage of rainfall, against each catchment are summarized in Table 3. It compares the percentage of water storage in terms of groundwater (G) and tank storage (S), with the percentage outflow (comprising E , ET , and R). The seasonal analysis showed that the groundwater storage was comparatively higher for winter and summer (between 15 and 39%) than monsoon seasons (between 2 and 10%). In addition to the further reasoning on this anomaly (analyzed previously in Sect. 3.5), another reason could be attributable to the delayed groundwater recharge from the monsoon rainfall. Since the tanks were mostly unmaintained (except for rural catchments), they remained silted, thus preventing early groundwater recharge. Additionally, the tank storage remained significantly erratic, especially during summer and S–W monsoon (ranging between 0 and 8%) though the general observation finds the increasing trend of tank storage from summer to the next years' winter. Catchment-wise, tank irrigation was observed to perform better in the rural catchment ($C1$ and $C2$), as the annual collective water availability of both G and S (between 15 and 31%) ensured irrigation to a greater extent. However, a similar collectiveness of water availability was lacking in the urbanized catchments. This was evident from the fact that the monsoon seasons (both S–W and N–E) resulted in a higher outflow in peri-urban ($C3$ and $C4$; outflow ranging between 90 and 97%) and urban ($C5$ and $C6$; outflow ranging between 83 and 92%) catchments. Even though collective water availability in the urban catchments was observed higher than rural catchments, especially during winter and summer, secondary issues, such as rapid urbanization and encroachment of the tank water spread area, deteriorated the tank irrigation. In summary, due to considerable changes in E , ET , and R , the restoration of the primary functionality of the VTCS, such as (1) irrigation water supply, (2) resistance from natural hazard including floods and droughts, (3) positively influencing micro-climatic conditions, and (4) recharging groundwater thereby wells in the command region across rural, peri-urban, and urban catchments, needed further attention from local communities, water user associations, policymakers, and village and district administrations. The aforementioned interventions require further understanding of the dynamics behind degrading tank functioning across VTCS, described as under:

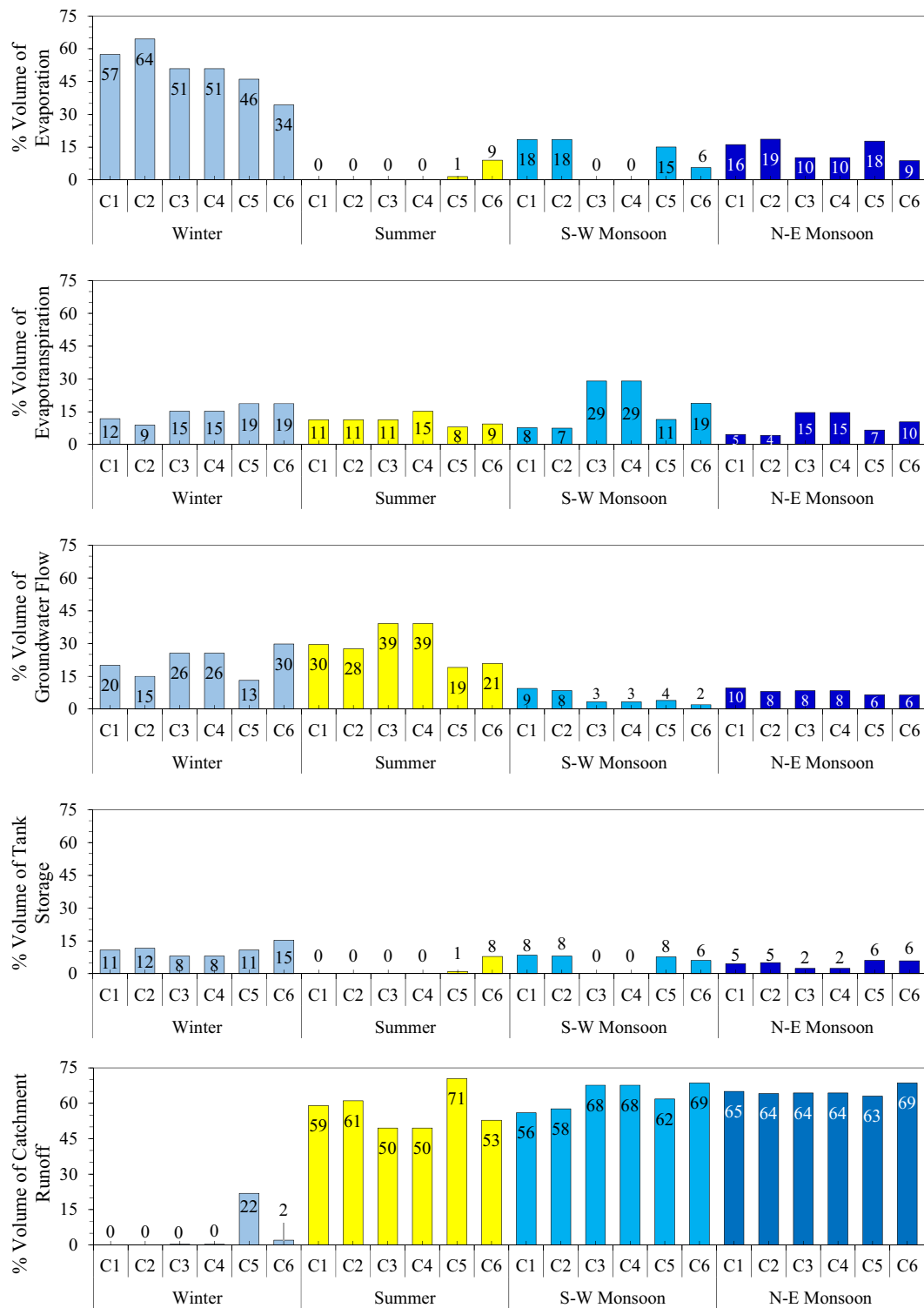


Fig. 7 Season-wise analysis of hydrological parameters (expressed in percentage volume of rainfall received in each catchment), viz., evaporation, evapotranspiration, groundwater flow, tank storage, catchment runoff across the study site (from C1 to C6) in Madurai

city [Note: C1 to C6 are interconnected catchments across VTCS, viz. C1: Kulamangalam; C2: Veerapandi; C3: Thiruppalai; C4: Siruvour; C5: Kosakulam–Parsurampatti–Kodikulam (KPK); C6: Vandiyur]

Table 3 Analysis of seasonal water balance components amidst field observations on the Vandiyur tank cascade system in Madurai city

Catchment	Water availability	% Seasonal water storage and flow within catchments				Field observations
		Winter	Summer	S–W monsoon	N–E monsoon	
C1 (rural)	Groundwater	20	30	9	10	Tank irrigation was observed feasible within the monsoon seasons
	Storage	11	0	8	5	
	Outflow ^a	69	70	81	85	
C2 (rural)	Groundwater	15	28	8	8	
	Storage	12	0	8	5	
	Outflow	73	72	83	87	
C3 (peri-urban)	Groundwater	26	39	3	8	Tank irrigation was observed poorer; agricultural land thus left abandoned
	Storage	8	0	0	2	
	Outflow	66	61	97	90	
C4 (peri-urban)	Groundwater	25	39	3	7	
	Storage	8	0	0	2	
	Outflow	67	61	97	91	
C5 (urban)	Groundwater	17	30	9	10	Tank irrigation was observed challenging given the rapid urbanization
	Storage	14	0	8	5	
	Outflow	69	70	83	85	
C6 (urban)	Groundwater	30	21	2	6	
	Storage	15	8	6	6	
	Outflow	55	71	92	88	
Range	Groundwater	15–30%	21–39%	2–9%	6–10%	Inconsistent
	Storage	8–15%	0–8%	0–8%	2–6%	Low
	Outflow	55–73%	61–72%	81–97%	85–91%	Significant

^a% Catchment Outflow = % Catchment Runoff (*R*) + % Evaporation (*E*) + % Evapotranspiration (*ET*)

- The decline in the tank irrigation across VTCS can further be attributed to increasing population density, which, in turn, is further stressing the need for well irrigation. Substitutability of tanks with wells could not be an appropriate option as both the sources are hydrologically connected to each other.
- Overall environmental degradation is further silting the tank, thereby the storage potential. As a consequence, unprecedented rainfall during monsoon results in a flash flood, while low or no rainfall causes complete water scarceness. Field investigation, contemplated that the ability of the VTCS to resist floods and droughts in Madurai city is impeding.
- Negative impacts on the tank functionality are further deteriorating the micro-climatic parameters such as increased evaporation, increased evapotranspiration, and diversion of the surface runoff from the feeder channel of the VTCS network. Due to this, depleted recharge in the wells of the command region, declining green cover in the vicinity of the tank region, and threats to aquatic life forms as a result of spreading invasive weeds are rising substantially.

Field investigation on the rainwater harvesting aspect of the VTCS revealed three peculiarities of this traditional practice. One, the construction material, mostly silt, used for constructing tank bunds, was locally available. With the available local technology, this silt provided the possibility for strengthening the earthen bunds of tanks. Two, the operation of the VTCS was community-driven, at least in rural areas, where the sense of ownership impelled villagers in contributing to the maintenance of tanks. On the contrary, the same was observed as challenging in the rapidly urbanizing catchments. Three, the existence of the tanks was the emblem of the decentralized water management scheme, which since its creation was meant for conservation and disciplined use of natural resources. However, in recent times, VTCS suffered from serious water deficiency all-year-round possibly due to higher outflows from each catchment. Despite VTCS having the potential to irrigate most parts of the command area, external factors, such as increased population, higher living standards, advancement in technologies associated with ground and surface water extraction, and changing paradigm of development, altogether ignored the VTCS. This brought a substantial shift from surface water civilization

to groundwater civilization and further to groundwater exploitation in the city of Madurai [21, 43, 54]. The declining tank irrigated area and expanding Madurai city was observed as a simultaneous process prevailing across the VTCS region. Under such a context, catchment-specific treatments and measures could pave the way to restore the primary functionalities of the tanks in the present context.

4.2 Catchment-specific interventions for improving tank systems

The framework for a sustainable water management plan in the study site was much needed, given the declining potential of VTCS. Based on the available guidelines proposed by the integrated mission for sustainable development [34] and with the intention to facilitate sustainability in water management [55] at the study site, catchment-specific appropriate interventions/measures are proposed (Table 4). It was primarily driven by the process of collecting and concentrating catchment runoff either into the run-on area (rain-fed-based agricultural land) or in the storage structures (system tanks or through decentralized rainwater harvesting in urban residential zones). The

appropriate measures for each catchment were prioritized given the findings from field surveys, PRA, and recommendations proposed by active NGOs, WUAs, PWD, and local Government authorities. Development of Human Action (DHAN) Foundation, a grassroot level not-for-profit organization in Madurai, is actively working on revival projects for urban and rural tanks. DHAN Foundation's CURE in association with HCLF (a division of Corporate Social Responsibility under Hindustan Computers Limited—HCL) launched the project 'REVIVAL' (Revitalizing Vandiyur Lake) in December 2018. The project is primarily focusing on restoring systems tanks through collective actions and planning.

All the catchment at the study site were classified into three priority classes, viz. high, moderate, and low. Out of six interconnected catchments, three catchments fall under a high priority class (C6, C5, and C3), while one catchment falls under a moderate priority class (C4). This was signifying the need for water conservation and management measures, especially in the peri-urban and urban catchments. However, there were few general measures proposed to be implemented for all catchments. Based on the priority, suitable field level measures (structural and non-structural) and user-level measures (community

Table 4 Proposal for priority catchments for soil and water conservation measures at Vandiyur tank cascade system (VTCS) in Madurai city

Type of interventions/measures required	Priority	Interconnected catchments (C1 to C6) of VTCS					
		Urban		Peri-urban		Rural	
		C6	C5	C4	C3	C2	C1
Field-level interventions:							
Creation of additional dead storage	High	✓	✓	✓	✓		
Construction of sedimentation pond in tank	High	✓	✓		✓		
MAR techniques for groundwater recharge	High	✓	✓	✓	✓		
Channel bed modification	High					✓	✓
Inclusion of Rabi cropping	High	✓					
De-siltation of tanks and Vaigai river	High	✓				✓	✓
Reuse of silt obtained during de-siltation	Moderate	✓				✓	✓
Conjunctive use of water	Moderate	✓				✓	✓
Leveling of the farm field	Moderate	✓				✓	✓
Reuse of irrigation water by pumping back	Moderate	✓				✓	✓
Multiple cropping	Moderate	✓				✓	✓
Forestry at the barren land	Moderate	✓				✓	✓
Canal irrigation	Low	✓				✓	✓
Strengthening of bund	Low	✓	✓	✓	✓		
User-level interventions:		✓	✓	✓	✓		
Mobilization of community	High	✓	✓	✓	✓		
Household-level rainwater harvesting	High	✓	✓	✓	✓		
Creation of water user associations	Low		✓	✓	✓		
Priority class of catchments		High	High	Moderate	High	Low	Low

MAR: Managed Aquifer Recharge

mobilization) were suggested for the vulnerable catchments. The former included revival, restoration, and rehabilitation measures for VTCS such as provisioning dead storage in tanks to create water storage during non-monsoon seasons; provisioning sedimentation tanks to keep a check over the intrusion of silt transported from upstream catchments; and de-siltation of tanks to create an additional volume of water storage. The aforesaid provisions were required primarily across all catchments. However, extensive desiltation and water hyacinth removal measures were much needed for both the Vandiyur tank (T8) and the Vaigai river. Due to sewage and solid-waste disposal into these water bodies, a thick layer of muck was observed at the bed instead of silt during the non-monsoon seasons. As a result of this, not only the storage potential was compromised, the quality of water too degraded for aquatic life forms and irrigational purposes. Besides this, the provisioning of groundwater recharge in urban catchments, more specifically inside the tank water spread area, including the Vaigai river, was required. This study proposes to implement Managed Aquifer Recharge (MAR) techniques in these water bodies, such as through well, shaft, or borehole recharge techniques, spreading methods, induced bank infiltration techniques, in-channel modifications, and runoff harvesting methods [15]. In agriculture, the cropping season was observed limited to one or two seasons (at the interface of S–W monsoon and N–E monsoon or depending upon the tank storage) with paddy cultivation as the only crop. Despite poor water availability, paddy was the most preferred crop at the study site. Less water-consuming crops along with paddy can be introduced to balance the demand and water availability. In addition, improvising irrigation facilities using simple land treatment measures like leveling off the field, mulching, ridging, and compartmental bunding was yet another set of priorities considered for active irrigation tanks (such as for T1, T2, and T8). The purpose was to enhance in-situ soil moisture conservation, consumptive use, and even distribution of water. The latter considered user-level mobilization as the principal component in decentralized water management design. Except for Vandiyur and rural catchments, the remaining catchments did not have focused communities managing water resources. This study recommends more registration of WUAs for the comprehensive management of VTCS as a whole. In addition to the above, with a primary focus on conservation and resource mobilization, organizing mega-events such as the Madurai marathon, Vaigai river restoration pageant, and protection of the rural, peri-urban, and urban tanks under VTCS could be yet another public-participatory approaches for achieving grassroot-level mobilization.

It was also understood, via surveys with DHAN Foundation, that there was no dedicated Government agency to maintain the VTCS, with only NGOs working on them. Therefore, even though the historic and traditional water storage infrastructure exists, a lack of understanding of process drivers and improper management has led to decreased water storage. To summarize, traditional water harvesting structures have the potential to ease the water stress in the current scenarios, however, without appropriate public and Government participation and policies, the revival of this traditional infrastructure is challenging. Therefore, rather than investing in new water infrastructure, this study urges for a collaborative effort from policymakers and Government agencies in understanding long-term impacts to tanks and encourage periodic maintenance and management of traditional water infrastructures that can aid sustainable water development in India.

4.3 Future directions

The study proposes to conduct the following future researches to further strengthen the rehabilitation measures for cascading tank and overall water management of the catchment across VTCS:

- As the objective of the present study was to understand the water balance scenarios of VTCS considering baseline period 2002–2018 and draw attention to vulnerable catchments concerning the functionality of their respective tank(s), the study did not consider developing a hydrological model. Therefore, no future scenarios were developed or predicted; however, major findings from the analysis of the existing water balance scenarios on catchment-wise water budgets were validated and its applicability was confirmed by conducting field investigations and qualitative research methods. The present study urges the use of advanced hydrological models to develop future scenarios considering present and future climate change impacts. This may additionally aid in developing a priority index that can prioritize diverse watershed management and water conservation measures with regard to the hydrological conditions at the catchment scale.
- There is a potential for uncertainty errors due to limited observation data networks, instrumentation and measurement errors, and data quality issues. Future research should focus on improving methodologies to reduce uncertainty errors in measurement data, which can be used to reduce uncertainty errors in the water balance approach.
- It was identified that infiltration, local storage, interception, and evaporation are quite difficult to meas-

ure, especially in the Madurai area, because of the strong heterogeneity of Madurai urban land-use, wherein spatial variability and temporal changes in land-use are typically high. In addition to this, catchment characteristics such as slope, imperviousness, and soil texture are variable in space and time and this variability affects the hydrological response of the Madurai urban area. Future studies should focus on bringing the impacts of the change in the aforementioned characteristics in coherence with the study objectives to further ascertain how hydrological response is impacting the functionality of VTCS. Besides this, future studies should focus on conducting an advanced analysis in LULC changes to differentiate between vegetation cover, barren land, and the forest (cover) leaves.

- There is an urgency to reconsider tank sedimentation in a contemporary rural–urban context. Given the solid-waste disposal, widespread invasion of water hyacinth, changing socio-economic dimensions, and climate change impacts over the micro-climate of tanks, provisioning of the natural silt (tank sediments), which remained a commonly applied source in farmlands to enrich the fertility of the adjoining command areas, is endangered. Hence, the prevailing circumstances stress future studies to deliver a further understanding of the correlation between tank sedimentation, buffering capacity of the cascading tanks, and their comprehensive impacts on agricultural productivity.
- Future studies can devise methodologies to measure the volume of rainfall obtained under the residential rainwater harvesting schemes, which can be useful to generate additional storage within each catchment. Furthermore, there is also a need to estimate actual groundwater recharge from the VTCS, as the present study estimated the same using the water budget equation. This may be attained by conducting evidence-based field experiments inside the tank water spread area. This may provide precise estimates for conducting the desiltation program of existing tanks in order to increase groundwater percolation.
- The development of open-source web-application-based water budgeting tools can be an effective way to arrive at the water balance of the given catchment through minimal inputs. The development of such applications provides scope to the local administration and communities to remain aware of the water balance scenarios of their catchment.

5 Conclusions

Limited attempts have been made to understand the efficiency of the traditional tanks, and thus, revival efforts are futile. Lack of a holistic understanding of processes that impact the functioning of tanks and the absence of dedicated capacity to manage tanks have been key reasons for the dismal performance. This study, for the first time, identified long-term physical drivers that impacted the potential of the Vandiyur tank cascade system (VTCS) and also document the administrative constraints that prevent the management of VTCS. The study also assessed the potential of VTCS located at an upstream of the Vaigai river in Madurai city of Tamil Nadu. In the context of the limited data availability, the investigation was compounded by the various hydrological parameters and their behavior with the changing land use land cover (LULC) pattern across rural, peri-urban, and urban catchments. Using quantitative and qualitative research methods, the water availability in the catchments given hydrological components was measured with the purpose to quantify water imbalance across the study site. Based on the results, suitable catchment specific water conservation measures were proposed comprising field-level interventions (structural and non-structural) and community-level mobilizations. Inclusion of the Vaigai river, which is one of the major missing links while designing site-specific rehabilitation works, in master and structural planning coupled with groundwater recharge component from the VTCS was given specific attention. The implementation of these measures would allow more surface water–groundwater interactions and would provide better economic opportunities to the population of each catchment. In addition, this would also help the planners to adopt sustainable water management measures in a phased manner. Apart from this, the outputs of this research also provide scopes to addressing general issues such as unreliable tank water supply, silting and unmaintained tanks, rain-fed-based cultivation, limited cropping season, abandoned agricultural land in peri-urban and urban catchments, lack of roof-based rainwater harvesting systems, and similar interventions aiming to conserve water.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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