A study on the effectiveness of percolation ponds as a stormwater harvesting alternative for a semi-urban catchment

Abhinav Wadhwa and Pavan Kumar Kummamuru

ABSTRACT

One of the challenges in urban stormwater management is to identify a suitable stormwater management method which will be socially, technologically and economically viable. In this paper, a study on the effectiveness of decentralized and interconnected percolation ponds as a stormwater harvesting technology, for a partially urbanized (semi-urban) catchment is presented. When applied to a case study region in Katpadi, Tamil Nadu, the results were encouraging. The investment required for implementing the proposed stormwater harvesting came to be about ₹555 Million for Option I and ₹714 Million for Option II. The annual volume of water that can be added to the groundwater system through infiltration from the ponds was found to be 1.22 Mm^3 in the case of Option I and 0.74 Mm^3 in the case of Option II. The percentage area under stormwater harvesting for the entire catchment was found to be 6.14% under Option I and 9.36 under Option II. The hydrologic performance of the proposed stormwater harvesting system indicated that for peak runoff values Option II is more efficient (in terms of minimizing runoff volume) compared to Option I; however, for daily rainfall values, Option I is hydrologically more efficient when compared to Option II.

Key words | decentralization, low impact development (LID), stormwater harvesting techniques, urban hydrology

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HIGHLIGHTS

- Decentralized percolation pond arrangement at sub-catchment and sub-catchment unit level.
- Series of interconnected percolation ponds for semi-urbanized catchment.
- Adaptation of proposed percolation pond arrangement for a haphazard urban catchment unit.

INTRODUCTION

With growing urban population and urban water demand, stormwater harvesting (SWH) is becoming one of the preferred approaches for stormwater management in urban areas. Urban SWH refers to the practice of collecting, storing/infiltrating and treating runoff from impervious areas such as roof tops, parking lots, roads, etc., for partially meeting water demands of a community (Larm 2000; Rauch *et al.* 2012; Nnadi *et al.* 2015; Bonneau *et al.* 2017; Niaizi *et al.* 2017). Conventional urban stormwater systems do not have the provision for harvesting stormwater, rather they were mostly built for safely discharging the excess runoff from impervious areas (Burns *et al.* 2012, 2015). Apart from the

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hydrological impacts of urbanization on runoff and infiltration processes, the other notable impact of urbanization is the skewness in water availability and water demand. Urbanization results in an increase in population which inherently results in increased demand for water. To meet the twin objectives of runoff volume reduction and partially meeting water demands locally, countries like the USA, Australia and New Zealand have developed technologies for sustainable management of urban stormwater. Such techniques are variously termed as LID (low impact development), SUDS (sustainable urban drainage system), WSUD (water sensitive urban design), and LIUDD (low impact urban design and development) in various countries (Elliott & Trowsdale 2007; Ray *et al.* 2010; Sitzenfrei *et al.* 2013; Fletcher *et al.* 2015; Eckart *et al.* 2017). Burns *et al.* (2012), Her *et al.* (2017), Holman-Dodds *et al.* (2003) and Tillinghast *et al.* (2011) performed a study to relate urban development with receiving watercourse attenuation. The results suggested that the increase in peak flows during a particular rainfall event are mainly influenced by changes in the urban layer which restricts the water being infiltrated into the soil. Qin *et al.* (2016), Tillinghast *et al.* (2011) and Zhou *et al.* (2015) performed studies to provide awareness for improvement in levels of water infiltrated and attaining the natural peak flow values in urban hydrographs. The major target is on improving the percentage of deteriorating groundwater levels and increasing water demand. Green infrastructure, another way to reduce stormwater flow, includes infiltrative rain gardens which have no impact on the environment and this technique requires less maintenance (Yang *et al.* 2015; Limos *et al.* 2016; Shaneyfelt *et al.* 2017; Wadzuk *et al.* 2017). Potentials to reduce peak runoff, reuse excess water and mimic pre-developed scenarios for an urbanized catchment furthermore includes the resilient design dimensions sustaining mutable storm events (Sorup *et al.* 2016). For managing urban runoff quantity, Fletcher *et al.* (2015) suggested that stormwater infiltration and retention-based technologies may be adopted either close to the source or at the end of the catchment (commonly known as decentralized SWH practice). Burns *et al.* (2012) demonstrated that the typical rainwater tank scenarios can concurrently assist in restoring pre-development flow regimes and reliably augment potable supply. Many studies on the application of permeable pavements and rainwater harvesting tanks in reduced pervious areas report that in the case of area restriction for construction of stormwater control measures (SCM), permeable pavement or rainwater harvesting or their combination is relatively effective in reducing potential urban runoff (Fletcher *et al.* 2007; Hamdan 2009; Alam *et al.* 2012; Mahmoud *et al.* 2014; Mankad *et al.* 2015). For micro-scale studies, implementation of SWH like infiltration trenches (Ahammed *et al.* 2013) and bioretention in combination with rain gardens and bioswales (Luell *et al.* 2011), in a decentralized manner, promises substantial achievement in stormwater goals. From a management perspective, infiltration trenches and bioretention tanks require periodic cleaning and pre-treatment. Measures like green roofs and grass swales (Singh & Kandasamy 2009; Penn *et al.* 2013) were found to be the best alternative to reduce the peak runoff but due to load considerations, their implementation on old buildings and commercial regions becomes highly questionable. For developing countries like India, Gogate *et al.* (2017) and Koh *et al.* (2016) developed a multiple attribute decision-making process for selecting the most suitable stormwater management alternative for a part of Pune city, and they concluded that leaky wells combined with rain gardens was the most suitable SWH alternative.

In summary, it can be stated that the choice of an appropriate SWH method, in general, is controlled by factors like economy, space availability, ease of implementation, and technology available locally. By taking into account the aforementioned factors in selecting an appropriate SWH technology for a locality, research is being presented in this paper to demonstrate the effectiveness of percolation ponds as a viable alternative for SWH for towns/cities in a developing country like India, where the implementation of LIDs like rain gardens, porous pavements, vegetative swales, bio-filters and infiltration trenches may not be feasible both practically and economically. The inspiration for use of percolation ponds as a SWH system was derived from the ancient temple tank system prevalent in South India. In ancient and medieval times, a temple tank served not only a spiritual purpose but also served as a water harvesting structure (Rao & Han 1987; Lei *et al.* 2008; Arulbalaji & Maya 2019). These tanks were more common in South Indian temples, since all the rivers in South India were rain-fed, and hence were less dependable for their flow during dry months. To overcome a shortage of water during dry months ponds were constructed which stored excess runoff during rainy seasons and percolated the water into the groundwater system. These ponds were well connected with each other such that excess flow from one pond would flow to the next connected pond. Hence, the ponds not only served as percolation units but also served as temporary detention for flood water. Other reasons for selecting percolation ponds is that they are economical, can be constructed with locally available technology, can be easily retrofitted into the existing storm sewer system and, more importantly, can facilitate in increasing groundwater levels locally through infiltration (Central Groundwater Board 2007; Gogate *et al.* 2017). In this paper, we present a methodology for SWH by emulating the ancient temple tank systems. The SWH system is designed by adopting a decentralized approach. In a decentralized approach a larger catchment is divided into smaller units so that it becomes easy to construct and maintain a SWH system. To check the efficacy of the proposed SWH system, the optimization model was applied to a case study area which is a part of Katpadi Town in the state of Tamil Nadu, India. The size of the study area is about 19 km^2 and almost 33% of this area is residential, the remaining area consisting of undeveloped land and vegetated land. The results indicated that a decentralized approach to SWH through a system of percolation ponds and lined channels can improve water availability potential locally.

METHODOLOGY FOR THE PROPOSED STORMWATER HARVESTING SYSTEM

Figure 1 shows the detailed methodology flow chart for the proposed SWH system using percolation ponds. As can be seen from the flow chart, the entire methodology consists of three blocks: rainfall-runoff processing for the catchment (Block 1), optimization model framework (Block 2) and performance evaluation of the SWH system (Block 3). In Block 1, peak runoff resulting from impervious surfaces within the catchment is generated for pre-urbanized and post-urbanized catchment characteristics. The pre-urbanized and post-urbanized land use details for the catchment can be obtained through Google Earth satellite data. The peak runoff is estimated using rational method formula:

$$Q = 0.00278CiA \tag{1}$$

where Q is the peak runoff from the catchment (m^3/s), i is the design rainfall intensity for a design return period estimated using intensity distribution function (IDF) relationship (mm/hr), A is the catchment area in hectare, and C is the rational coefficient which is a function of land use type. To determine the runoff volume, the discharge obtained from

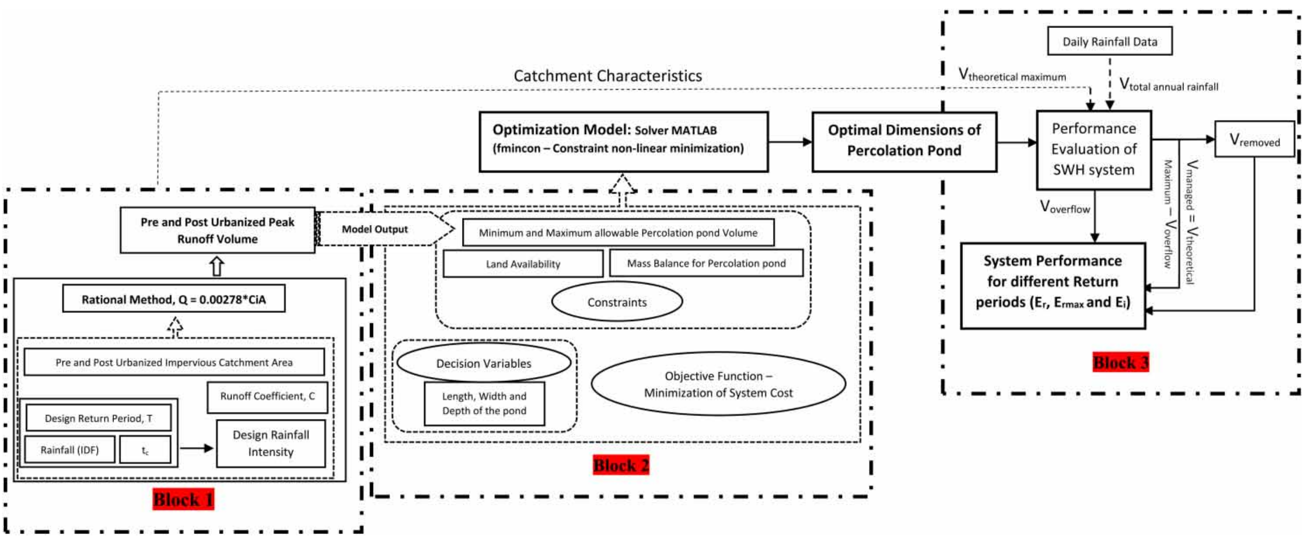

Figure 1 | Methodology flow chart for the design and performance measure of optimal stormwater harvesting system.

the rational formula is multiplied by time of concentration (Deodhar 2008). The time of concentration, t_c (in minutes), was determined for each sub-catchment (shown in Table 1) and sub-catchment unit using the Kirpich formula:

$$t_c = 0.0078 * L^{0.77} S^{-0.385} \quad (2)$$

where, L is the flow path length of the catchment unit (in metres) and S is the slope (m/m).

The pre- and post-urbanized runoff resulting from Block 1 is used as input to one of the constraints in the optimization model. Block 2 consists of the optimization model framework, wherein decision variables, objective function and constraints are discussed. The optimization model is solved using the appropriate optimization tool. The output of Block 2 will be the optimal dimensions of the percolation ponds required. Finally, the performance of the designed percolation ponds under different rainfall events are determined using pre-defined efficiency measures through the performance evaluation of the SWH system. A detailed application of the proposed methodology to a case study area is discussed in the next section.

Table 1 | Topographical data for sub-catchments

Sub-catchment ID	Width (in m)	Slope	Time of concentration (in minutes), t_c
SC1	5,781	0.091	22.7
SC2	3,752	0.106	15.4
SC3	2,898	0.099	12.9
SC4	4,322	0.111	16.8
SC5	5,642	0.105	21.1
SC6	4,838	0.110	18.4
SC7	2,880	0.094	13.1
SC8	7,313	0.216	30.2
SC9	5,016	0.110	18.9
SC10	2,896	0.072	14.6
SC11	4,301	0.069	20.1
SC12	4,434	0.092	18.4
SC13	8,197	0.081	31.1
SC14	4,206	0.092	17.6
SC15	7,057	0.085	27.2
SC16	7,320	0.079	28.7
SC17	7,087	0.072	29.0
SC18	7,913	0.076	31.0

APPLICATION OF METHODOLOGY TO A CASE STUDY AREA

To demonstrate the applicability of the proposed SWH system, the optimization model was applied to a case study region in Vellore, Tamil Nadu. Table 2 shows the topographical characteristics of the case study area. The case study area selected is a part of the larger Katpadi region, which in itself is a part of larger Vellore town. The total geographic area of the study area is about 19.01 km^2. In this area about 30.7% is urbanized, water bodies occupy about 3.1% of the area, 28% is vegetated land and about 38.2% is barren or undeveloped land.

A schematic figure of the case study area can be seen in Figure 2. The major portion of the urbanized area is residential with a small portion occupied by commercial developments and institutions like schools and local offices. There exists a combined sewer system in the study area, laid along the major roads to carry domestic wastewater and stormwater (https://www.twadboard.tn.gov.in/). The average annual rainfall for the region is about 971 mm and much of the rainfall in the region occurs between the months of July and November. Most of the residences in the area do not practise any water harvesting methods. The average groundwater level in the

Table 2 | Topographical data and list of maps used for the study

Map type	Spatial resolution	Year map developed
SOI toposheets	1:25,000	1997 and 2003
Google Earth images	60 m (for 1995–2001), 5 m (for 2002–2020)	1995–2020
Landsat images	TM (60 m), ETM+ (28.5 m), OLI/TIRS (28.5 m)	1995–2011 (TM), 1999–2019 (ETM+, SLC failed), 2013–2020 (OLI/TIRS C1 level 1)
Digital elevation models (DEMs)	30 m	2000 (SRTM 1-arc second)
Ward-wise study area map	–	2016

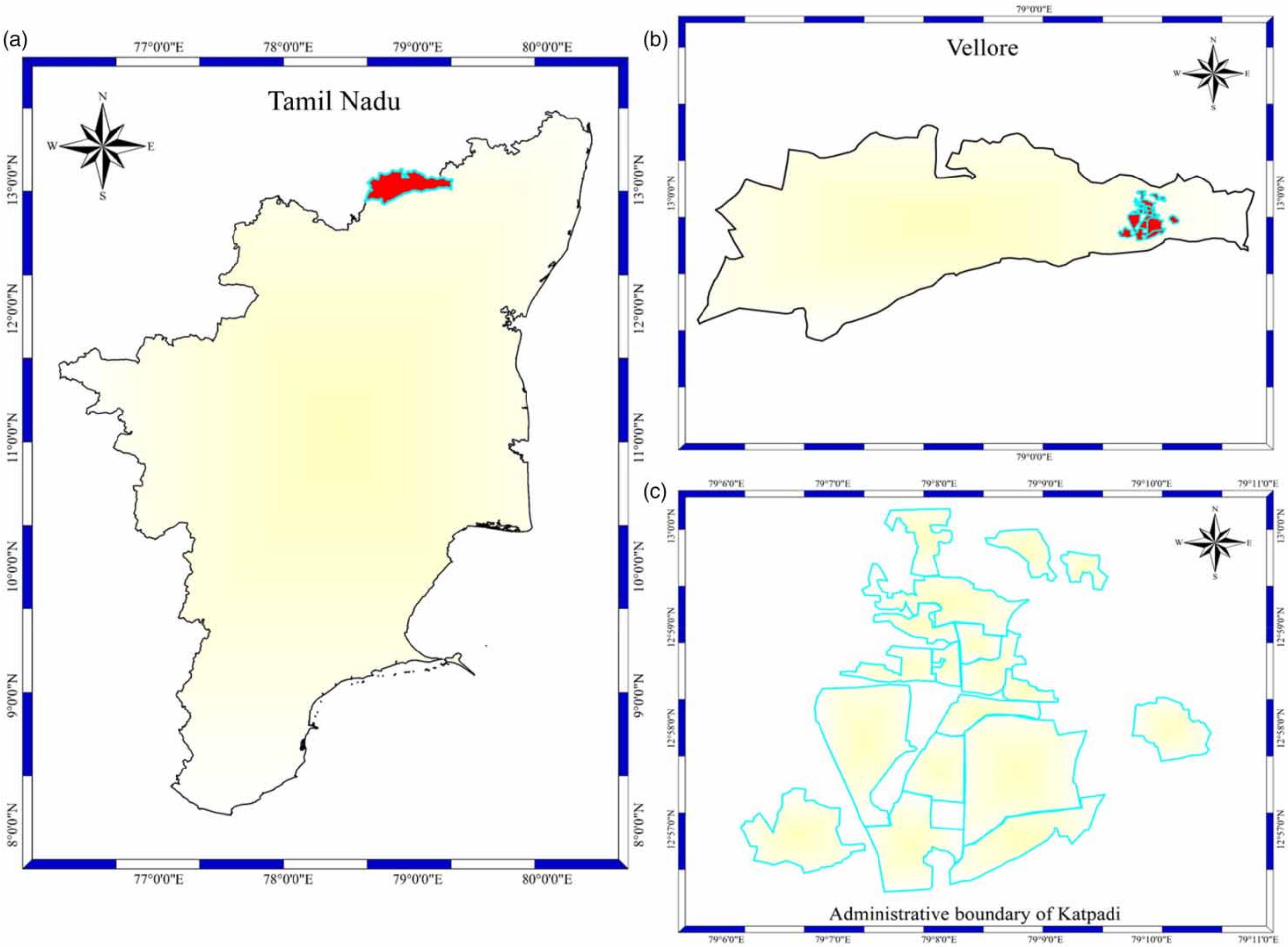

Figure 2 | Schematic illustration of the case study area: (a) Tamil Nadu, (b) Vellore District, (c) Katpadi town.

area measured along the 21 bore and open wells (http://www.fnwm.gov.in/) fluctuates between a maximum of 17.1 m bgl (below ground level) to a minimum of 8.41 m bgl. The only source of groundwater recharge in the area is due to natural infiltration process, and no specific measures are being taken by the community in the area to improve groundwater level (Shanmugasundharam *et al.* 2017). As per the CCBP report (CCBP 2019), Katpadi town is categorized as a high risk zone for water shortage wherein ward nos. 1, 2, 13, 14 and 15 corresponding to the sub-catchment numbers 1, 4, 6, 7, 13, 14 and 16 as per the catchment division proposed in the study, experience water shortage problems throughout the summer season. The soil type in the study area is sandy loam with an average hydraulic conductivity of 1.1 cm/h (Kanagaraj *et al.* 2019). In future, as the area becomes more urbanized and the population grows, immense stress on the groundwater source can be expected. It is, therefore, the right time to implement suitable SWH measures which will increase the water level in the groundwater table. To assess the level of decentralization that will be beneficial from a hydrologic and economic perspective, the following two SWH options were considered:

- Option I: SWH through a series of interconnected percolation ponds and with decentralization at sub-catchment unit (SCU) level.
- Option II: SWH through a series of interconnected percolation ponds, with decentralization at sub-catchment (SC) level.

The catchment here is the entire study area; sub-catchment is the unit of division when the catchment is divided into smaller units; and sub-catchment unit is the unit of division resulting from further division of a sub-catchment.

Arrangement of percolation pond within a SC and SCU

For decentralization of the SWH system at SC level, the entire catchment area was divided into 18 sub-catchments, with each sub-catchment roughly corresponding to a ward as defined by Vellore Municipal Corporation (https://www.tn.gov.in/dtp). The further division of a sub-catchment into SCUs was accomplished by roughly identifying the area enclosed within the major roads (Figure 3).

For this purpose, Google Earth VHR satellite image depositories with a spatial resolution ranging from 15 m to 15 cm were used. The final classification of the study area into SCs and SCUs can be seen in Figure 4. One of the primary assumptions in the proposed optimization model is that each SC or SCU will have only one percolation pond such that all the surface runoff from the impervious area within an SC/SCU will flow through gravity towards the pond. This will be possible if the pond is located at the lowest elevation within a SC/SCU. The lowest elevation point within a SC/SCU was identified using elevation profile mapping of the study area in Google Earth and this lowest point in a SC/SCU is identified as the suitable site for situating a percolation pond (the arrangement of interconnected tanks is shown in Figure 5). It should be noted that the soil type is similar (sandy loam) throughout the study area and the groundwater table is well below the ground level in all the sub-catchments. Figure 5 shows a schematic representation of interconnected ponds within a sub-catchment. Within the catchment, the ponds are arranged in such a fashion that the excess runoff from an upstream pond will flow into the next pond. All the ponds therefore are interconnected and the entire arrangement of percolation ponds at

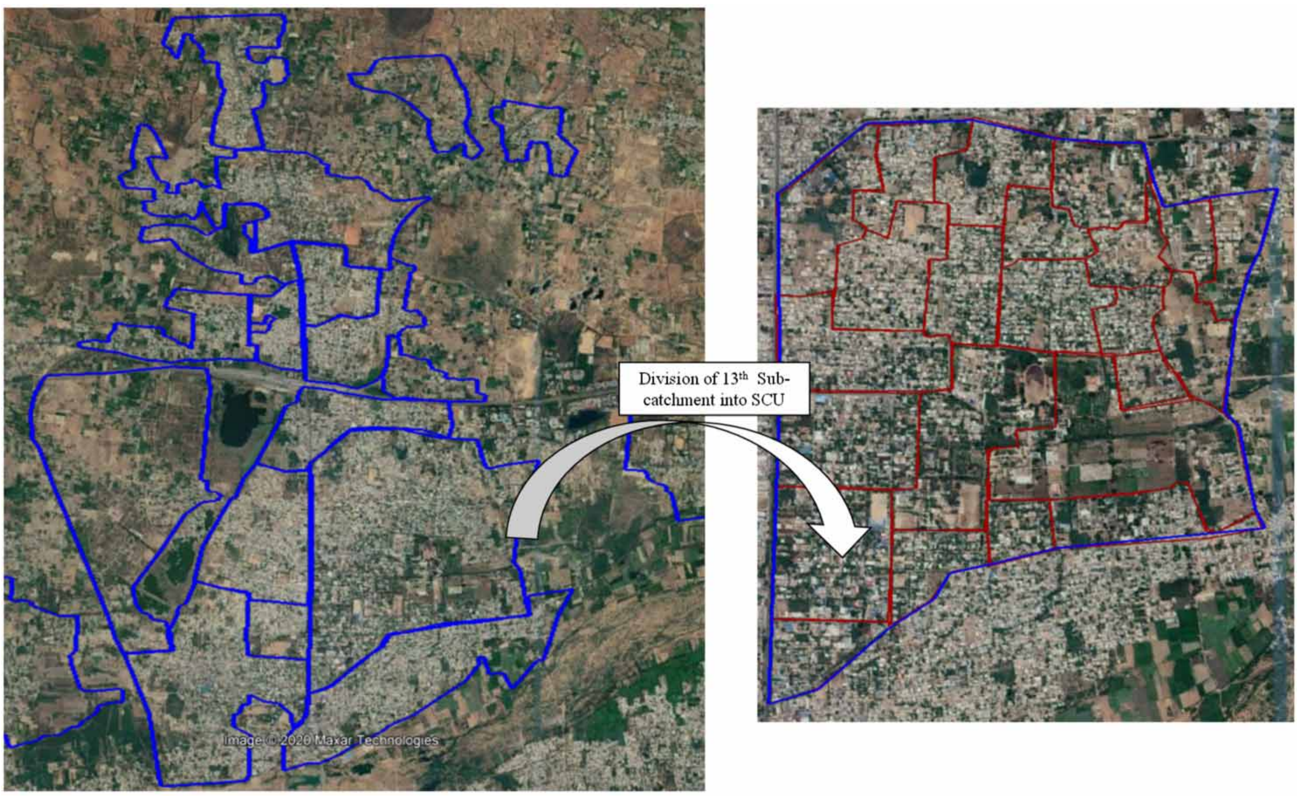

Figure 3 | Demonstration of division of SC/SCUs in the study area along the major roads.

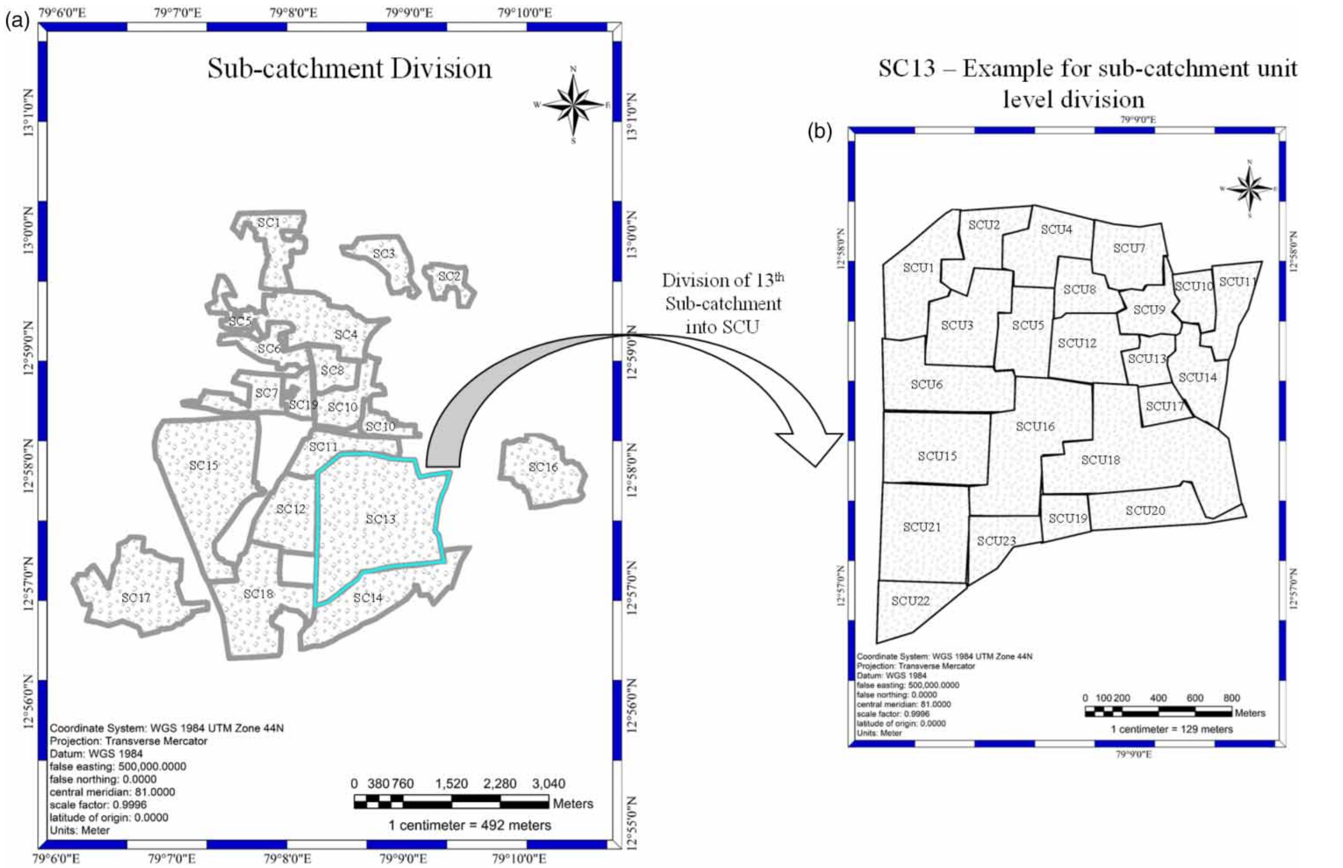

Figure 4 | Division of study area to (a) sub-catchment (Option II) and (b) sub-catchment units (Option I).

catchment level can be envisaged as a cascade of micro-reservoirs.

Constraints for the design of percolation ponds

Construction of a SWH system like percolation ponds requires a lot of space, which can be very difficult to acquire for semi-urbanized catchments such as the study area presented in this research paper, where land acquisition can be both difficult and costly. To reflect this reality in the optimization model, a constraint was defined to limit the usable space within a SC/SCU for the construction of a pond. Since all the ponds were assumed to be trapezoidal with side slopes of 1/2H:1 V, the constraint on space availability for a pond can be expressed as:

$$L_i \times (B_i + D_i) \leq A_i \ \forall i = 1, 2, \ldots, n \qquad (3)$$

where, L_i is the length of the pond (in m), B_i is the bottom width of the pond (in m), D_i is the depth of the pond (in m), A_i is the area available in catchment unit i (in m^2) and n is the number of divisions within the catchment. The maximum area available for the construction of a pond in a sub-catchment is shown in Table 3. Apart from capturing the surface runoff and infiltrating it into the groundwater system, the other important function of the pond is to reduce the peak runoff volume generated within a catchment unit. In the present study, this constraint was defined in such a way that the runoff volume resulting from a catchment unit after implementing the proposed SWH system will be greater than or equal to the difference between pre- and post-urbanized runoff volume (see Supplementary material, Codes SC1 to SC18). This constraint was added since restoring pre-urbanized flows is one of the important objectives of any SCM (Zhou 2014; Mankad et al. 2015; Fry & Maxwell 2017; Zhang & Chui 2018).

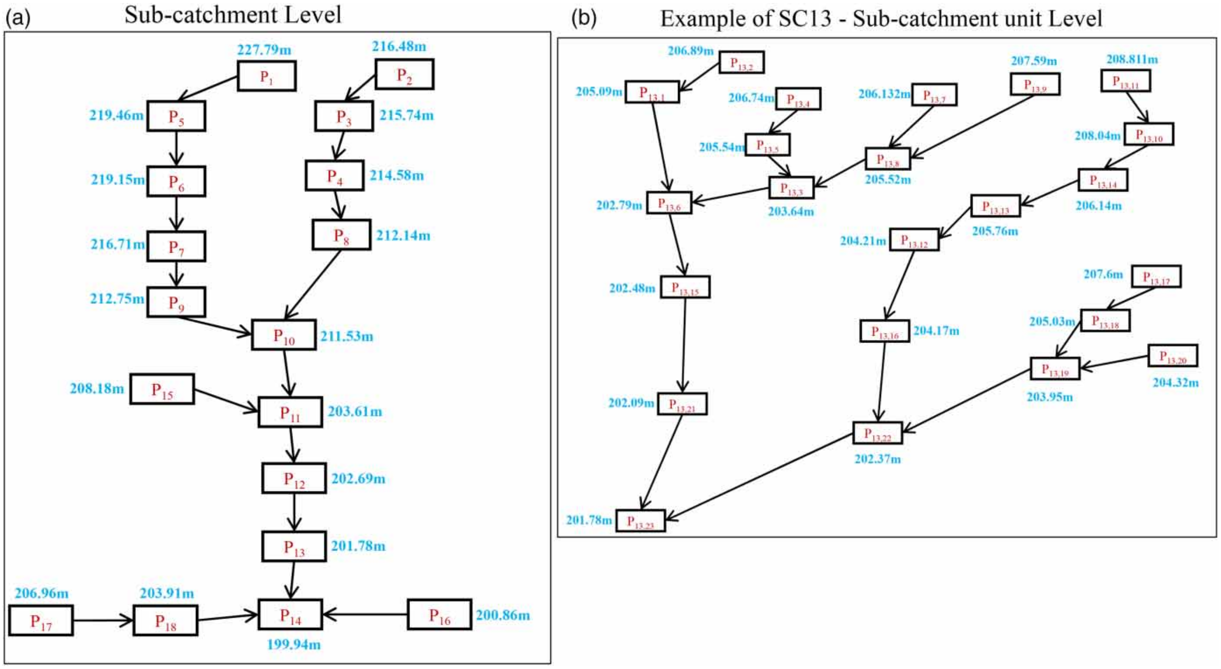

Figure 5 | Demonstration of network connectivity for the percolation pond at (a) sub-catchment and (b) sub-catchment unit level.

For the present study the land use characteristics of the study area as observed in year 2003 were considered as pre-urbanized, and post-urbanized land use characteristics were related to the year 2019. The reason for selecting year 2003 as pre-urbanized year is due to the availability of high-resolution Google Earth VHR images for the study area from year 2003 only. The details of total impervious area in a sub-catchment, its percentage with respect to the total sub-catchment area, for pre- (year 2003) and post- (year 2019) urbanization can be seen in Table 3. Hence, the constraint on absorbing portion of increasing in runoff due to urbanization can be expressed as:

$$L_i \times D_i \times (2B_i + D_i) \geq V_i^{post-urban} - V_i^{pre-urban} \quad \forall i = 1, 2, \ldots n \tag{4}$$

where, $V_i^{pre-urban}$ and $V_i^{post-urban}$ are the peak runoff volume (in m^3) from impervious area under pre-urban and post-urban catchment characteristics, respectively. The third constraint to the optimization model will be the storage-continuity equation for the pond, which can be mathematically expressed as:

$$L_i \times D_i \times (2B_i + D_i) = V_i^{Post-urban} + \sum_{j=1}^{k} V_j^{excess} - V_i^{excess} \; \forall i = 1, 2, \ldots .n \;\; and \; i \neq j \tag{5}$$

$$V_i^{excess} = \begin{cases} 0 \; if \; V_i^{post-urban} + \sum_{j=1}^{k} V_j^{excess} \leq L_i \times D_i \times (2B_i + D_i) \\ L_i \times D_i \times (2B_i + D_i) - \left[V_i^{post-urban} + \sum_{j=1}^{k} V_j^{excess} \right] \end{cases} \tag{6}$$

where V_i^{excess} is the excess volume from pond *i*; V_j^{excess} is the excess volume flow to pond *i* from pond *j* situated at a higher elevation; *k* is the number of ponds at higher elevation connected to pond *i*.

Decision variables

As the total system cost will directly depend on the size of the pond, the decision variables for the optimization model will be: length of percolation pond in catchment

Table 3 | Input data for the constraints of the optimization model

Sub-catchment ID	Sub-catchment area (ha)	Pre-urbanized impervious area (year 2003) (ha)	Post-urbanized impervious area (year 2019) (ha)	Imperviousness (%) (year 2003)	Imperviousness (%) (year 2019)	Design peak runoff (m^3/s)		Area available for construction of percolation ponds (m^2)
						Pre-urbanized (year 2003)	Post-urbanized (year 2019)	
SC1	69.5	2.94	12.93	4.23	18.61	7.65	8.96	531.04
SC2	50.9	4.37	9.62	8.59	18.89	6.38	7.15	104.84
SC3	28.2	4.62	7.61	16.38	26.96	4.07	4.55	51.78
SC4	31.9	4.21	9.04	13.20	28.35	2.07	3.34	257.70
SC5	113.8	8.01	25.57	7.04	22.48	12.5	15.43	615.22
SC6	46.3	2.25	7.18	4.86	15.49	5.25	6.03	149
SC7	101.8	10.97	23.42	10.78	23.01	14.32	18.23	407.24
SC8	29.8	7.18	16.15	24.08	54.2	4.67	6.05	751.4
SC9	55.7	3.03	13.16	5.44	23.64	6.28	7.67	225.09
SC10	27.3	1.25	4.02	4.58	14.72	3.28	3.78	60.97
SC11	98.3	8.30	28.58	8.44	29.07	11.29	14.13	494.53
SC12	66.1	18.51	32.28	28	48.83	9.76	11.53	547.28
SC13	346.5	42.78	136.89	12.35	39.51	20.22	47.3	10,649.14
SC14	97	13.05	42.88	13.45	44.19	12.26	16.36	920.01
SC15	166.5	23.49	76.21	14.11	45.78	18.31	24.92	2,506.89
SC16	148.3	31.87	78.3	21.49	52.79	17.22	22.15	2,436.33
SC17	166.4	2.76	19.51	1.66	11.72	15.78	18.1	398.91
SC18	256.6	1.12	13.28	0.44	5.18	23.37	25.24	179.87

division i, L_i (in m), width of the percolation pond in catchment division i, B_i (m), and depth of the percolation pond in catchment division i, D_i (m). The lower limit for the pond dimensions were selected arbitrarily as 5 m for length and width of the pond and 0.5 m for the depth of the pond. The upper limit for depth of the pond was taken as 4 m, since the maximum depth of a percolation pond, in general, is about 4 m (CPHEEO 2012). The upper limit for length and width of the pond in a catchment division were defined based on the area constraint for that respective catchment unit.

Objective function

The objective function for the optimization model is minimization of the total system cost. The system cost includes land acquisition cost, capital cost of constructing percolation ponds, and maintenance cost of the percolation pond. The design period of the project was taken to be 30 years, which is a typical design period value for a percolation pond (Massuel *et al.* 2014). The project cost was evaluated over the design period by considering an inflation rate of about 8%. The unit capital cost for the percolation pond was worked out through estimation and costing method (Todd *et al.* 1976; Dutt 2006), and pond maintenance cost was taken to be 2.8% of the capital cost of the pond (Marchi *et al.* 2016). Land acquisition cost was taken from the records maintained by local urban development body (Vellore City Municipal Corporation 2018). A summary of the cost details for the objective function can be seen in Table 4. The objective function therefore can be expressed as:

$$Z = \min \sum_{i=1}^{n} [C_{capital-cost} \times \{L_i \times D_i(2B_i + D_i)\} + C_{land-cost} \times \{L_i \times (B_i + D_i)\} + 0.028 \times PWF \times C_{capital-cost} \times \{L_i \times D_i(2B_i + D_i)\}] \quad (7)$$

Table 4 | Cost details used for objective function

Cost (C)	Variable	Cost evaluators
Capital cost of percolation pond (in rupees), $C_{capital\text{-}cost}$	Percolation pond volume, $V_{t_i} = (L_i^* D_i^* (2B_i + D_i)$	$152.9^* V_{t_i}$
Land acquisition cost (in rupees), ($C_{land\text{-}cost}$)		$10{,}324^* V_{t_i}$
Maintenance cost of percolation pond (in rupees)	Capital cost ($C_{capital\text{-}cost}$)	2.84% of ($C_{capital\text{-}cost}$)
Present worth factor (PWF), r	$PWF = \frac{(r+1)^t - 1}{r(r+1)^t}$	10%

where, $C_{capital-cost}$ is the capital cost of constructing a percolation pond (₹/m^3); $C_{land-cost}$ is the land acquisition cost (₹/m^2); and PWF is the present worth factor, which is given by:

$$PWF = \frac{(r+1)^t - 1}{r(r+1)^t} \tag{8}$$

where, r is the inflation rate in percentage and t is design period of analysis in years.

RESULTS AND DISCUSSION

The optimization model discussed in the earlier section was applied to the case study area of Katpadi, a semi-urbanized catchment. The optimal dimensions of the pond in the catchment unit were determined for either of the options for a design rainfall intensity of five-year return period. The design rainfall intensity for each catchment unit was determined using the IDF equation shown in Table 5. The IDF curve was developed using daily rainfall data from the years 1950 to 2019. When applied to a catchment unit, the duration of rainfall in the IDF equation was taken equivalent to the time of concentration of the catchment unit (a valid assumption made in the application of rational method (Chow *et al.* 1987).

Table 5 | Data for water balance attributes and the catchment characteristics

Area of the catchment (in km^2), A	19.01
Total rainfall depth for year 2019 (in mm), P	1,151
Design return period selected (in years), T	5
Total area under urbanization, (in km^2)	5.84
IDF equation	$i = \frac{6.1T^{0.2}}{(t+0.5)^{0.8}}$

The optimization model was solved using the *fmincon* (non-linear constrained optimization algorithm) toolbox in MATLAB. After solving the optimization model in MATLAB, the optimal pond dimensions for Option I and Option II were obtained. The optimal dimensions for the percolation ponds under Option II and a sample result of optimal dimensions of percolation ponds under Option I are shown in Table 6.

Due to a paucity of space, the optimal pond dimensions for remaining sub-catchments under Option I are provided in the Supplementary material (Tables SCU1 to SCU18). From the results, it can be inferred that the size of the pond in a catchment unit is majorly influenced by factors such as size of the catchment unit, location of the pond in the series and space availability within the catchment unit. For instance, SC13 has the largest pond dimensions as it receives runoff from many upstream sub-catchments; also, the space available is sufficiently large. For the catchment units of roughly equivalent size (SC15, SC16 and SC17) and not receiving any runoff from upstream ponds, the size of the pond (Table 6) is influenced by the percentage of imperviousness (45.78%, 52.79% and 11.72% for SC15, SC16 and SC17, respectively) of the catchment unit (Table 3). In Table 7, the percentage area occupied by percolation ponds in a catchment unit with respect to the total impervious area of that catchment unit are shown.

From the results shown in Table 7, it can be inferred that the distribution of percolation ponds in Option II is more commensurate with the space availability constraint and imperviousness of the sub-catchment, whereas in Option I it can be inferred that the size of percolation ponds in a sub-catchment is mostly influenced by the percentage imperviousness in the sub-catchment. This can be observed for sub-catchment SC15 and SC17, which have almost the same area, i.e., 166.5 ha and 166.4 ha, respectively. The percentage of area under percolation ponds is 0.75% for SC15 and 0.39% for SC17, which is almost

Table 6 | Optimal dimension of percolation ponds

Percolation tank ID at sub-catchment unit level	Option I			Percolation tank ID at sub-catchment level	Option II		
	Length	Width	Depth		Length	Width	Depth
$P_{13,1}$	20.50	10.10	2.95	P_1	30.11	15.07	1.15
$P_{13,2}$	23.63	11.63	3.08	P_2	12.09	6.09	1.51
$P_{13,3}$	32.09	15.82	3.23	P_3	7.90	4.01	1.52
$P_{13,4}$	24.61	12.12	3.17	P_4	20.21	10.13	1.51
$P_{13,5}$	16.16	7.90	3.19	P_5	32.48	16.26	1.67
$P_{13,6}$	29.68	14.61	3.37	P_6	14.82	7.45	1.57
$P_{13,7}$	7.64	3.77	2.80	P_7	26.01	13.03	1.50
$P_{13,8}$	12.47	6.12	2.93	P_8	36.20	18.12	1.52
$P_{13,9}$	12.98	6.36	2.98	P_9	18.74	9.40	1.52
$P_{13,10}$	4.90	2.45	2.67	P_{10}	8.73	4.42	1.55
$P_{13,11}$	8.91	4.39	2.70	P_{11}	28.91	14.47	1.52
$P_{13,12}$	21.22	10.45	3.06	P_{12}	30.54	15.29	1.51
$P_{13,13}$	10.59	5.19	2.92	P_{13}	143.31	71.66	2.12
$P_{13,14}$	5.94	2.97	2.53	P_{14}	40.32	20.18	1.52
$P_{13,15}$	25.49	12.53	3.31	P_{15}	68.20	34.11	1.59
$P_{13,16}$	17	8.34	3.06	P_{16}	67.19	33.61	1.60
$P_{13,17}$	6.86	3.39	2.80	P_{17}	24.70	13.69	1.48
$P_{13,18}$	13.86	6.82	2.67	P_{18}	16.51	8.29	1.52
$P_{13,19}$	7.78	3.81	3.07				
$P_{13,20}$	14.18	7.12	3.38				
$P_{13,21}$	22.07	10.84	3.24				
$P_{13,22}$	8.98	4.39	3				
$P_{13,23}$	14.62	7.13	3.35				

proportional to the percentage impervious area of SC15 (45.78%) and SC17 (11.72%), respectively. This is in contrast to Option II in which percentage area under percolation ponds is significantly less for SC15 (0.02%), compared to SC17 (0.19%), implying that the size of pond is inversely related to percentage impervious area. In Option I, SWH is more evenly distributed, with eight sub-catchments having more than 0.3% area under percolation ponds; seven sub-catchments having percentage area under percolation ponds between 0.15% and 0.3%; and three sub-catchments having percentage area under percolation pond as less than 0.15%. In Option II, there are six sub-catchments where the percentage area occupied by percolation ponds is less than 0.15%; in five sub-catchments the percentage area under percolation ponds is between 0.1% and 0.2%; in three sub-catchments percentage area under percolation ponds is between 0.2% and 0.5%; and there are four sub-catchments where percentage area under percolation ponds is more than 0.5%. This implies the area under SWH is more skewed under Option II when compared to under Option I.

In Table 8, an economic comparison is shown between Option I and Option II. The capital cost of the SWH system under Option I was obtained as Rs. 555 Million, whereas under Option II it is Rs. 714 Million. The unit cost of SWH system (calculated as a ratio of volume of water infiltrated to the capital cost of the system) under Option I is better when compared to under Option II. Hence, it can be inferred that economically Option I is preferable to

Table 7 | Percentage area under percolation ponds for each sub-catchment

Sub-catchment ID	Total impervious area in a sub-catchment (ha)	Total area under percolation ponds (m^2)		% Area under percolation ponds	
		Option I	Option II	Option I	Option II
SC1	12.93	235.5	488.50	0.18	0.38
SC2	9.62	184.02	43.64	0.19	0.05
SC3	7.61	318.1	91.94	0.42	0.12
SC4	9.04	251.5	235.34	0.28	0.26
SC5	25.57	1,634.07	582.62	0.64	0.23
SC6	7.18	171.3	133.54	0.24	0.19
SC7	23.42	318.98	378.07	0.14	0.16
SC8	42.91	2,362.75	204.54	0.55	0.05
SC9	13.16	131.38	52.09	0.10	0.04
SC10	4.02	79.69	710.89	0.20	1.77
SC11	28.58	796.71	462.45	0.28	0.16
SC12	32.28	560.17	10,573.13	0.17	3.28
SC13	136.89	4,598.13	874.92	0.34	0.06
SC14	42.88	3,378.79	2,434.50	0.79	0.57
SC15	76.21	5,705.89	161.90	0.75	0.02
SC16	78.3	3,140.7	513.12	0.40	0.07
SC17	19.51	769.21	374.58	0.39	0.19
SC18	13.28	116.29	2,365.59	0.09	1.78
Total area under percolation ponds for the entire catchment	583.386	24,753.28	20,681.39	6.140	9.364

Table 8 | Economic evaluation of stormwater harvesting options

System performance measure	Stormwater harvesting option	
	Option I	Option II
Capital cost of the system (₹ million)	555	714
Annual infiltration (Mm^3)	1.22	0.74
Per-capita water demand that can be met (lpcd)	86	52
Unit cost of SWH system (₹/litre)	0.46	0.96

Option II. Table 8 also shows the per-capita water demand that can be delivered to the population of the study area (which is about 38,908 as in year 2019) under Option I and Option II, which is 86 lpcd and 52 lpcd, respectively. This indicates a better per-capita water demand can be achieved with Option I when compared to Option II.

Hydrologic performance of percolation ponds

Apart from economic criteria the proposed SWH options were also compared for their performance in utilizing potential rainfall for SWH, replicating pre-urbanized runoff hydrograph and runoff capture efficiency. The efficiency measures for runoff capture and potential rainfall utilization were determined based on the efficiency measures proposed by Sorup *et al.* (2016). The efficiency related to volumetric rainfall (E_r) expresses how well a SWH system is able to exploit rainwater as a resource and is defined as:

$$E_r = \frac{V_{managed}}{V_{total\ annual\ rainfall}} \quad (9)$$

where, $V_{managed}$ is the runoff volume managed by SWH entering from the impervious regions of the catchment and

$V_{total\ annual\ rainfall}$ is the total annual rainfall received by the catchment.

E_{rmax} is the spatially independent efficiency measure expressing the ratio between managed volume ($V_{managed}$) and the volume of runoff received by the proposed SCM ($V_{theoretical\ maximum}$):

$$E_{rmax} = \frac{V_{managed}}{V_{theoretical\ maximum}} \tag{10}$$

In Equation (10), $V_{managed}$ is the volume of runoff retained by the SWH system and $V_{theoretical\ maximum}$ is the runoff volume from the contributing catchment unit.

Finally, the efficiency of the stormwater harvesting system to infiltrate the runoff from the contributing impervious area (E_i) can be expressed as the ratio of total annual infiltration ($V_{infiltrated}$) to $V_{total\ annual\ rainfall}$. This is an efficiency measure defined by us to determine the infiltration potential of the proposed SWH system. This measure is expressed as:

$$E_i = \frac{V_{infiltrated}}{V_{total\ annual\ rainfall}} \tag{11}$$

Table 9 provides a summary of the efficiency measures under Option I and Option II. As can be observed from their definitions, E_{rmax} is defined for a single rainfall event, whereas E_r and E_i are defined for total annual rainfall. To understand the performance of the proposed SWH system in managing peak runoff of different magnitudes, E_{rmax} was determined for three different return periods, defined as day-to-day domain (0.2-year return period), design domain (5-year return period) and extreme event domain (66-year return period) (Sorup *et al.* 2016). E_r and E_i were determined for the daily annual rainfall data for the latest year 2019. The efficiency results are tabulated in Table 9. From the results it can be observed that the runoff capture efficiency is significantly higher for Option II for all the rainfall domain events, when compared to Option I. Between the different rainfall domains, E_{rmax} is higher for both SWH options for day-to-day domain and reduces significantly for extreme event domain. It is, however, interesting to note that the difference in E_{rmax} value between Option I and Option II for the day-to-day rainfall event is significantly large which implies that Option II is significantly better at capturing runoff resulting from low rainfall events when compared to Option I. Even for extreme events, Option II performs better when compared to Option I. When it comes to E_r, which indicates the ability of a SWH system to exploit rainwater as a resource, there is little significant difference between Option I and Option II. This implies that for daily rainfall events, division of catchment into sub-catchments or sub-catchment units has little bearing on reducing runoff volume. The last column in Table 9, E_i, indicates the capability of the proposed SWH system in infiltrating the stored water. This is again higher under Option I (5.56%) when compared to under Option II (3.37%).

To understand the functioning of the percolation ponds in controlling peak runoff volume and infiltrating the captured runoff within the pond, the designed optimal SWH system was simulated for a daily rainfall data series (23 days) of year 2015 (the highest rainfall year within the past 25 years). The rationale for selecting this set of data was that it was the duration in which a total depth of about 504.7 mm of rainfall occurred, which was about 38% of the total annual rainfall (1,374 mm) in that year.

Table 9 | Efficiency measures for the proposed SWH system under option I and option II

Stormwater harvesting system	Return period (years)	$V_{theoretical\ maximum}$ (m^3)	$V_{managed}$ (m^3)	E_{rmax} (%)	$V_{total\ annual rainfall}$ (year 2019) Mm^3	$V_{managed}$ (Mm^3)	E_r (%)	$V_{infiltrated}$ (Mm^3)	E_i (%)
Option I	0.2	2,813.7	1,359.4	51.7	21.98	1.81	8.21	1.22	5.56
	5	6,471.4	4,619.9	28.6					
	66	11,693.2	9,763.4	16.5					
Option II	0.2	10,020.8	912.5	90.9		1.73	7.87	0.74	3.37
	5	23,364.7	4,935.1	78.9					
	66	46,054.5	23,670.1	48.6					

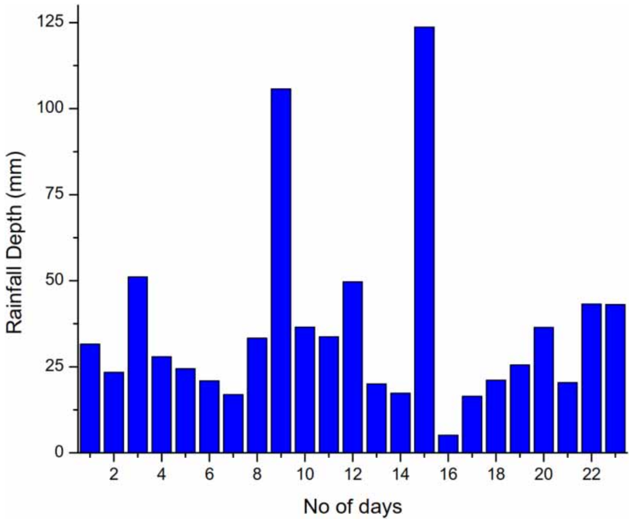

Figure 6 | Rainfall hyetographs for a series of maximum rainfall days in the year 2015.

The rainfall hyetograph for the data used for simulating the SWH system is shown in Figure 6. For the sake of brevity, the hydrographs are shown only for a few sub-catchments, i.e., most impervious (Figure 7(b)), least impervious (Figure 7(a)), smallest (Figure 7(c)) and largest (Figure 7(d)), along with the hydrograph for the entire catchment. The result indicates that implementation of Option I, when compared to Option II, has a significant effect on peak reduction in the largest sub-catchment, whereas for least urbanized sub-catchment there is little significant effect on runoff volume reduction in either of the options. For the largest sub-catchment, the runoff hydrograph resulting from Option I is closer to the pre-urbanized hydrograph, compared to the runoff hydrograph from Option II. When the entire study area is considered, the resulting runoff hydrograph (Figure 8) is very similar in both the SWH options, and in both cases, the resulting runoff hydrograph is lower than the post-urbanized hydrograph.

Finally, Figure 9 shows the potential depth of monthly infiltration that can be achieved after implementing the proposed SWH system. The values are for the monthly rainfall data of the year 2019.

SUMMARY AND CONCLUSION

In this paper, a decentralized SWH system using a series of percolation ponds for a semi-urbanized catchment has been proposed. The methodology of the proposed SWH design starts with the division of a larger catchment into smaller sub-catchments and sub-catchment units, determination of suitable location for situating percolation ponds using DEM and Google Earth archive and, finally, determining the optimal dimensions for the percolation ponds against minimization of the total system cost. The proposed methodology was applied to a case study area in Vellore, Tamil Nadu. The efficiency of the proposed SWH system in reducing peak runoff volume was estimated for rainfall intensity pertaining to day-to-day domain, design domain, and extreme domain values. The results indicated that the performance of percolation ponds in reducing the peak runoff is better for Option II when compared to Option I, under all three domains. The inference from this result can be that further division of a sub-catchment into SCUs can have a negative impact on peak runoff volume reducing capacity of the ponds. However, with respect to capital cost for implementation, unit cost of SWH, potential volume of water infiltrated, percentage area under stormwater harvesting system for the entire catchment and the ability of the proposed SWH system in exploiting rainwater as a resource, Option I fare better compared to Option II in all the aforementioned metrics. When the proposed SWH system was evaluated for the highest rainfall month that had occurred within the last 25 years, the resulting runoff hydrographs (Figure 7(a)–7(d)) for the least urbanized, most urbanized, largest and smallest sub-catchments indicated that there was a considerable reduction in peak runoff in both Option I and Option II.

Although, in the present study, the viability of using a series of interconnected percolation ponds for SWH has been discussed, there are however certain limitations in the proposed methodology. The primary limitation is with respect to the use of percolation ponds, which should be adopted only when the groundwater table is well below (preferably 8 m bgl) the ground level and also the underlying soil should be moderately permeable to facilitate faster infiltration of water from the ponds. Also, the methodology discussed will be more suitable for towns/cities where sufficient space is available for the construction of ponds. Existence of a well-laid out storm sewer network for an area can minimize the cost and effort in diverting water

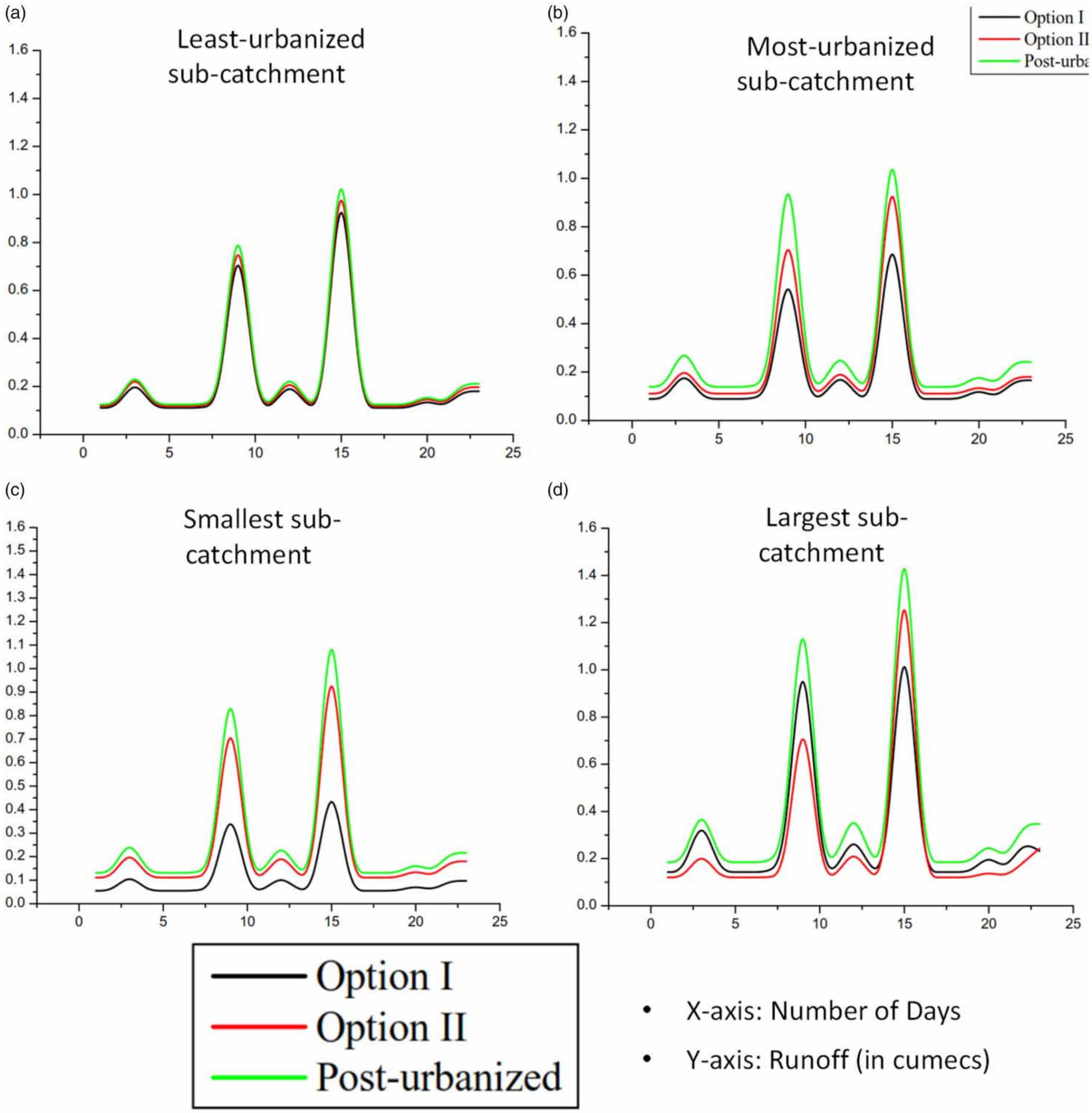

Figure 7 | Impact of SWH measures on peak runoff in four different types of sub-catchment: (a) least urbanized; (b) most urbanized; (c) smallest; and (d) largest sub-catchment.

from impervious areas to the ponds. The optimization model was solved using a deterministic approach, whereas, in a more realistic setting, there can be many uncertainties involved, for example, uncertainty in rainfall, uncertainty in estimating infiltration rate from the ponds and uncertainty in land use changes. However, the methodology presented in this research paper can be considered as a step towards designing a more complicated SWH system using percolation ponds which can include the aforementioned uncertainties.

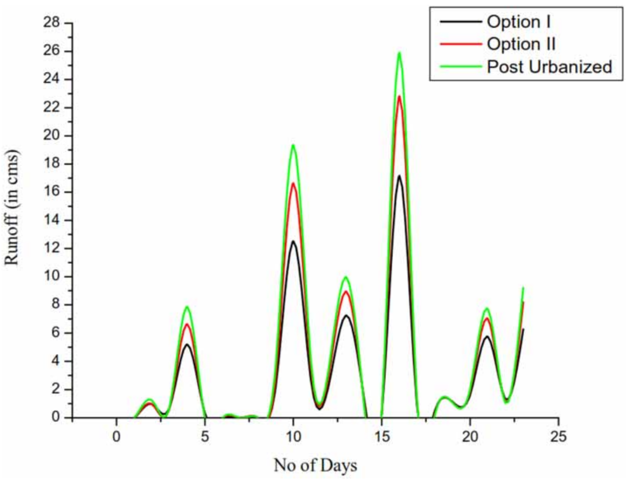

Figure 8 | Runoff hydrograph for the entire study area catchment for a series of maximum rainfall days in the year 2015.

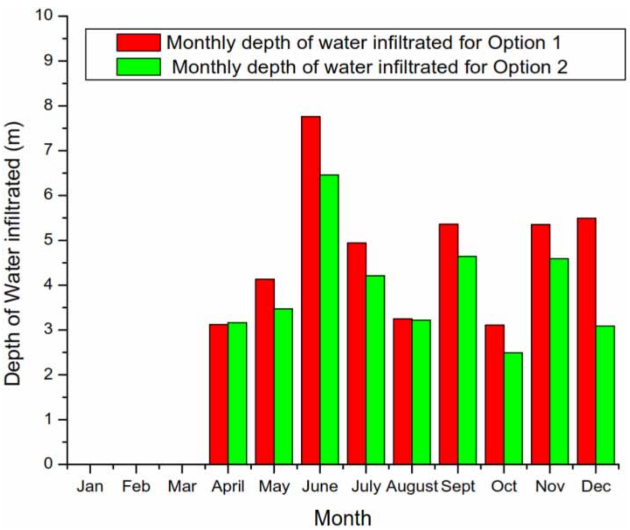

Figure 9 | Potential depth of water infiltrated under Option I and Option II.

To conclude, we feel there are many cities/towns across India, where the proposed SWH system can be implemented beneficially, notwithstanding the limitations mentioned above. There is, however, a lot of scope for further improving the proposed method of SWH using percolation ponds. For example, in the optimization framework, the possibility of supplying the harvested water for satisfying a proportion of daily water demand was not considered. When included in the optimization model, this can affect the sizing of the ponds. Another interesting area for research would be to examine the uncertainties involved in the percolation process through the ponds, and its effect on their recharge potential. It will also be interesting to evaluate the performance of the proposed SWH system under climate change scenario and potential change in urbanization of the area in future.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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