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Stormwater reuse for water-sensitive city – Integrated analysis of urban hydrology for efficient alternatives of Amaravati city, India

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ABSTRACT

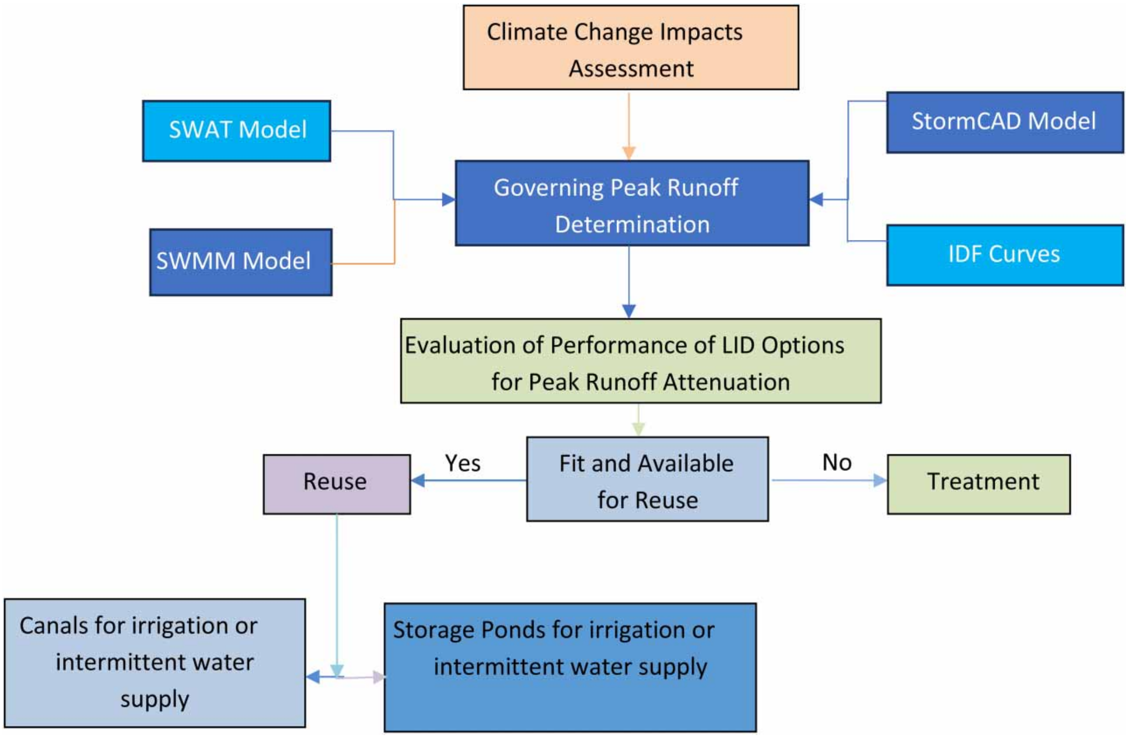
In the present study, Amaravati, a proposed city of Andhra Pradesh, India, is identified for stormwater reuse analysis and for various efficient options for reuse. Peak runoff from the entire catchment is determined for the management of stormwater using different models such as soil and water assessment tool (SWAT), stormwater management model, and intensity–duration–frequency curves by the log Pearson Type III method. Further, the bio-retention cell low-impact development option with 60% impervious area, 60% zero depression impervious area, bio-retention cell for 40% area for each sub-catchment, and the underground stormwater network system, for part of peak runoff reduction, remaining peak runoff is considered for reuse. The remaining peak runoff is proposed to be reused for irrigation purposes (option 1), and storage retention ponds as extended detention ponds (option 2). Also, *in situ* storage/percolation is recommended for unaccounted stormwater within or around each premise. The findings can help to propose, implement, and maintain various stormwater reuse measures and/or practices for any city.

Key words: reuse, runoff, stormwater, water-sensitive city

HIGHLIGHTS

- The methodology adopted is novel in regard to considering urban hydrologic study as an integrated study for various stormwater reuse efficient options.
- The present study is an integrated study considering climate change, water quality, and so on, and further study on various efficient options for stormwater reuse considering low-impact development and irrigation canal options is novel of its kind.

GRAPHICAL ABSTRACT



NOMENCLATURE

SWAT	soil and water assessment tool
SWMM	stormwater management model
IDF	intensity–duration–frequency
LID	low-impact development
WSUD	water-sensitive urban design
LIUDD	low-impact urban design and development
E. coli	*Escherichia coli*
RTC	real-time control
AP CRDA	Andhra Pradesh Capital Region Development Authority
AMRDA	Amaravati Metro Region Development Authority
R	R Programming
USGS	United States Geological Survey
FAO	Food and Agriculture Organization
CCCR	Centre for Climate Change Research
IITM	Indian Institute of Tropical Meteorology
CPHEEO	Central Public Health and Environmental Organisation
Q	discharge
GHG	green house gas
SS	suspended solids
A.P.	Andhra Pradesh
CGWB	Central Ground Water Board

1. INTRODUCTION

The requirement for stormwater reuse has been progressing which is vital as the increase of population becomes significant which is enhancing water stress. Reuse of stormwater can also decrease the degradation of water in urban areas since the reduction of volume of stormwater for urban areas discharge follows. However, as of now a significant barrier to the widespread execution of the reuse of stormwater is the lack of techniques and methods that can afford water for different requisites such as gardening, irrigation, and commercial and industrialized actions.

Stormwater reuse entails an integrated technique to the stormwater management of urban systems which develops on their current multi-function activity as a component of the recent urban communities. Although most stormwater systems of urban environments were initially designed to take out stormwater as one of the flood protection techniques, it has now been recognized that these approaches are an essential component in the health of the ecosystem of receiving waters. They also take a vital environmental and social position as natural corridors within the broader environment built. The confrontation for stormwater managers of urban areas is to make an equilibrium between water quality, flood protection, the health of the ecosystem, and values of aesthetics.

There have been various research studies outlining different reuse of stormwater systems for sustainable and resilient stormwater management of urban areas including water-sensitive urban design (WSUD) (Wada *et al.* 2002; Muirhead 2008; Gatt & Farrugia 2012; Lloyd *et al.* 2012; Kinkade 2013; Huang & Zhou 2014; Wu *et al.* 2014; Jonasson *et al.* 2016; Ahammed 2017; Jahanbakhsh 2017; Palazzo 2018; Charalambous *et al.* 2019; Deitch & Feirer 2019; Day & Sharma 2020; Olivieri *et al.* 2020; Shafiquzzaman *et al.* 2020).

Various frameworks and approaches were recommended by Mishra & Arya (2020), Coutts *et al.* (2010), Mishra *et al.* (2020), Saraswat *et al.* (2016), Ellis *et al.* (2008), and Webber *et al.* (2018) for management of stormwater in urban environments taking into account a range of scenarios with climate change effect. Permeable pavements and porous utilization for the reuse of stormwater through the experimental procedure were described by Beecham *et al.* (2010) and further application of PERMPAVE software. Permeable and porous pavements are WSUD methods that permit infiltration onsite or retention of stormwater runoff (Beecham *et al.* 2010).

Zhang *et al.* (2020b) have developed a stormwater management model (SWMM)-based method for the control of runoff volume and suspended solids (SS) elimination. A sponge system comprising bio-retention cells, grassed pitches, permeable pavements, and gardens of stormwater may reduce risks of flooding with a 5-year interval of recurrence, while preserving water quality with a 56% reduction in SS (Zhang *et al.* 2020b)

Various evaluation methods for finding the efficiency of various risk assessments with the reuse of stormwater for various purposes were appraised (Ahmed *et al.* 2019). An examination of the overall performance of WSUD for high-intensity rainfall scenarios was done (Lariyah *et al.* 2011). The treated water may be utilized for water supply with treatment of an extensive/advanced nature (Lariyah *et al.* 2011). This kind of water is suitable for potable purposes and irrigation requirements (Lariyah *et al.* 2011). Treated wastewater reuse from wetlands for irrigation purposes meeting quality standards has been suggested (Tuttolomondo *et al.* 2020). Coombes *et al.* (2015) evaluated the rational method for stormwater sophisticated design techniques. Zimmer *et al.* (2007) found that low-impact development (LID) techniques are efficient for attenuation of the undesirable effects of hydrology because of any kind of urbanization. LID components can completely regulate flow peaks in summer with a probability of exceedance of 0.2 or higher in a year (Zimmer *et al.* 2007). Control of flow peaks from less probability of bigger events may need stormwater ponds to be additional to the LID system (Zimmer *et al.* 2007). More forest cover and more bio-retention infiltration are the most impactful in regard to reduction in peak flow and volume of total flow (Zimmer *et al.* 2007). The application of integrated spatial decision support systems for the decrease of runoff was studied by Rufino *et al.* (2018). Goonetilleke *et al.* (2017), Gogate & Raval (2015), Maneewan & Roon (2017), and Muirhead (2008) recognized significant impediments to the reuse of stormwater, the complexities in eliminating them in urban environments, and the approaches to overcome the barriers even applicable for India. N-nitrosomorpholine treatment for the reuse of potable water was demonstrated by Glover *et al.* (2019). A novel approach to the improvement of stormwater quality mechanism called the 'Green Gully' that accumulates, treats, and reuses stormwater all through an automated system was studied and presented by Begum & Rasul (2009). A tertiary treatment approach needs to be provided with Green Gully capacity for treatment and reuse of stormwater for the entire period of an automated system for irrigation requirements (Begum & Rasul 2009). Zabłocka & Capodaglio (2020) have analysed various alternatives such as the retention tank, decrease in stormwater overflows and providing allowance for local water reuse for sustainable stormwater management. The need for the management of stormwater with multi-criterion policies and approaches as resolutions for erosion, flooding, and water quality was highlighted by McCuen & Moglen (1988). Siekmann & Siekmann (2015) established that added flexibility and higher adaptation capability of decentralized facilities meant for WSUD with climate change effects. Green stormwater infrastructure optimization projects for stormwater reuse following treatment with management systems, for instance, dry well chambers, catch basins, wetlands, permeable surfaces, cisterns, bioswales, and rain gardens were performed by Sadeghi *et al.* (2018). Madison & Emond (2008) recognized the novel numerous opportunities for reuse and stormwater treatment. Trajkovic *et al.* (2020) found that infiltration trenches, vegetative swales, bio-retention cells, and rain barrels had paramount efficiency in the management of atmospheric stormwater. The efficacy of best management practices intended for stormwater reuse was reviewed by Ding (2017). Shen *et al.* (2019) developed strategies for real-time control (RTC) with the validation of biofilters in favour of efficient water quality for harvesting and reuse through long-term experimentation. It was shown that sediment and nutrient exclusion were lofty with RTC. Multicriteria optimization was applied by McArdle *et al.* (2010) to spot Pareto optimal solutions for collecting, storing, and stormwater treating to potable water requirements to allow use for the potable water distribution. Zhan *et al.* (2020) investigated the cost-effectiveness of the treatment method design for the reuse of stormwater and recommended that the reduction of heavy metals (especially copper), organic matter, and bacteria growth control should be the important purification aspects meant for toxicity attenuation. Management of risk, financial assessment, and criteria of funding for the reuse of stormwater was proposed by Furlong *et al.* (2017) for similarity and prioritization of upcoming reuse projects. The reuse of bulk sediment past the treatment was examined by Pétavy *et al.* (2007). Permeable pavement base course aggregates' effect on the quality of stormwater meant for reuse of irrigation was studied by Kazemi & Hill (2015). Jung *et al.* (2019) and Hatt *et al.* (2007) found the biofilters' potential application to the treatment of greywater and reuse. Savings of potable water up to 36% of the annual average of household potable water requirement due to stormwater reuse was determined by Jenkins *et al.* (2012). Rodak *et al.* (2020) described the effect of stormwater control devices at the catchment scale on urban stormwater. The application of membranes for more quality reclaimed water with advanced technology to assist the reuse of safe water has been studied (Kog 2020; Zhang *et al.* 2020a).

Table 1 gives a review of various research studies of integrated urban stormwater management covering aspects such as water quality and LID.

The stormwater runoff treatment using a sand–gravel filter brought in the comprehensive elimination of suspended impurities and limited hardness removal in Delhi, India (Pipil *et al.* 2022). Further application of a built wetland was performed to eliminate the impurities of organic in nature in Delhi, India (Pipil *et al.* 2022). Holistic urban local water requirements may be fulfilled if the stormwater in urban areas is used by harvesting and storing in water bodies at the surface (Pravin *et al.* 2021). The urbanization impacts on the trends of precipitation and the storage volume in reservoirs need to be studied, along with the impacts of rising temperature at a global scale on precipitation patterns (de Lima *et al.* 2018).

Gogate & Raval (2015) studied and analysed the implementation of urban stormwater management in India considering Pune as a case study. Unrestrained extension in urban areas with climate change impacts and the non-availability of integrated mechanisms are significant constraints for efficient urban stormwater management including reuse which may be applicable to India as well (Gogate & Raval 2015).

Thus, from the aforementioned literature, there are no studies carried especially in India for integrated urban stormwater management including reuse (Gogate & Raval 2015; de Lima *et al.* 2018; Pravin *et al.* 2021). Also, the sensitivity and optimization of hydrologic variables such as precipitation, infiltration, and evaporation and consideration of urbanization in terms of imperviousness changes, and climate change impacts have also not been carried out in much detail.

As Amaravati city is an urbanizing area, the plausibility of various stormwater management options needs to be studied for peak runoff attenuation. Also, the management of stormwater with reuse alternatives is vital as the availability of water becomes scarce, attributed to poor management rather than availability in urban environments. Thus, Amaravati city is considered in the present study.

The objective of the research depicted in this article was to study and analyse various options for stormwater reuse for the intended Amaravati city, Andhra Pradesh, India.

1.1. Study area

Amaravati city of the bifurcated new state of Andhra Pradesh has been chosen as a study area in the present study. Amaravati city is situated on the banks of the Krishna River in the Guntur district. The area of the proposed Amaravati city is 217.50 km^2 and is positioned at 16.51° N latitude and 80.52° E longitude. This city area is intended to constitute lands of agriculture and 29 prevailing villages of different mandals of the Guntur district.

Map of the study area, i.e., detailed master plan of Amaravati city, is being taken for this research study as made available from Andhra Pradesh Capital Region Development Authority (AP CRDA)/AMRDA web portal. This study area map is given for set reference in Figure 1.

Table 1 | Research review of integrated stormwater management

Reference	Year	Main feature	Other features	Application	Findings
Wang & Roon	(2020)	Stormwater resilience			Sustainable stormwater management
Rodina	(2019)	Stormwater resilience			Sustainable stormwater management
Valentukevičienė & Najafabadi	(2020)			Different sorbents with diverse concentrations	Stormwater quality management
Ekka *et al.*	(2020)	Swales	Grass swales having check dams or infiltration swales		Attenuation of runoff, sediment, and removal of heavy metal
Ahmed *et al.*	(2019)			Best management practices (BMP) and WSUD	Reduction of pathogens and faecal indicators
Valenca *et al.*	(2021)	Reduction of the *Escherichia coli*		Potential of biochar	Urban stormwater quality management
Marino *et al.*	(2018)	Framework of water-sensitive design		Participatory approach	Blue–green infrastructure
Maharaj & Scholz	(2010)	Various water quality parameters such as biochemical oxygen demand and total coliform			Performance of various water quality parameters such as biochemical oxygen demand and total coliform before and after treatment
Montazerolhodjah	(2019)	LID and LIUDD		Design of various tools and processes	Review of LID and LIUDD
Ishimatsu *et al.*	(2017)	Functioning of rain gardens			Sustainable management of stormwater
Pitt & Clark	(2008)	Various stormwater controls		High pollutant concentrations or high flows	Integrated and sustainable stormwater management
Webber *et al.*	(2019)	Decision support		A framework	Management of surface water
Trajkovic *et al.*	(2020)	Performance of various techniques of LID		Reduction of all contaminants from atmospheric stormwater	Analysis of various LID techniques
Torres *et al.*	(2016)	Environmental principles	Energetic principles	E^2STORMED, a decision support tool	Stormwater management
Chouli	(2006)	Source control techniques			Stormwater management

1.2. Novel aspects and objectives of the present study

There have been no stormwater reuse studies for the proposed urban areas using highly efficient LID concepts and irrigation purposes as a combination at a catchment scale to date, available especially for India, in the literature (Gogate & Raval 2015; de Lima *et al.* 2018; Pravin *et al.* 2021). Also, the integration and further application of watershed scale reuse studies to the entire water-sensitive city are not carried out in much detail. Integration of various model studies such as SWMM, SWAT, and climate change impact assessment studies using R programming, StormCAD, and intensity–duration–frequency (IDF) curves for a very short-duration and high-intensity storm resulting in peak runoff determination at catchment scale for the proposed water-sensitive city for stormwater reuse has not been performed in much detail to date from the available literature. The provision of accommodation devices for peak runoff attenuation of a water-sensitive city to various locations of a water-sensitive

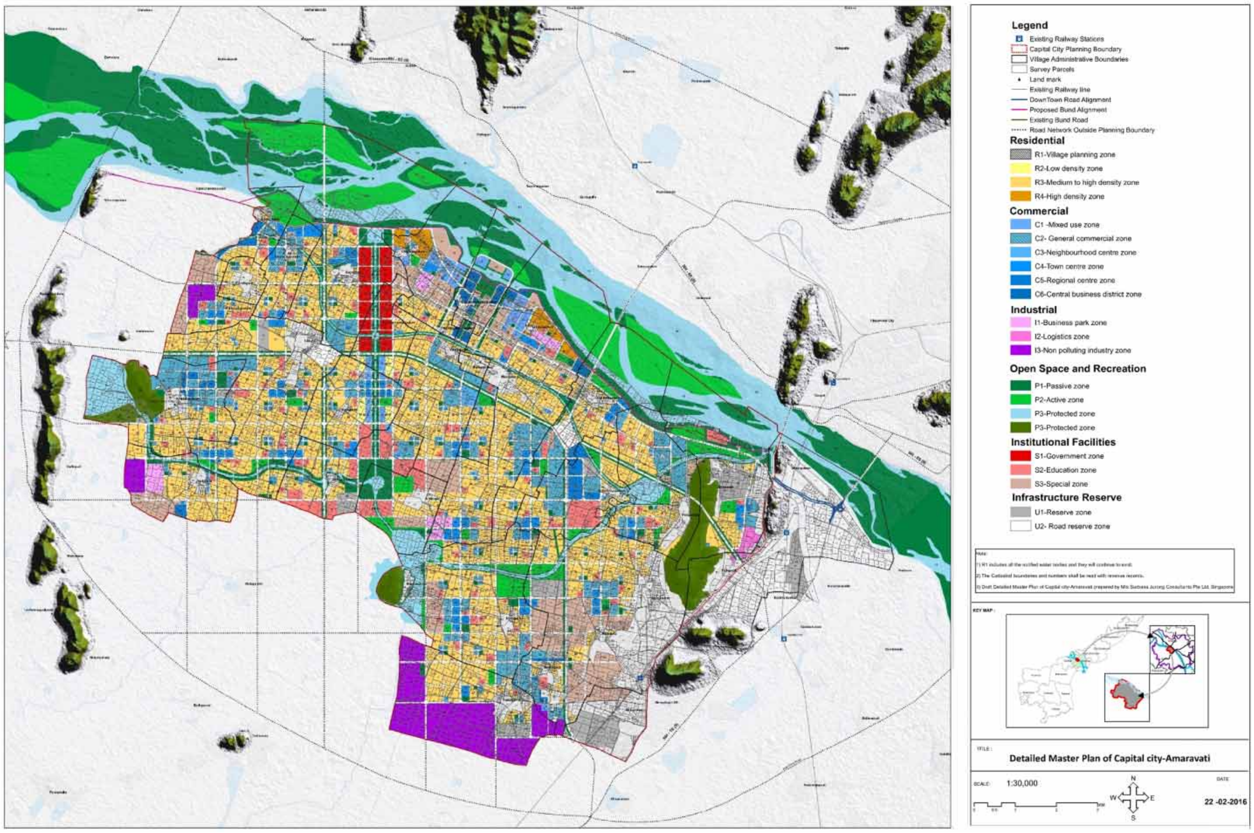


Figure 1 | Detailed master plan of Amaravati city (*Source*: AP CRDA/AMRDA).

city by finding highly efficient LID mechanisms for irrigation and various other purposes by applying optimization and sensitivity analysis has not been studied to date. To develop on current knowledge and to fill up gaps as illustrated, the present study set the objectives to study and analyse various stormwater reuse options for proposed water-sensitive cities by determining highly efficient LID mechanisms for irrigation and other purposes as an integrated model study from various models/studies such as SWAT, SWMM, climate change impact assessment using R programming, StormCAD, and IDF curves.

- The methodology adopted is certainly and thoroughly novel and carries the study of urban hydrology to the next level in regard to considering urban hydrologic study as an integrated study for various stormwater reuse efficient options.
- The present study is an integrated study considering climate change, water quality, and so on, and further study on various efficient options for stormwater reuse considering LID and irrigation canal options is novel of its kind.
- The methodology adopted in the present study may be useful for the integrated analysis of urban hydrology for efficient reuse options in any part of the world.

2. METHODOLOGY

Several trials/iterations are performed for the given data to apply optimization and sensitivity analysis for the SWMM model. The optimal results in terms of runoff attenuation are obtained after executing several trials by varying impervious and pervious area proportions. The optimal results of various LID control options obtained are compared regarding the no LID option for total peak runoff from the entire catchment. Also, the optimal results are verified by varying the same and differing areas for impervious and zero depression impervious areas. The sensitivity of considering the same and different areas for impervious and zero depression impervious areas has been analysed in terms of peak runoff from each sub-catchment. Also, the sensitivity of considering evaporation from temperatures and monthly averages has been analysed, and the results have shown that variation in evaporation and peak runoff from each sub-catchment is nominal. Further, the sensitivity of %

ground slope, Manning's N for pervious and impervious areas, depression depth in the impervious area, and depth of zero depression in the impervious area on peak runoff magnitude variation of each sub-catchment has been analysed, and it has been found that variation of peak runoff is negligible though these parameters are influencing total runoff from pervious and impervious areas. Peak runoff has been determined by performing various model studies such as SWAT, SWMM, and IDF curves of very short-duration and high-intensity rainfall from the entire basin of the proposed city. The maximum out of various peak runoffs from different model studies is found. Also, climate change impact assessment using R programming is studied and taken into account. Sustainable and/or resilient mechanisms for peak runoff attenuation are worked out. Optimization and sensitivity analysis are performed to obtain efficient LID mechanisms for peak runoff attenuation in the SWMM model study. Various highly efficient LID approaches for peak runoff reductions are found in the SWMM model study. Considering, the best LID mechanisms concerning peak runoff decrease and developing stormwater network systems using the StormCAD model for attenuation and/or accommodation of part of peak runoff, various options are analysed for remaining peak runoff reuse such as irrigation and other purposes to develop the proposed city as sustainable and resilient about the management of stormwater.

The assumptions and further simplifications are carried out with the intent to simulate similar and further equalization of hydrologic conditions in all the model studies performed such as SWAT, SWMM, and StormCAD.

Figure 2 shows various steps that need to be adapted for efficient urban stormwater management including reuse.

2.1. Data considered

Following are various sources of data and values considered for various parameters/variables associated with different model studies in the entire study (Table 2).

For the Climate Change Study, precipitation data are considered and extracted from high-resolution climate change simulation over the south Asia region performed by Centre for Climate Change Research (CCCR) of Indian Institute of Tropical Meteorology (IITM), Pune, relevant to the Amaravati study area. Precipitation data are made available as monthly averages of the historical periods (1951–2005) and future projected (2006–2095) period.

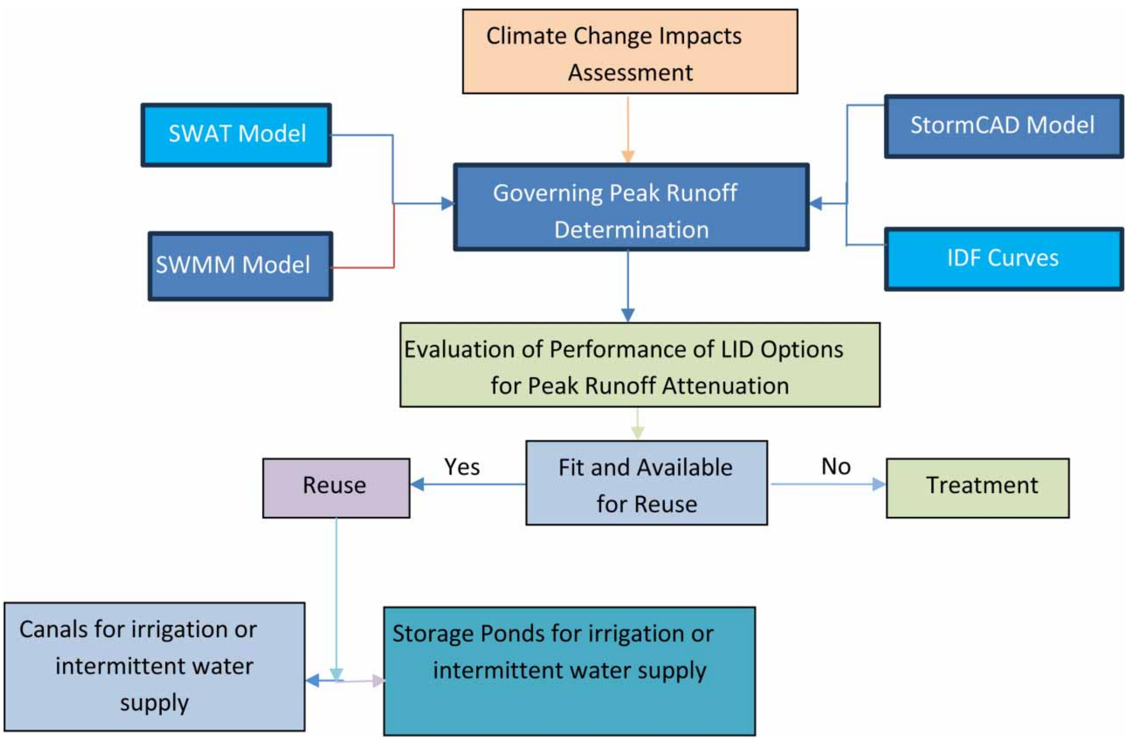


Figure 2 | Process diagram of stormwater reuse.

Table 2 | Sources of SWAT inputs

Data	Source
Digital Elevation Model, DEM	Landsat USGS Earth Explorer
Land Use/Land Cover, LULC	AP Space Applications Centre
Soil data	FAO and indianremotesensing.com
Weather data	globalweather.tamu.edu
India Average Data	swat.tamu.edu/data/india-dataset/

For the SWMM model study, the percentage of the ground slope is assumed as 0.1, i.e., 1 in 1,000, which means for every 1,000 m distance on the ground, it is assumed that there is a ground drop of 1 m. Impervious Manning's N is considered as 0.013 (for concrete with float finish surface), and pervious area Manning's N is considered as 0.03 (for earth winding and sluggish and with grass, some weeds). No depression storage is considered for both impervious and pervious areas. The infiltration process is considered as per the curve number method.

3. ANALYSIS AND RESULTS

Analysis and results for stormwater reuse are presented with various efficient options as an integrated model study from different models and/or studies of the proposed city as described below.

From the StormCAD Model Study, the allowed discharge through the developed stormwater network system is 20.51 m^3/s.

From the climate change impact assessment study using R programming, it has been found that the climate change effect on precipitation is 0.5268% per decade on precipitation. This effect is taken into account while designing various stormwater management options including reuse to affirm sustainable and resilient management of stormwater and to develop the anticipated city as a water-sensitive city.

3.1. Stormwater management through the canal system

If green house gas (GHG) emission impacts from non-treated wastewater diluted in surface streams are related to the life cycle evaluation of the treatment of wastewater with reuse in irrigation, the treatment with reuse event produces a 33% reduction in life cycle scheme-wide GHG releases (Miller *et al.* 2017). Treatment of water with reuse in urban irrigation may augment GHG mitigation and further in a direct manner preserve groundwater (Miller *et al.* 2017).

3.1.1. SWAT model study

Hydrological models are developed with actual and projected data using SWAT software for the study area to find the natural hydrological cycle including the parameters affecting precipitation, infiltration, evaporation, and runoff (Figure 3). A hydrological model with actual data is performed for the simulation period from 1 January 1979 to 31 July 2014 and with projected data for the period of simulation from 1 August 2014 to 31 December 2050. The total catchment for the study area is separated into 11 sub-catchments/sub-basins and their areas are obtained using SWAT.

Peak runoff from the entire catchment for a period of simulation from 1 January 1982 to 31 July 2014 is 191.28 m^3/s (Table 3). Peak runoff from the entire catchment for a period of simulation from 1 August 2014 to 31 December 2050 is 140.04 m^3/s (Table 4). To reuse stormwater available as surface runoff for irrigation purposes within the study area, i.e., anticipated Amaravati city of Andhra Pradesh, the following canal section may be adopted.

The following tables indicate peak runoff through various sub-basins for periods of simulation with actual (Table 3) and projected data (Table 4).

3.1.2. Design of canal section for reuse of stormwater available

From sub-basin 2 for the period of simulation from 1 January 1982 to 31 July 2014, the maximum peak runoff from the SWAT Model is 48.30 m^3/s, and discharge considered to allow through the underground box section is 20.51 m^3/s (total runoff from the entire catchment). The difference in discharge/peak runoff is 27.79 and 28.00 m^3/s, respectively. This difference in runoff can be made to flow through an open channel with the following design section.

Considering the most economical trapezoidal channel, assumed, side slopes, n is 0.5.

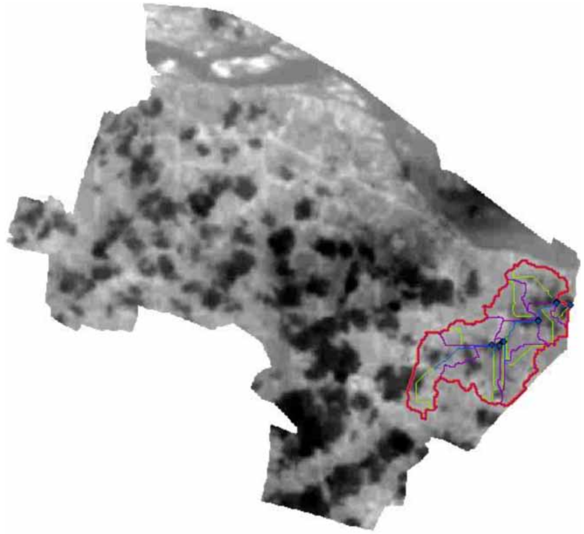


Figure 3 | Study area map with sub-basins.

Table 3 | Peak runoff rate for period of simulation from 1 January 1982 to 31 July 2014

Sub-basin	Sub-basin-based peak runoff, m^3/s
1	5.64
2	48.30
3	4.54
4	36.89
5	32.46
6	4.64
7	14.75
8	23.12
9	7.58
10	5.25
43	8.11

Note: Total peak runoff from entire catchment is 191.28 m^3/s for period from 1 January 1982 to 31 July 2014.

Discharge carrying capacity of the channel, $Q = A \times V = 17.28 \times 1.71 = 29.63\ m^3/s >$ discharge required $= 28.00\ m^3/s$.

Provided, an open channel with dimensions as most efficient/economical trapezoidal channel, i.e., bed width, b is 3.9 m, depth of flow, d as 3.16 m, slope, S is 1/1000, and Freeboard is 0.6 m.

3.1.3. SWMM model study – stormwater management through various LID control options for each sub-basin

Consider, area of each LID unit = 2 acres = 8,093.7 m^2, surface width per unit = 500 m, percentage initially saturated = 0, percentage of non-LID impervious area treated = 95%, percentage of non-LID previous area treated = 95%.

Total peak runoff from No LID (with 9.52% impervious area, zero percentage zero depression impervious area, and evaporation from monthly averages) option = 207.17 m^3/s – Option (1). Table 5 presents a comparison of various LID control options for runoff reduction.

Thus, any of the aforementioned LID control options for efficient stormwater management in sub-basins 2, 4, and 5 is considered where peak runoff in those sub-basins exceeds the value of 20.51 m^3/s.

Table 4 | Peak runoff rate for period of simulation from 1 August 2014 to 31 December 2050

Sub-basin	Sub-basin-based peak runoff, m^3/s
1	4.15
2	35.30
3	3.35
4	27.28
5	23.46
6	3.39
7	10.64
8	16.94
9	5.55
10	3.87
43	6.11

Note: Total peak runoff from entire catchment is 140.04 m^3/ for period from 1 August 2014 to 31 December 2050.

Table 5 | Comparison of various LID control options for runoff reduction

LID control option	Description of LID control option	Total peak runoff (cumecs)	Percentage of total runoff reduction with respect to NO LID Option (1)
Bio-retention cell	With 60% impervious area, 60% zero depression impervious area, bio-retention cell for 40% area	4.5	97.83
Bio-retention cell	With 50% impervious area, 50% zero depression impervious area, and bio-retention cell for 50% area	5.28	97.45
Infiltration trench	With 50% impervious area, 50% zero depression impervious area, and 50% area with infiltration trench	3.52	98.30

3.1.4. Peak runoff determination using Gumbel distribution method

Various models such as SWAT, SWMM, StormCAD, and IDF curves with the application of log Pearson type III method are considered in the study to find the peak discharge.

The mean and standard deviation of the maximum annual series of rainfall depth for various durations are computed (Table 6) as short-duration and high-intensity storm events result in peak runoff.

The governing peak runoff from the entire basin is the outcome of short-duration and high-intensity storm events, which can be determined with the use of IDF curves in urban environments. Thus, Gumbel and log Pearson Type III distribution methods are considered (Tables 7 and 8, Figures 4 and 5) for finding peak runoff.

3.1.5. Peak runoff determination from IDF curves by log Pearson type III method

In the log Pearson type III method, the variate (rainfall data series) is transformed into a logarithmic form either on base 10 or e, and the transformed data are then analysed (CPHEEO 2019). If X is the variate of random hydrologic series such as precipitation, then Z represents the series of the variate, X as $Z = \log X$ (CPHEEO 2019).

Table 9 shows the peak runoff value that can be adopted from various models and studies, i.e., SWAT model, SWMM model, and IDF curves by using the Gumbel and log Pearson type III distribution method.

Table 6 | Mean and standard deviation of maximum annual series of rainfall depth, mm

Rainfall duration, min	15	30	45	60	75	90	120	180
Mean, mm	22.81	28.74	32.90	36.21	39.01	41.45	45.63	52.23
Standard deviation, mm	7.85	9.89	11.32	12.46	13.42	14.26	15.69	17.97

Table 7 | Computation using Gumbel distribution method (considering the 5-year return period)

Rainfall duration, min	15	30	45	60	75	90	120	180
Mean ($\bar{X}$), mm	22.81	28.74	32.90	36.21	39.01	41.45	45.63	52.23
Standard deviation (σ), mm	7.85	9.89	11.32	12.46	13.42	14.26	15.69	17.97
$\alpha = \left(\frac{\sqrt{6}}{\pi}\right)\sigma$, mm	6.12	7.71	8.82	9.71	10.46	11.12	12.24	14.01
$u = \bar{X} - 0.5772\ \alpha$, mm	19.28	24.29	27.81	30.61	32.97	35.04	38.56	44.14
$y_T = -\ln\left[\ln\left(\frac{T}{T-1}\right)\right]$	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
$X_T = u + \alpha y_T$, mm/rainfall duration (min)	28.46	35.86	41.04	45.18	48.66	51.71	56.92	65.15
Intensity, mm/h	113.83	71.71	54.73	45.18	38.93	34.48	28.46	21.72

Note: Adapted from Table 3.15 of CPHEEO Manual on stormwater drainage systems, August 2019.

Table 8 | Computation using log Pearson type III method

Rainfall duration, min	15	30	45	60	75	90	120	180
Mean, $\bar{Z}$	3.07	3.30	3.43	3.53	3.60	3.67	3.76	3.90
Standard deviation, σ	0.36	0.36	0.36	0.36	0.36	0.36	0.36	0.36
K_z	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
$Z_T = \bar{Z} + K_z\sigma$	3.30	3.53	3.66	3.76	3.83	3.89	3.99	4.12
$X_T = \exp\ (\bar{z} + K_z\sigma)$, mm/rainfall duration (min)	26.98	33.99	38.91	42.83	46.14	49.03	53.96	61.77
Intensity, mm/h	107.92	67.99	51.88	42.83	36.91	32.69	26.98	20.59

Note: K_z is frequency factor which is a function of recurrence interval T and coefficient of skewness C_s. K_z values are adopted from Table 3.16 of CPHEEO manual on stormwater drainage systems, August 2019, related to return period of five years and exceedance probability of 0.2.

Log Pearson type III distribution is widely used for frequency analysis for stream flows and can also be used for rainfall (CPHEEO 2019; Malik & Pal 2021). The values obtained by log Pearson type III distribution are more satisfactory as it has a three-parameter distribution that considers the mean, standard deviation, and skewness of the data series (CPHEEO 2019). Hence, a peak runoff value of 1,009.61 m^3/s is adopted for efficient integrated stormwater management including reuse from various models and study results.

$$\text{Considering, peak runoff from the entire catchment from log Pearson type III distribution method } = 1009.61\ \text{m}^3/\text{s} \quad (1)$$

Providing, bio-retention cell LID option with 60% impervious area, 60% zero depression impervious area, and bio-retention cell for 40% area for each sub-catchment,

$$\begin{aligned}\text{Reduction in peak runoff } &= 207.17\ \text{m}^3/\text{s[Peak runoff from SWMM Model]} \times 97.83\% \\ &= 202.67\ \text{m}^3/\text{s}\end{aligned} \quad (2)$$

$$\text{Considering, design water carrying capacity of the stormwater network } = 23\ \text{m}^3/\text{s} \quad (3)$$

$$\begin{aligned}\text{Thus, remaining or available stormwater discharge for reuse } &= (1)\text{–}[(2) + (3)] \\ &= 1009.61\text{–}[202.67 + 23] \\ &= 783.94\ \text{m}^3/\text{s}\end{aligned} \quad (4)$$

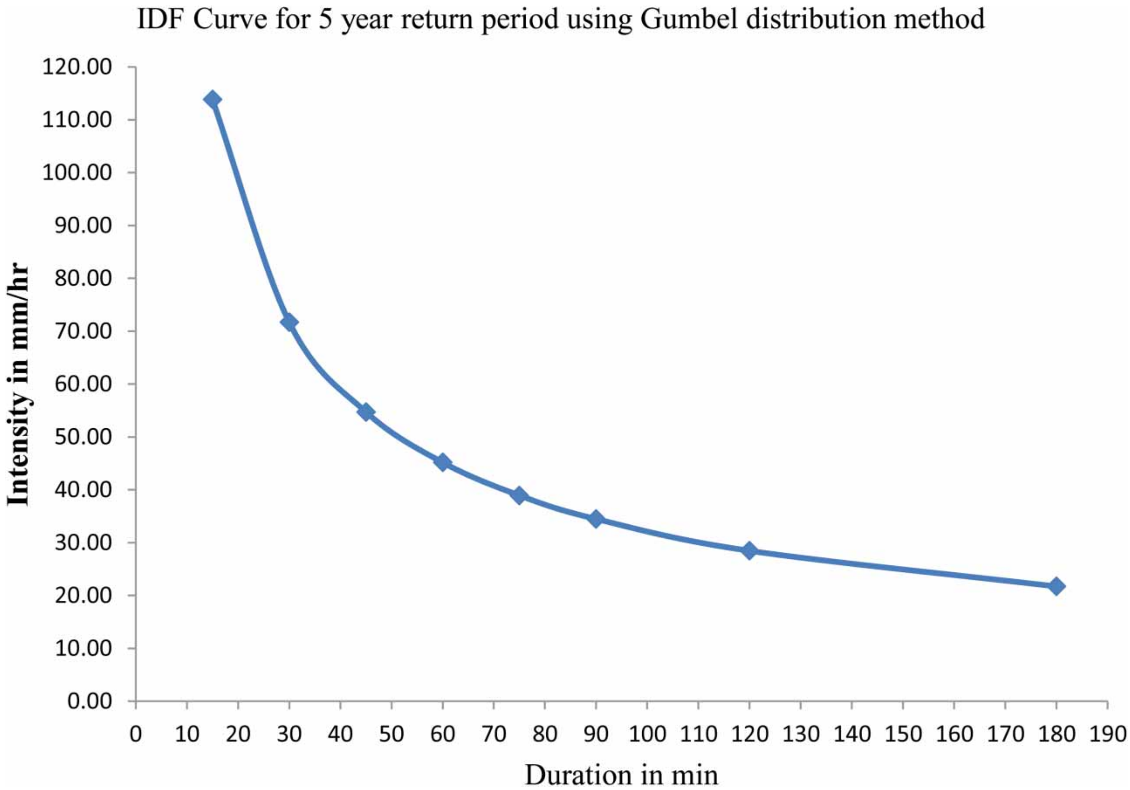


Figure 4 | IDF curve for 5-year return period using Gumbel distribution method.

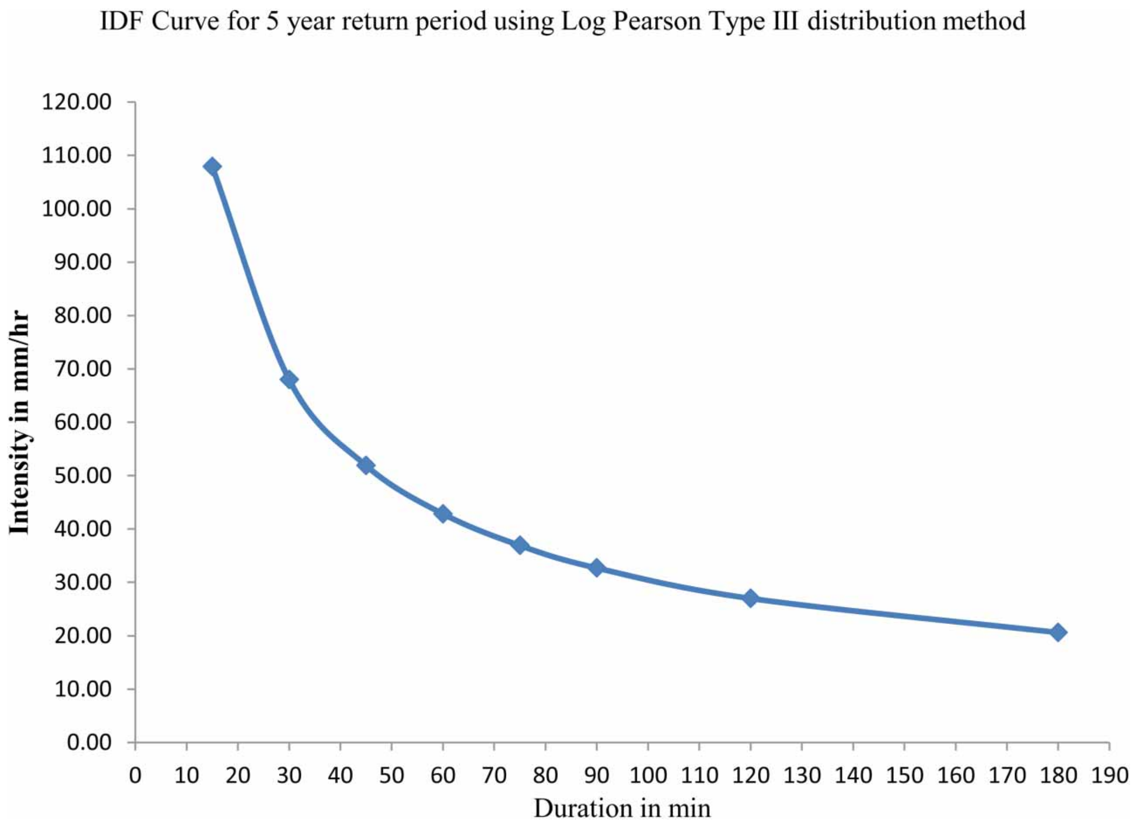


Figure 5 | IDF curve for 5-year return period using log Pearson type III distribution method.

Table 9 | Peak runoff from various models and studies

S.No.	Model/study	Peak runoff, m^3/s	Remarks
1	SWAT model with actual data	191.28	Period of simulation – from 1 January 1982 to 31 July 2014
2	SWAT model with projected data	140.04	Period of simulation – from 1 August 2014 to 31 December 2050
3	SWMM model	207.17	With 9.52% impervious area, zero percentage zero depression impervious area, and evaporation from monthly averages option
4	IDF curves based on Gumbel's method (considering average limiting velocity 1.9 m/s)	1,071.27	With maximum annual series for various durations such as 15 min and 30 min
5	IDF curves based on log Pearson type III distribution (considering average limiting velocity 1.9 m/s)	1,009.61	With maximum annual natural log series for various durations such as 15 min and 30 min

Plausible reuse options in regard to stormwater management of the study area and from available literature studies are for irrigation and storage ponds. The type of soil within the major part of the study area is deltaic alluvial soil. Rock type varies from unconsolidated sand with/without clay, silt, and calcareous hard sedimentaries to non-calcareous sedimentaries. Also, permeability varies from cumulative high to low within the study area (source: Hydrogeological and Hydrological Atlas of A.P. Central Ground Water Board (CGWB) 1983).

Thus, the study area is fit for irrigation and storage ponds with regard to soil characteristics. The same approach is adapted and described in subsequent sections for reuse.

3.2. Stormwater reuse option 1

Available stormwater is provided for irrigation purposes, and 25% of Amaravati city's proposed area is adopted for irrigation; thus, the area available for irrigation is 5,437.5 ha. Base period, B is assumed as 360 days. The depth of water available, $\Delta_{\text{available}}$ is 27.62 mm, which is ignored (source: Revap from shallow aquifer from hydrologic cycle diagram from SWAT model for the period of simulation from 1 January 1982 to 31 July 2014 with actual data). Depth of water required, $\Delta_{\text{reqd.}}$ is assumed as 1 m. Duty available, D is 3,110.4 ha/cumec. Discharge required, Q is 1.75 m^3/s. A total of 20% losses in the canal system are considered, and then, discharge required for irrigation, Q is 2.19 m^3/s. An open channel is finally proposed as the most efficient trapezoidal section with the dimensions as follows: Bed width, $b = 3.9$ m, depth of flow, $d = 3.16$ m, slope, $S = 1/1000$, and freeboard $= 0.6$ m.

Then, the discharge carrying capacity of the channel, Q is 29.63 m^3/s. As the number of villages integrated with the proposed city is 29 in number, thus providing the above-described canal section as the most efficient and/or economical trapezoidal section in all the 29 villages as SEPARATE CANAL(S), which may provide stormwater for various purposes as mentioned below:

i. Irrigation or drinking water after treatment or any other required purposes such as gardening, industrial, and commercial needs in the particular village;
ii. Irrigation in any other area;
iii. Discharge water to the nearby Krishna river.

Therefore, total water made available for 29 villages $= 859.27\ m^3/s > 783.94\ m^3/s =$ remaining or available stormwater discharge for reuse.

3.3. Stormwater reuse option 2

Providing storage retention ponds as extended detention ponds in 29 villages and two towns of proposed Amaravati city.

Remaining or available stormwater discharge for reuse is 783.94 m^3/s (Equation (4)), with consideration of 1 h of detention time, remaining or available stormwater volume for reuse is 2,822,184 m^3. For each village or town, the remaining or available stormwater volume for reuse per village/town is 91,038.19 m^3 and with consideration of 0.25 acres of land for each storage pond, 1 m depth of stormwater allowance for storage, and number of stormwater retention ponds per village/town is 90.

Thus, 90 stormwater retention ponds are proposed, i.e., 22.5 acres of land in each village/town is to be allocated for sustainable and resilient management of stormwater regarding developing and maintaining storage ponds. This storage pond in each village/town may serve as a reservoir for intermittent water supply after treatment and disinfection as per standards/ requirements.

3.4. Stormwater harvesting and/or reuse option 3 with option 1 or option 2: *in situ* storage/percolation within or around premises (rainwater harvesting system)

Efficient stormwater management within or around premises, which is commonly known as 'Rainwater harvesting techniques' for each premise includes but is not limited to the following:

i. Rooftop rainwater collection potential;
ii. Conveyance system;
iii. Size of rainwater pipes for roof drainage;
iv. Percolation of runoff into the ground;
v. Percolation pits;
vi. Percolation trenches;
vii. Recharge wells.

Guidelines, specifications, and/or recommendations of the Central Public Health and Environmental Organisation (CPHEEO) manual on stormwater drainage systems, August 2019, may be adapted to these various *in situ* storage/percolation within or around premises for sustainable and/or resilient rainwater harvesting systems.

This option, i.e., option 3, must be provided with before mentioned option(s) 1 or 2. However, the attenuation of peak runoff due to the provision of this option, i.e., various in situ storage/percolation provisions within or around premises has not been considered as part of efficient stormwater management or reuse of available stormwater for the proposed Amaravati city.

4. CONCLUSIONS

Various model studies such as SWAT, SWMM, and climate change impact assessment using R programming, StormCAD, and IDF curves for very short-duration and high-intensity rainfall are performed to find peak runoff from the entire basin and further attenuation and disposition of peak runoff developing from the proposed city. Optimization and sensitivity analysis are applied to find highly efficient LID mechanisms/tools for peak runoff attenuation. The maximum value of peak runoff from different model studies is determined. Part of peak runoff is allowed to flow through a developed underground stormwater network system. Further to the attenuation of certain parts of peak runoff using highly efficient LID approaches, the remaining part of peak runoff is considered for stormwater reuse purposes. Various stormwater reuse options such as irrigation, intermittent water supply, and storage ponds are applied to accommodate part of peak runoff. *In situ* storage/ percolation within or around premises is proposed as a rainwater harvesting technique that is meant for unaccounted water. Detailed options will affirm the reuse of available stormwater based on peak flow from IDF curves by log Pearson type III method which governs peak runoff from various models and/or studies performed for sustainable and resilient innovative integrated management of stormwater for the anticipated city to enact as water-sensitive city for an extended period.

4.1. Limitations of the study

Reuse options for water supply and water quality analysis are not carried out in the present study. Also, water supply and wastewater are also not considered to assess plausible options for efficient integrated urban water management.

4.2. Recommendations and scope for future study

Integrated study with various models such as SWAT, SWMM, and StormCAD including climate change impacts assessment is vital for efficient urban stormwater management. Also, a study on various reuse options including for potable water supply to cater for urban areas may be performed in the future. Further, evaluation studies on water quality and to assess their suitability for various urban requirements might be considered as a future study. Water supply and wastewater can also be considered to assess plausible options for efficient integrated urban water management.

The findings of the current study can aid as a tool for local stakeholders, water managers, policymakers, and governing bodies to realize, propose, and implement adaptation measures and/or practices for stormwater reuse of any existing and/or proposed city in the world.

DATA AVAILABILITY STATEMENT

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

CONFLICT OF INTEREST

The authors declare there is no conflict.

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