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Urban stormwater management for sustainable and resilient measures and practices: a review

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ABSTRACT

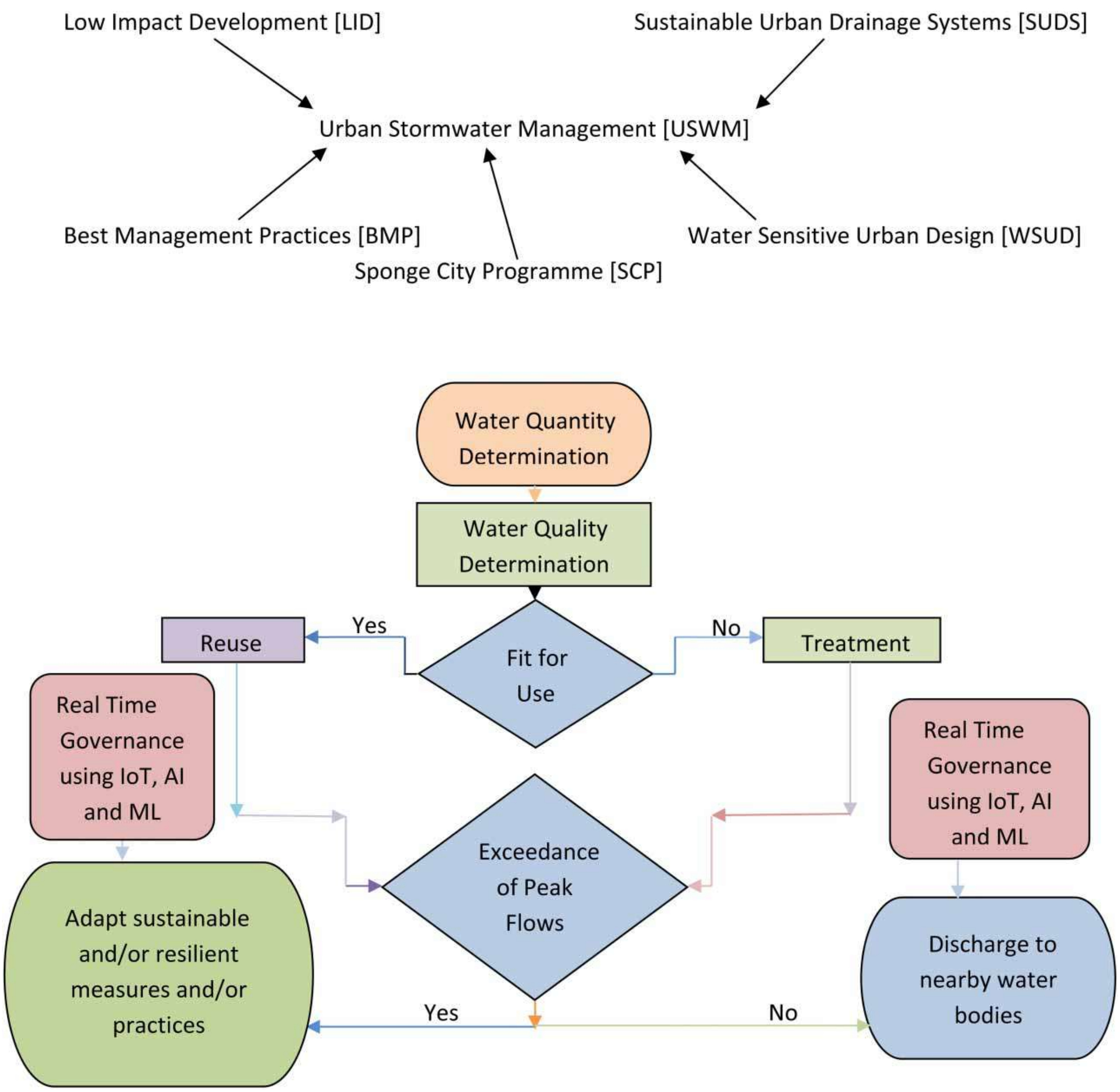
Stormwater drainage in urban areas has become a challenge due to the rapid and random growth of urban areas, removal of vegetation, reduction in the effectiveness of drainage infrastructure, and climate change. Sustainable Urban Drainage Systems (SUDS), Low Impact Development (LID), Best Management Practices (BMP), Water Sensitive Urban Design (WSUD) and the Sponge City Programme (SCP) are various aspects for urban stormwater management in a few parts of the world. Urban hydrology plays a vital role in the urban stormwater management system. However, optimal results can only be possible when the combined effect of climate change, land use patterns, reuse, treatment, ecology, and societal aspects are considered. There is a need to provide sustainable and resilient urban drainage systems to manage stormwater more efficiently. The present review has thoroughly discussed various features related to urban stormwater management, highlighted key drivers, identified knowledge gaps in each of the measures and/or practices, recommended future research needs of urban stormwater management to become sustainable and resilient. Integrated modelling approaches considering various key drivers including reuse and real time governance enables stormwater management to be sustainable and resilient in urban environments.

Key words: climate change, key drivers, real time governance, reuse, urban hydrology, urbanization

HIGHLIGHTS

- A review of the state of the art on integrated urban stormwater management (USWM) is presented.
- Various aspects affecting integrated USWM including climate change, water quality, reuse and treatment perspectives of USW are discussed.
- Various innovative, advanced integrated USWM measures and/or practices such as LID, BMP, SUDS, WSUD and SCP are reviewed.
- Specified critical remarks and expressed views on future research needs for integrated USWM are given.

GRAPHICAL ABSTRACT



1. INTRODUCTION

The hydrology of a place influences the availability of water at that place. Various processes such as runoff, infiltration and evaporation associated with hydrologic cycle affect the presence, movement and distribution of precipitation in an area (Fletcher *et al.* 2013). Water is needed for different human activities and purposes and is becoming scarce due to poor management rather than availability. In this context, there is an increasing need for the management of water especially in urban areas where the water requirement is substantially higher. As stormwater is available from nature, conservation of stormwater is of utmost importance in urban environments and requires urgent attention. For effective and efficient stormwater management, there are various practices followed around the world. The present paper reviews the state of the art in different schemes for stormwater management, analysis of results for each of the schemes, specifies critical remarks and expresses views on future research needs. Stormwater management is becoming a challenge in various stages of its implementation, starting from the planning stage, due to expansion of the urban area, change in existing soil permeability characteristics by construction activities, decrease in vegetation, climate change, change in rainfall and subsequent runoff patterns.

Sustainable Urban Drainage Systems (SUDS) (Fryd *et al.* 2010; Zhou 2014; Ellis & Lundy 2016; Lim & Lu 2016; Casal-Campos *et al.* 2018; Arahuetes and Cantos 2019; Altobelli *et al.* 2020; Kändler *et al.* 2020; Lin *et al.* 2020; Kwon *et al.* 2020;

Hager *et al.* 2021), Low Impact Development (LID) and Best Management Practices (BMP) (Strecker *et al.* 2001; Dietz 2007; Motsinger *et al.* 2016; Mani *et al.* 2019; Nowogoński 2020; Men *et al.* 2020; Song *et al.* 2020; Zhang *et al.* 2020a, 2020b; Khurelbaatar *et al.* 2021), Water Sensitive Urban Design (WSUD) (Lariyah *et al.* 2011; Beecham & Razzaghmanesh 2015; Siekmann & Siekmann 2015; Marino *et al.* 2018; Ahmed *et al.* 2019) and Sponge City Programmes (SCP) (Wang *et al.* 2018) are some of the stormwater management schemes that are being adopted in different countries.

SUDS, WSUD and LID concepts have related aims such as managing the urban water through a sustainable approach, preserving the flow conditions close to nature, maintaining the water quality and that of receiving waters, and conserving water resources overall (Fletcher *et al.* 2013). BMP cover practices that contain non-structural (procedural or operational) and structural (engineered or built infrastructure) characteristics (Fletcher *et al.* 2015).

The SCP is meant to enhance urban water resilience due to growth and climate change with the key goals of mitigation of waterlogging and floods, enhancement of quality of water, refurbishment of the water's role on ecology, use of rainwater as a resource and improving the microclimate of urban environments (Wang *et al.* 2018).

1.1. Novel aspects of the review

Although there have been various reviews on the subject (Hatt *et al.* 2006; Chouli 2006; Dietz 2007; Roy *et al.* 2008; Gabe *et al.* 2009; Fletcher *et al.* 2013; Hamel *et al.* 2013; Zhou 2014; Ellis & Lundy 2016; Sörensen *et al.* 2016; Ahammed 2017; Palazzo 2018; Mishra *et al.* 2020), the present review is *novel* in considering various aspects for urban stormwater management to *value-add* prevailing measures and practices to be more sustainable and resilient. The aspects related to urban stormwater management such as LID, BMP, SUDS/SuDS and the SCP are reviewed with regard to knowledge gaps and future research needs which brings novelty to the present review in covering all the existing measures and practices of urban stormwater management and further proposing the application of real-time governance and reuse options that enhance the present review to the *next level* regarding urban stormwater management. Also, climate change aspects, urbanization aspects and their impacts on urban hydrology and ecology, water quantity and quality characteristics are reviewed thoroughly and we recommended various options to improve present measures and practices for urban stormwater management to be sustainable and resilient. The present review is also described in the form of tables (Tables 1–3) and figures (Figures 1 and 2) for better and easy interpretation. Table 4 presents *key drivers* of integrated urban stormwater management. Thus, overall, the present review is certainly and thoroughly novel in the review of urban stormwater management with discussion, review, mentioning key drivers, highlighting knowledge gaps and suggesting future research needs for various measures and practices to attain integrated, sustainable and resilient urban stormwater management.

2. LOW IMPACT DEVELOPMENT AND BEST MANAGEMENT PRACTICES

LID refers to the principles, techniques and practices that can be adapted to develop certain urban activities duly maintaining the equilibrium of natural processes and resources.

LID and Low-Impact Urban Design and Development (LIUDD) are methods for urban development that use various urban planning and design policies and strategies to conserve natural resource systems and reduce infrastructure costs with a cost-effective approach and mitigate potential environmental impacts (Montazerolhodjah 2019).

Various studies have been designed for the application LID and BMP (Motsinger *et al.* 2016). Certain LID options have been found to be effective such as pervious pavements and bioretention (Dietz 2007; Davis *et al.* 2009). Bioretention practice, although effective, needs to be associated with hydrologic, water quality and environmental aspects (Davis *et al.* 2009). Also, BMPs may be applied to water quality for better treatment performance (Motsinger *et al.* 2016). Various approaches exist for implementation of LID and to make them BMP. However, LID implementation is affected by associated problems (Strecker *et al.* 2001). During implementation, certain limitations were found while practicing LIDs such as high contaminant loading areas, steep slopes, rock depth and rise of water table (Dietz 2007). Thus, there is a continuous need for carrying out research on LID and BMPs for efficient implementation (Dietz 2007). Furthermore, LID approaches had been continuously studied for their integration with various novel techniques for better performance and wide range of applications. Rain barrels, permeable walkways or bioretention reservoirs have been applied by combining LID with StormWater Management Models (SWMM) for reduction of catchment imperviousness (Nowogoński 2020). In the Sponge City, SWMM was integrated with a preference-inspired co-evolutionary algorithm using goal vectors (PICEA-g) for LID practices (Men *et al.* 2020). An approach combined with SWMM and the multi-objective antilon optimization algorithm (MOALOA) was applied to recognize stormwater control measures (SCMs) as LID for control of runoff and mitigation of flood (Mani *et al.* 2019). Also,

Table 1 | Review of research on integrated stormwater management

Reference	Year	Main aspect	Other aspects	Application	Findings
Khurelbaatar *et al.*	(2021)	LID		MUST- B	Capacity of urban stormwater management
Dubey *et al.*	(2020)	Hydrology	Climate change	SWAT	Evapotranspiration
Men *et al.*	(2020)	Low Impact Development (LID)	Preference-inspired co-evolutionary algorithm using goal vectors (PICEA-g)	SWMM	LIDs for Sponge City
Nowogoński	(2020)	Low Impact Development (LID)		SWMM	LIDs for imperviousness reduction
Song *et al.*	(2020)	Low Impact Development (LID)	Reliability evaluation technique		Performance of existing systems for flood disasters
Zhang *et al.*	(2020a, 2020b)	LID	Interdisciplinary criterion	SWMM	Assessment of stormwater control for runoff volume
Anim *et al.*	(2019)	Stream hydraulics		2D Hydraulics Model	Benefits of Stormwater Control Measures (SCMs)
Zang *et al.*	(2019)	Hydrology	Land use	SWAT	Daily flood peak and annual runoff
Mani *et al.*	(2019)	Hydrology	Flood mitigation	SWMM, MOALOA	LID Stormwater Control Measures (SCMs)
Motsinger *et al.*	(2016)	Best Management Practice (BMP)	Water quality		Impact of various BMPs implementation
Kang *et al.*	(2016)	Urban drainage	Climate change	XP-SWMM	Climate change
Saraswat *et al.*	(2016)	Hydrology	Climate change		Runoff
Liu *et al.*	(2016)	Hydrology	Water quality		Runoff
Zhu *et al.*	(2016)	Hydrology	Water quality	Projection pursuit method, ordinary *Kriging* method	Flooding risks
Costa *et al.*	(2015)	Hydrology	Water quality	MT3DMS	Integrated Urban (IU) river corridor management
Hung Chang and Irvine	(2014)	Rainfall Extremes			Floods and droughts
Teemusk & Mander and Lee *et al.*	(2007), (2013)	Hydrology	Green roof		Runoff
Ficklin *et al.*	(2013)	Hydrology	Sedimentation	SWAT	BMP
Fletcher *et al.*	(2013)	Hydrology	Water quality		ISWM
Hamel *et al.*	(2013)	Hydrology	Urbanization		Baseflow
Dessu & Melesse	(2012)	Hydrology		SWAT	Rainfall–Runoff simulation
Dixon & Earls	(2012)	Hydrology	Land Use	SWAT	Hydrographs
Hirschman *et al.*	(2011)	Hydrology	Climate change		Stormwater management
Huong & Pathirana	(2011)	Flooding	Climate change	EPA-SWMM 5 with Brezo	Runoff
Singh and Gosain	(2011)	Hydrology	Climate change	SWAT	Climate change
Ghaffari *et al.*	(2010)	Hydrology	Land use	SWAT	Runoff
Mejia & Moglen	(2010)	Hydrology	Hydrographs		Impervious pattern

(*Continued.*)

Table 1 | Continued

Reference	Year	Main aspect	Other aspects	Application	Findings
Davis *et al.*	(2009)	Bioretention	Hydrologic, water quality and environmental issues		State of contemporary acquaintance of bioretention
Bormann *et al.*	(2009)	Hydrology	Land use	SWAT and TOPLATS	Land use scenarios
Dhar & Mazumdar	(2009)	Hydrology		SWAT	Assessment of projected parameters for farming operations
Nie *et al.*	(2009)	Flooding	Climate change	MOUSE	Precipitation
Semadeni-Davies *et al.*	(2008)	Climate change and urbanization		MOUSE (MOdel of Urban SEwers)	Sustainable Urban Drainage Systems (SUDS)
Wang *et al.*	(2008)	Hydrology	Climate change and land use	SWAT	Runoff
Wilby *et al.*	(2008)	Hydrology	Climate change		Flood frequency
Roy *et al.*	(2008)	Stormwater Management			Sustainable Stormwater Management
Dietz	(2007)	Low Impact Development (LID)			Review of the current condition and research needs of LID
Van Rooijen *et al.*	(2005)	Hydrology	Water supply, Irrigation	VENSIM	Water balance
Strecker *et al.*	(2001)	Best Management Practice (BMP)			BMP efficiency

assessment of performance of LID techniques had been carried. An evaluation of the performance of existing systems for flood disasters using the distance measure method may be carried (Song *et al.* 2020). Also, an appraisal of LID performance for stormwater control can be perfomed using SWMM with an interdisciplinary criterion (Zhang *et al.* 2020a, 2020b). Furthermore, the evaluation of stormwater management at block level in urban areas with LIDs may be performed (Khurelbaatar *et al.* 2021).

However, the application of various LID and BMPs for holistic urban stormwater management needs to be studied in much more detail with advanced and novel approaches such as the Internet of Things (IoT), Artificial Intelligence (AI) and Machine Learning (ML) for real-time monitoring and control of water quantity and water quality to enhance stormwater system performance concerning sustainable and resilient measures and practices.

3. HYDROLOGICAL ASPECTS OF CLIMATE CHANGE, URBANIZATION, AND RESILIENCE

The quality of input data is very much impacting parameters for modelling flows (Bormann *et al.* 2009). Also, a realistic representation of scenarios of land use and the application of proper techniques for interpolation and representation of boundary conditions of meteorology is very vital for the representation of data input (Bormann *et al.* 2009). Uncertainty remains the bottleneck and needs to be properly accounted for in flow analysis even from the assessment of errors in precipitation and peak flows (Wilby *et al.* 2008). The determination of frequencies of extreme flows needs assessed for varied characteristics of climate change and the responses of the surface of the land to hydrological parameters (Wilby *et al.* 2008).

Runoff varies with land use type and in reaches in mountains, and runoff is increased with more grassland area and less forested areas (Wang *et al.* 2008). Although runoff depends on precipitation, flow varies with temperature more during the melting of snow in spring (Wang *et al.* 2008). The response of hydrology to changes in land cover is not linear and shows a threshold tendency (Ghaffari *et al.* 2010). Surface runoff abruptly becomes more when rangeland removal is more than 60% and this threshold is applicable even in the recharge process of groundwater (Ghaffari *et al.* 2010).

Table 2 | Review of research on various water management and other aspects/practices

Reference	Year	Aspects studied	Findings/outcomes
Hager *et al.*	(2021)	Integrated framework	Decision support system for urban stormwater
Altobelli *et al.*	(2020)	Optimal management of urban drainage systems (UDS)	Real-time control and green technologies
Bell *et al.*	(2020)	BMPs	Runoff control factors
Deng	(2020)	Low-cost adsorbents	Treatment of urban stormwater
Kändler *et al.*	(2020)	Smart in-line storage system	Real time controlled actuators
Lin *et al.*	(2020)	Framework for UDS (urban drainage systems) design	Enhancement of optimization efficiency of UDS
Lam *et al.*	(2020)	SWMPs (Stormwater management ponds)	Chloride retention quantification and release
Kwon *et al.*	(2020)	Urban drainage systems (UDS)	A two-phase multi-scenario approach
Zabłocka & Capodaglio	(2020)	Sustainable SWM	Retention tank
Arahuetes and Cantos	(2019)	SuDS	Climate change adaptations
Casal-Campos *et al.*	(2018)	UDScapacity	Key perceptions of UDS
Wang *et al.*	(2018)	IUWM	Review of Sponge City
Li *et al.*	(2016)	Water quality and land use	Landscape thresholds
Sörensen *et al.*	(2016)	Urban resilience with integrated flood management	Urban flood resilience
Ellis & Lundy	(2016)	SUDS	Practices examination
Lim & Lu	(2016)	Small-scale distributed LID features	Evaluation of Singapore's ABC Waters Program
Buurman & Babovic	(2015)	A step-wise approach for designing adaptive systems	Urban water resilience
Beecham & Razzaghmanesh	(2015)	Water quantity and quality	Green roof systems
Zhou	(2014)	SUDS	Emerging studies
Liu *et al.*	(2013)	Water quality, urbanization	The threshold between Impervious surface area [ISA] and the chemical indicators of water quality
Davis *et al.*	(2010)	Water quality	Urban stormwater quality improvement methods
Fryd *et al.*	(2010)	Sustainable Urban Drainage Systems (SUDS)	Planning and decision making processes
Gabe *et al.*	(2009)	A top-down 'planner's approach' and a bottom-up 'community approach	Integrated Urban Water Management (IUWM)
Hatt *et al.*	(2007)	Water quality	Biofilters
Tortajada	(2006)	Water management practices and strategies	Need for implementing latest technologies, efficient use of limited water resources, proper watershed management, practicing water conservation measures
Hatt *et al.*	(2006)	Water quality	Treatment methods for stormwater pollution control
Goonetilleke *et al.*	(2005)	Water quality	Relationships between water quality and urban form
Chui	(1997)	Water quality	Runoff
Cheong	(1991)	Water quality	Runoff

The local area assessment is significant to find impacts of climate change on urban hydrology with regard to topography, lithology, drainage areas recognition and land use/land cover variations and thus for the determination of the runoff coefficient (Saraswat *et al.* 2016). If runoff reduces through infiltration and further recharge of groundwater, then LID practices become more resilient to climate change impacts (Hirschman *et al.* 2011). The changes in flood peak on a daily scale in

Table 3 | Review of research on stormwater reuse and treatment

Reference	Study
Valenca *et al.* (2021)	Capability of biochar for removal of the *Escherichia coli* (*E. coli*)
Valentukevičienė & Najafabadi (2020) and Zhang *et al.* (2020a, 2020b)	Application of different sorbents
Tuttolomondo *et al.* (2020)	Reuse of treated wastewater from wetlands
Zhang *et al.* (2020a, 2020b)	Suspended solids removal
Trajkovic *et al.* (2020)	LID techniques for removal of pollutants
Ekka *et al.* (2020)	Grass swales, sediment and heavy metal removal
Zabłocka & Capodaglio (2020)	Retention tank
Rodak *et al.* (2020)	Stormwater control devices
Zhang *et al.* (2020a, 2020b) and Kog (2020)	Application of membranes for high-quality reclaimed water
Zhan *et al.* (2020)	Cost–effectiveness of treatment system design for stormwater reuse
Ahmed *et al.* (2019)	Removal of fecal indicators and pathogens
Ahmed *et al.* (2019)	Efficiency of different risk assessments with stormwater reuse
Montazerolhodjah (2019)	Low-impact urban design and development (LIUDD)
Shen *et al.* (2019)	Real-time control (RTC) strategies for biofilters
Jung *et al.* (2019) and Hatt *et al.* (2007)	Application of biofilters to greywater treatment and reuse
Rufino *et al.* (2018) and Marino *et al.* (2018)	Participatory approach for WSUD
Goonetilleke *et al.* (2017), Gogate & Raval (2015), Maneewan & Roon (2017), and Muirhead (2008)	Key obstacles to stormwater reuse
Ishimatsu *et al.* (2017)	Rain gardens
Ding (2017)	BMP effectiveness for reuse of stormwater
Glover *et al.* (2019)	Treatment of *N*-nitrosomorpholine (NMOR) for potable reuse
Kazemi & Hill (2015)	Permeable pavement basecourse aggregates
Lariyah *et al.* (2011)	Overall performance of WSUD
Maharaj & Scholz (2010)	Biochemical oxygen demand, total coliform
Begum & Rasul (2009)	Green gully
Pétavy *et al.* (2007)	Bulk sediment re-use after the treatment
Chouli (2006)	Source control techniques

scenarios of high precipitation remain the same as that in the scenario of average precipitation on modelling at the daily scale (Zang *et al.* 2019). The assessment needs to be quantitative in nature in case of more flood hazards, which is significant for urban planning and to prepare for disasters (Huong & Pathirana 2011).

Scenarios of climate change need to be well defined for urban hydrology to assess its impacts on flooding and combined sewer overflows (CSO) (Nie *et al.* 2009). Climate change may result in more stormwater inflows and infiltration into sewers and cause decrease in system capacity (Semadeni-Davies *et al.* 2008). Adaptation to climate change scenarios may be possible with the application of SUDS and not allowing stormwater into combined sewers (Semadeni-Davies *et al.* 2008).

Climate change may impact certain parameters such as loss of transmission, water content of soil, potential evapotranspiration, evapotranspiration and reach lateral flow of river basins with the increasing trend for future scenarios (Dhar & Mazumdar 2009). The impacts of climate change on river basin hydrology were assessed to be vital on an annual scale

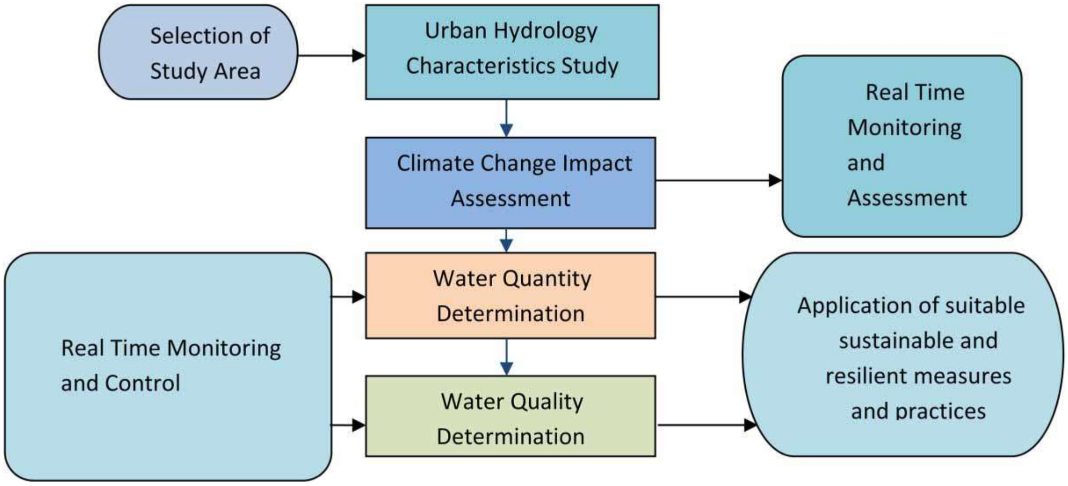


Figure 1 | Flow chart of urban hydrology characteristics study.

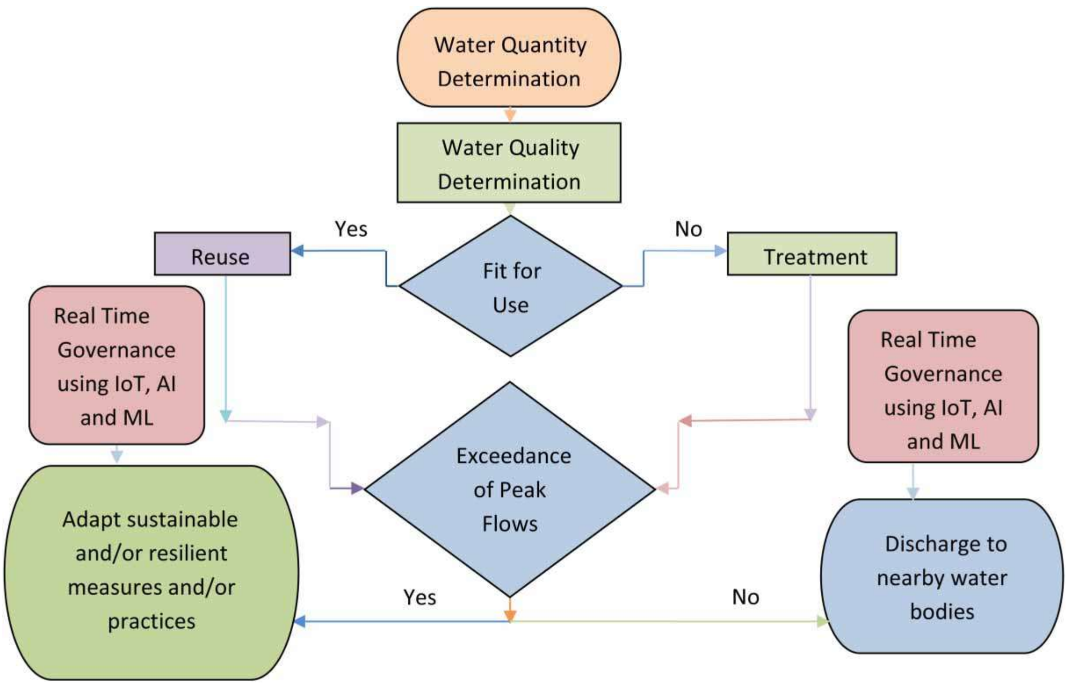


Figure 2 | Process diagram of integrated urban stormwater management.

(Singh & Gosain 2011; Dessu & Melesse 2012; Ficklin *et al.* 2013; Dubey *et al.* 2020). Impacts of climate change are more important than those due to land cover changes (Hirschman *et al.* 2011; Huong & Pathirana 2011).

There are certain vital adaptations of stormwater to climate change, which are the development of roads and sidewalks using porous materials, enhanced capacity of stormwater to cater for water supply and frequent flooding increase, revisions to stormwater design criteria, revising transmission systems with regard to sea levels and improving the infrastructure of stormwater (Hirschman *et al.* 2011). There is a need for future research to assess the implications of actual and simulated meteorological data for long-term urban planning and the management of urban hydrology for efficient stormwater management (Dixon & Earls 2012).

A three-step preparedness program for extremes that includes Preparation (vulnerability and risk identification, adaptive capacity building, and monitoring), Response (information dissemination and relief action) and Recovery was recommended for management of rainfall extremes (Hung Chang & Irvine 2014). There are certain measures to mitigate urban floods such

Table 4 | Key drivers of integrated urban stormwater management

Key driver	Characteristics
Data	Data need to be available for the period of model development at regular and continuous intervals. Also, data needs to be reliable, accurate, and suit the purpose of study both in space and time.
Model development	Model can be developed on the intent of the study as quantitative and qualitative. Also, model can be prepared as conceptual, detailed, deterministic and stochastic considering various other influencing parameters and required outcomes of the study.
Assessment of model	Developed model needs to be assessed with proper calibration, validation and uncertainty analysis and techniques.
Process	Aspects that can be ascertained from the model may be of hydrology, hydraulics, ecology, societal and economics etc. Furthermore, each of these aspects may be subcategorized and prioritized based on the requirements of the study.
Monitoring and maintenance of system	Way of implementation of the developed model needs to be monitored at regular intervals to check its adequacy with regard to setting objectives. Also, periodic maintenance has to be performed with proper methods, approaches that can make the system serve with expected efficiency for longer duration.
Reuse	Stormwater reuse after treatment needs to be analyzed as there is increasing water stress in urban areas.
Application of real-time technologies	Latest technologies such as the Internet of Things (IoT), Artificial Intelligence (AI) and Machine Learning (ML) are to be applied for real-time data, monitoring and control of water quantity and quality, assessment of climate change and land use/land cover impacts on stormwater.

as raising the adjacent land level, pumping stations installation, and enhancing pipe performance (Kang *et al.* 2016). An enhanced pipe capacity may cater for increased urban flooding as an adaptation measure/practice to climate change (Kang *et al.* 2016).

However, there is a need to study the impacts of climate change and urbanization on regional hydrology in much more detail with more accurate and relevant data at the local scale even after downscaling. Furthermore, stormwater management has to be studied for sustainable and resilient measures and practices to accommodate extreme events and for combined effects. The application of integrated models for climate change impact assessment, varying land use, urban floods and on entire urban hydrology needs to be highlighted for urban stormwater management to be efficient.

Also, as evapotranspiration has vital role for hydrology of urban environments, it becomes complex for the development of methods to model and compute evapotranspiration. Thus, this area needs to be studied in much more detail for accurate interpretation of urban hydrologic cycles.

4. HYDROLOGICAL – WATER QUANTITY AND QUALITY ASPECTS

Urbanization processes such as increased imperviousness modifies local water balance and improves flow for downstream (Van Rooijen *et al.* 2005). Imperviousness affects hydrological response with regard to its spatial extent and thus there is a need to consider spatial patterns of precipitation and impervious areas to find the hydrological response of catchments of urban environments (Mejia & Moglen 2010). High intensity–short duration rainfall events are the key drivers for stormwater treatment design (Liu *et al.* 2016). Impervious surface connection to the receiving water governs hydrologic behaviour of urban basins (Fletcher *et al.* 2013). When there are considerable overland flow lines between the area of imperviousness and the receiving waters then the hydrologic response of the impervious surface likely recedes (Fletcher *et al.* 2013).

Stormwater source control technologies may be applied which are ecologically relevant and realistic to find the impacts of urbanization on baseflow variations (Hamel *et al.* 2013).

Also, there is a need for integrated planning of urban river corridor management considering groundwater and water quality as well for sustainable solutions for stormwater management (Costa *et al.* 2015).

Constraints to sustainable urban stormwater management are (Roy *et al.* 2008): (1) uncertainties in performance and cost, (2) inadequate engineering standards and guidelines, (3) disjointed responsibilities, (4) lack of institutional capability, (5) lack of legislative directive, (6) lack of financial support and effective market encouragements, and (7) confrontation to change (Source: Roy *et al.* 2008)

Solutions to sustainable urban stormwater management are (Roy *et al.* 2008): (1) Carry out research on costs and catchment-scale performance, (2) produce a model ordinance and support guidance articles, (3) combine management across levels of government and the cycle of water, (4) extend targeted workshops to train professionals, (5) apply grassroots attempts to acquire support for ordinances and rules, (6) attend to barriers in market methods to give funding mechanisms, (7) teach and appoint the public through actions (Source: Roy *et al.* 2008).

Risk-based integrated SWMM are to be applied to qualitatively and quantitatively assess the inundation risks in urban drainage systems (UDS) (Zhu *et al.* 2016). Stormwater management which can make complete retention, collection and infiltration of surface runoff will have a considerable impact if the runoff volume becomes nearly the same as that prior to urbanization (Anim *et al.* 2019). Green roofs may increase the quality of urban runoff by absorption and filtration processes and also release pollutants into water (Teemusk & Mander 2007; Lee *et al.* 2013). Membranes may be extensively applied in integrated processes to produce high-quality reclaimed water (Zhang *et al.* 2020a).

Modelling flows below and close to the ground surface still remains a complex phenomenon and the accurate assessment of subsurface flows needs to be studied in much detail. However, furthermore, there is a need to study integrated stormwater management with holistic models for quantitative and qualitative analysis of urban hydrology in much more detail.

5. ECOHYDROLOGICAL AND HYDROBIOLOGICAL ASPECTS

Sequential Purification Systems with sedimentation, biogeochemical and wetland zones with biodegradable geofibers would augment the efficiency of purification with ecohydrological operations for urban areas with blue-green environments to adapt to climate change (Zalewski *et al.* 2012). Approaches using nature-based solutions (NBS) are resilient and adaptable for urban ecosystem management (Krauze & Wagner 2019). There is a need for a three-fold target with enabling, restoring or preserving nature for urban environments to be sustainable in the context of ecosystems of urban waters (Krauze & Wagner 2019). There are various drivers of water ecosystems for efficient integrated urban water resources management (IUWRM) (Wagner & Breil 2013). Integration of ecosystem methods in urban environments would build cities to be more resilient (Wagner & Breil 2013). Utilization of rivers in urban areas enhances stormwater management to be more resilient (Wagner & Breil 2013). The principles of ecohydrology offer a framework for management of urban water (Zalewski & Wagner 2005). Integrated urban water management Integrated Urban Water Management (IUWM) with ecohydrology aspects would decrease peak flows, and enhance stormwater quality (Zalewski & Wagner 2005). There is a need for integration of aquatic ecosystems and greenery in urban areas for enhanced urban water management and to improve the mechanisms of protection of habitats against the impacts in urban environments (Zalewski & Wagner 2014). A system of hybrids (collective of engineering and biological measures) with an underground separator system with a sequential sedimentation–biofiltration system (SSBS) is capable of decreasing the hydraulic stress due to peak flows and mitigated flows for precipitation of less than 9 mm (Jurczak *et al.* 2018). SSBS are efficient for treating an urban river with significant stormwater inflows and the geochemical barrier and biofiltration zone each extensively enhance overall efficiency (Szklarek *et al.* 2018). Various conventional water quality restoration methods and comprehensive ecohydrological restoration methods such as SSBS may be applied for urban rivers with stormwater inflow (Jurczak *et al.* 2019). Restoration enhances the majority of the indicators of water quality in general (Jurczak *et al.* 2019). The combined LID optimal scenario with the proportions of rain garden as 3.75%, green roof as 3.75%, and permeable pavement as 7.5% have better regulatory effects than a single facility of LID for sponge cities (Gao *et al.* 2021). The Sponge City optimization scheme with LID can efficiently lessen non-point source pollutants of nutrients in receiving water (Yang & Dong 2021).

Table 1 presents a list of research on various aspects of integrated stormwater management with applications used and outcomes.

6. URBAN WATER AND RESILIENCE MANAGEMENT

Efficient utilization of inadequate water resources in an economical manner, adapting to the recent technological approaches to develop 'new' water sources, increasing storage capacities by appropriate watershed management, implementing water management measures, and accounting present social, environmental and economic factors are the key drivers for sustainable and resilient urban water management including stormwater management (Tortajada 2006).

Urban resilience is an adaptive process for society to learn in an unremitting manner to manage with varying socio-economic situations, land use of urban and climate change (Sörensen *et al.* 2016). A framework method which combines high level targets with quantifiable indicators needs to be adapted for efficient urban stormwater management (Gabe *et al.* 2009). Indicators are to be recognized on two varied approaches i.e. a top-down 'planner's approach' and a bottom-up 'community approach' for urban development and IUWM (Gabe *et al.* 2009). Another high level framework which is a stepwise approach with policymaking to adapt pathways for adaptation and analysis of real options may also be applied for designing adaptive systems for urban water resilience (Buurman & Babovic 2015).

The stepwise approach by Buurman & Babovic (2015) recognized that numerous investments to adapt to climate change are not investments of 'now-or-never' and are with a flexible approach to develop, reduce or revise. Also, the framework identified that investments for adaptation are infrequent investments of an 'all-or-nothing' nature, however they are options to extend price, profit and risk (Buurman & Babovic 2015).

More-informed decision-making is necessary to attain sustainable urban environmental management by recognizing the thresholds (Li *et al.* 2016). Urban flood risk management sets targets to assess and decrease flood risk and to prepare to respond and recover after real floods, with the intention of keeping disturbances and disruptions to minimum and developing resilient urban water management systems (Sörensen *et al.* 2016).

The 'Sponge City' as an IUWM strategy with integrated approaches, with consideration of all aspects of urban hydrology and anthropogenic as well as ecological requisites may be applied for IUWM (Wang *et al.* 2018).

However, there is a gap in studies on urban water management, specifically stormwater management, considering integrated models and application of the IoT and AI for accurate assessment of impacts of various drivers, real-time control (RTC) and supervision, which can enable urban stormwater management to be integrated and realistic.

7. WATER QUALITY ASPECTS

Urban planning plays a vital role in protecting the urban water environments (Goonetilleke *et al.* 2005). Structural measures need to be adopted to reduce pollutants in urbanized basins and also the climatic and physical characteristics of the urban watershed area are to be significantly considered (Goonetilleke *et al.* 2005). High density urban development needs to result in a minimum footprint (Goonetilleke *et al.* 2005). Understanding and establishing thresholds between urbanization and water quality is the key driver for urban stormwater quality management (Liu *et al.* 2013).

Dry weather periods and rainfall intensity are significant in affecting Total Suspended Solids (TSS) and Chemical Oxygen Demand (COD) concentrations (Cheong 1991; Chui 1997). However, TSS and COD contamination loads are very much dependent on total precipitation volume (Cheong 1991; Chui 1997). Heavy metals cause huge risks for reuse of stormwater at safe levels (Hatt *et al.* 2007). Chloride retention quantification and release is significant in influencing the water quality of stormwater management ponds (SWMPs) (Lam *et al.* 2020). Adsorbents at low cost can be considered as a viable option for treating urban stormwater (Deng 2020).

The regionalization of control factors of runoff, limits and treatment needs to be adapted for BMPs of stormwater (Bell *et al.* 2020). Green roof systems are one of the effective mechanisms for maintaining urban stormwater quality (Beecham & Razzaghmanesh 2015).

Fundamental principles need to be followed to develop enhancing techniques for urban stormwater quality (Davis *et al.* 2010). The development of innovative technologies or revival of prevailing technologies is vital for receiving, treatment and conservation of stormwater (Hatt *et al.* 2006). If these measures are not implemented, stormwater reuse becomes nominal and the setting of design standards is needed for efficient treatment of stormwater (Hatt *et al.* 2006).

However, there is a continuing knowledge gap on developing tools for realistic assessment of the impacts of water quality on the receiving waters which can further affect urban stormwater management. Also, trend analysis of parameters associated with water quality due to continued urbanization has not been carried in much detail. Furthermore, an integrated modelling approach has not been applied for urban water quality management due to continued urbanization, climate change, and land use changes.

8. SUSTAINABLE URBAN DRAINAGE SYSTEMS (SUDS/SuDS)

There have been various emerging studies carried on sustainable drainage in urban areas (Zhou 2014).

SuDS/SUDS may be applied to improve planning and the decision-making process in urban environments (Fryd *et al.* 2010). There needs to be vision on aims, standards and practices and firmness on funds and adaptation aspects for SUDS realization (Ellis & Lundy 2016). Guidelines for design and targets for accomplishment are vital for the triumphant adaptation of LID practices for tropical urban areas to have uniformity in terms of design and monitoring of performance (Lim & Lu 2016). Also, the performance of the features of design during extreme environments needs to be revised with relevant design guidelines to adapt to the predicted climate change aspects (Lim & Lu 2016).

Key insights such as sustainability, resilience and consistency of urban drainage need to be described and calculated to evaluate robustness during large uncertainty for gray, green and hybrid methods to improve the capacity of systems (Casal-Campos *et al.* 2018). RTC and green technologies need to be integrated for UDS for management of urban water at optimum levels (Altobelli *et al.* 2020). Real-time controlled actuators are to be applied to find precipitation trends which may act as a smart in-line storage system (Kändler *et al.* 2020).

There is a framework for design of UDS to improve system efficiency of optimization to make practicable solutions (Kwon *et al.* 2020; Lin *et al.* 2020). An integrated framework as the decision support system may be adapted for urban stormwater at the community level (Hager *et al.* 2021). The framework such as the One-Water approach may be considered with most fitting strategies of LID, conventional infrastructure and stormwater reuse approaches with integration of stochastic aspects, impacts of climate change and fuzzy clustering analysis for sustainable and resilient stormwater management (Hager *et al.* 2021).

However, there is a gap in the practice of SUDS operation and maintenance, awareness of interface with other water bodies, and interpretation of organizational obstacles towards SUDS implementations. Thus, there is a need to study SUDS with regard to execution as an integrated modelling approach for urban stormwater management in much more detail and find mechanisms for overcoming barriers associated with them.

Table 2 summarizes the research on various management aspects/practices for integrated urban water including stormwater management.

9. REUSE AND TREATMENT WITH MANAGEMENT ASPECTS

Urban stormwater reuse is one of the most significant methods to alleviate scarcity of water resources. The need for stormwater reuse has been progressively vital with the increase in the predominant population which is causes more water stress. Stormwater reuse can also reduce the degradation of urban water as the decrease of volume of urban stormwater discharge follows. However, at present, an important impediment to extensive execution of stormwater reuse is the lack of techniques and approaches that can afford water for various requirements such as irrigation, gardening, commercial and industrial activities.

There have been numerous research studies outlining various stormwater reuse schemes for sustainable and/or resilient urban stormwater management including 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 measures and framework have been recommended by Ellis *et al.* (2008), Coutts *et al.* (2010), Saraswat *et al.* (2016), Webber *et al.* (2018), Mishra & Arya (2020), Mishra *et al.* (2020) for urban stormwater management, considering various scenarios with climate change effects.

The rational methods for stormwater advanced design methods have constraints to address complexities of urban catchments, variations in rainfall in terms of spatial and temporal characteristics and changes in precipitation processes (Coombes *et al.* 2015).

Appropriate spatial and temporal resolutions of models need to be chosen to characterize the cumulative outcomes of minute scale processes for bigger scale watersheds (Rodak *et al.* 2020).

Stormwater resilience concepts can be applied for sustainable stormwater management (Rodina 2019; Wang & Roon 2020).

Stormwater reuse has to be applied with emphasis on 'water that is fit for purpose' (Muirhead 2008; Gogate & Raval 2015; Goonetilleke *et al.* 2017; Maneewan & Roon 2017). Stormwater reuse requires tailor-made prevailing methods and utilization of approaches to fit the given conditions (Muirhead 2008; Gogate & Raval 2015; Goonetilleke *et al.* 2017; Maneewan & Roon 2017).

Multicriteria stormwater management policies and methods need to be adapted as solutions for flooding, erosion and water quality (McCuen & Moglen 1988). Levels of acceptance of pollution risk to set standards for treatment of stormwater need to be defined (Chouli 2006). Use of source control techniques and collaboration of various stakeholders can substantially decrease the expenditure for stormwater management (Chouli 2006).

Management of contaminated stormwater needs to have solutions that can maintain rigorous economic and environmental prerequisites (Pétavy *et al.* 2007).

Local variations in site attributes, ecological parameters, and soil conditions will affect the availability, category, and efficacy of LID choices for a particular site (Montazerolhodjah 2019).

LID techniques were found to be efficient in attenuating the adverse effects of hydrology due to any type of urbanization (Zimmer *et al.* 2007). LID techniques such as vegetative swales, rain barrels, infiltration trenches, and bioretention cells were found to give the best outcomes that could completely remove all contaminants (Trajkovic *et al.* 2020).

The choice of control technologies has to be affected by realistic data and the relevance of every control technology for catchment conditions to establish sustainable stormwater management (Pitt & Clark 2008).

There are various innovative methods for efficient stormwater management such as wet lands, reuse, collection, storage and distribution (Madison & Emond 2008). 'Green Gully', is a novel stormwater quality improvement mechanism that collects, purifies, and reuses stormwater throughout an automated system (Begum & Rasul 2009). Green infrastructure with rain gardens may be vital for urban environments to enhance resilience to climate change impacts such as recurrent stormwater; it also improves biodiversity and shields the landscape (Ishimatsu *et al.* 2017).

Porous and permeable pavements can be utilized for stormwater reuse as part of sustainable and resilient stormwater management (Beecham *et al.* 2010). Permeable pavements which contain chosen basecourse aggregates may generally develop a water quality that is sufficient for reuse for irrigation (Kazemi & Hill 2015). Permeable pavements and geothermal (geoexchange) systems use in combination for application in built-up areas checks and decreases the flooding and contamination of water and also reduces expenditure on energy with the use of a green source of energy that includes numerous environmental profits (Maharaj & Scholz 2010).

Stormwater reuse for potable purposes has to address the important impacts on society, the economy and finding sites for storage and treatment and the acceptance by the community for drinking stormwater after treatment (McArdle *et al.* 2011). The community participatory approach with the application of a Water Sensitive Design Framework is vital for a green-blue infrastructure at every stage of planning (Marino *et al.* 2018).

There are various WSUD criteria for sustainable and resilient stormwater management such as improving water quality, reducing peak flows and flood risk, and maximizing water reuse (Lariyah *et al.* 2011).

Stormwater reuse may give savings of potable water to the extent of 36% of the annual average household demand of potable water (Jenkins *et al.* 2012).

Decentralized facilities can offer more flexibility and high adaptation capacity for WSUD to adapt to climate change effects (Siekmann & Siekmann 2015).

Reverse osmosis (RO) or ultraviolet (UV) light processes need to be applied for potable reuse systems to remove *N*-nitrosomorpholine (NMOR) to comply with regulatory guidelines (Glover *et al.* 2019).

E^2STORMED, a decision support tool with energetic and environmental criteria can be applied for the analysis of stormwater management impacts on urban environment fields such as water supply, treatment of wastewater, management of urban energy and urban planning (Morales Torres *et al.* 2016).

The advance of sustainable stormwater management systems is an enhancing established approach that unites various methods for BMPs to accumulate, store, treat,and transmit stormwater for harvest and reuse, thus increasing the numerous value of stormwater (Ding 2017). Risk management, financial appraisal and funding criteria for stormwater reuse need to be studied for comparison and prioritization of stormwater reuse (Furlong *et al.* 2017).

Integrated Spatial Decision Support Systems (SDSS) may be applied for runoff reduction (Rufino *et al.* 2018). A framework with approaches for strategic surface water management monitoring may be applied to augment decision support in cities (Webber *et al.* 2019).

Green Stormwater Infrastructure (GSI) project optimization needs to be carried for reuse of stormwater after treatment considering the systems such as catch basins, dry well chambers, wet lands, cisterns, permeable surfaces, rain gardens and bioswales for sustainable and resilient stormwater management (Sadeghi *et al.* 2018).

WSUD and BMP are effective and efficient to remove fecal indicators and pathogens (Ahmed *et al.* 2019). Microbial risk will be the significant severe risk for stormwater reuse with waterborne pathogens risk. Various categories of WSUD and BMPs are able to decrease microbial pollution, but there remains a knowledge gap on the functioning of these treatment obstacles. Chemical risks may be the drivers of health aspect and relationships among multi-contaminant disclosures must be investigated (Ahmed *et al.* 2019).

Biofilters have the potential application to treat greywater and reuse (Hatt *et al.* 2007; Jung *et al.* 2019). RTC strategies with validation techniques for biofilters for efficient water quality to harvest and reuse through long term experimentation may be applied and it has been found that nutrient and sediment removal was high with RTC (Shen *et al.* 2019).

Different sorbents may be used at varied concentrations for efficient urban stormwater quality management (Valentukevičienė & Najafabadi 2020). Use of a hemp sorbent is more efficient for treating water and decreasing pH, turbidity, colour, and conductivity (Valentukevičienė & Najafabadi 2020).

Membranes are in wide use for integrated processes for high quality reclaimed water development to aid safe water reuse (Kog 2020; Zhang *et al.* 2020a). Bioswales and wet swales need to be considered as options for stormwater control (Ekka *et al.* 2020). Grass swales with check dams or infiltration swales are effective for runoff attenuation, and sediment and heavy metal removal (Ekka *et al.* 2020). Treated wastewater reuse from wetlands may be provided for irrigation purposes that can meet quality standards (Tuttolomondo *et al.* 2020; Zabłocka & Capodaglio 2020).

Removal of organic matter, heavy metals (especially copper), and control of bacteria growth must be the significant treatment methods for reduction of toxicity (Zhan *et al.* 2020).

Biochar is capable of the removal of the *Escherichia coli (E. coli)* and thus for urban stormwater quality management (Valenca *et al.* 2021).

Table 3 presents a list of various studies carried out on numerous stormwater reuse and treatment measures and/or practices for efficient integrated urban stormwater management.

However, there is a knowledge gap on detailed integrated study related to efficient stormwater reuse for potable purposes after treatment on a large scale, which is the significant requirement of urban areas. Also, the proportion of stormwater for reuse with and without treatment for specific purposes needs to be studied in much more detail. Figures 1 and 2 present and describe integrated urban stormwater management processes that need to be adapted with real-time governance. Various drivers such as climate change that impact the assessment, water quality, reuse and treatment are to be taken into account for efficient and optimal outcomes.

Urban hydrology characteristics are to be studied as an integrated study, considering the impacts of climate change, flow characteristics and water quality assessment (Figure 1). If water quality is fit for use, then water may be reused, otherwise water needs to be treated (Figure 2). If flows exceed peak flows in urban environments, then any suitable sustainable and/or resilient measures and/or practices such as LID, BMP, SUDS, WSUD and SCP are to be adapted. If flows do not exceed peak flows, then they may be discharged into water bodies in the vicinity after treatment (Figure 2).

Table 4 describes various key drivers of integrated urban stormwater management to develop to be efficient, sustainable and resilient.

10. CRITICAL REMARKS

There is a need for standardization of measures and practices for integrated stormwater management that should consist of innovative technologies, climate change impact assessment, and uncertainty analysis associated with prevailing aspects, as water resources are becoming scarce day by day due to poor management rather than availability. Also, it is necessary to treat and reuse available stormwater with sustainable and resilient management adaptations for various requirements such as irrigation and potable purposes on a large scale. For climate change impact studies on urban stormwater runoff and its efficient management, appropriate trend analysis needs to be performed with modifications specific to the region. Small magnitude and more frequent rainfall events need to be considered for the accurate and realistic assessment of governing flows in urban areas. Also, standardized performance assessment methods are very much needed for total urban stormwater management. Catchment-specific evaluations of flow changes due to urbanization are required. Real-time monitoring mechanisms such as IoT, AI and ML are to be applied for accurate, realistic and more efficient urban stormwater management.

Various researchers have worked on different aspects of stormwater management specific to the urban regions. However, still there is further scope to carry out research on innovative measures and practices for stormwater management as an integrated part of urban water management, which needs to be sustainable and resilient as water resources are under stress when fulfilling exponentially growing urban water requirements. The following section describes various research needs for integrated urban stormwater management.

11. FUTURE SCOPE OF WORK/RESEARCH NEEDS

Based on the literature review presented above, the following future research needs on urban storm water management may be explored.

Effect of climate change is to be assessed and adaptation actions need to be specific to the region. Uncertainty analysis related to heterogeneous climate change, extreme hydrologic events like floods, land use/cover interventions, treatment, reuse and economic factors is to be performed. Key drivers and their influencing mechanism for urban stormwater management needs to be considered. Assessment of models is to be performed with realistic, continuous and long-term data. Monitoring and maintenance of the systems are to be carried with real-time application technologies such as the IoT, AI and ML for real-time monitoring, and control of water quantity and water quality, and for accurate assessment of climate change impacts and land use/land cover interventions. The reuse of stormwater needs to be analyzed with the intent of potable use on a large scale to provide for the various needs of urban areas. The role of stormwater for reuse with or without treatment for specific purposes needs to be studied.

12. CONCLUSIONS

From the present study on review of urban stormwater management, the following points are the various conclusions

- Characteristics of urban hydrology need to be studied in much detail with regard to spatial and temporal variations especially for better interpretation of precipitation.
- Trends of precipitation due to land-use variability have to be evaluated with realistic and long-term data.
- Determination of rainfall–runoff relationships is vital and needs to be established as specific to the region of study and considering all key drivers that can impact urban hydrology and further urban stormwater management.
- There remain barriers to understanding peak flows due to lack of interpretation of urban hydrologic indicators and lack of accurate assessments of various impacts of urbanization.
- The integrated urban hydrologic models need to be *assessed accurately for associated uncertainty*.
- Various stormwater reuse methods *as a resource* for various purposes to urban areas need to be examined further, as an emerging research area, which can enhance sustainable and resilient measures for integrated urban stormwater management.
- The impact of climate change on precipitation in urban environments is a significantly increasing issue that needs to be assessed *specific to the region* as a matter of urgent concern to better interpret urban rainfall varying patterns.
- Development and application of accurate regional specific climate models that are realistic need to be undertaken for efficient integrated urban stormwater management systems.
- Real-time monitoring of governing parameters of climate and the assessment of the impact of climate change on the regional scale need to be carried out.
- Periodical supervision and monitoring of standards and guidelines for various measures and practices for stormwater management to verify their adequacy is essential. If found to be not meeting the present climatic, land-use and other impacting conditions, design standards and guidelines are to be amended accordingly.
- Selection of appropriate sustainable and resilient measures and practices that are further cost effective is the key for successful implementation of stomwater management in urban environments.
- Identification and implementation mechanisms of key drivers in a holistic manner plays a significant role for efficient urban stormwater management.
- Application of the Internet of Things (IoT), Artificial Intelligence (AI) and Machine Learning (ML) techniques are needed to develop urban stormwater management to be more sustainable, resilient and to the next level.
- Real-time governance needs to be adapted for accurate and efficient urban stormwater management.

ADDITIONAL INFORMATION

Data Availability Statement – No data were used or generated

CONFLICT OF INTEREST STATEMENT

The authors declare that they are not affiliated with or involved with any organization or entity with any financial interest or non-financial interest in the subject matter or materials discussed in this paper.

DATA AVAILABILITY STATEMENT

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

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