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The Potential of Stormwater Management Strategies and Artificial Intelligence Modeling Tools to Improve Water Quality: A Review

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Abstract
Stormwater management modeling tools have been utilized to enhance stormwater operating systems, assess modeling system efficiency, and evaluate the impacts of urban growth on stormwater runoff and water quality. This review explores the potential of stormwater management strategies and Artificial Intelligence modeling tools in enhancing water quality. The study focuses on evaluating stormwater modeling tools for planning and improving stormwater systems, assessing modeling efficiency, and understanding the impacts of new development on stormwater runoff and water quality. Various stormwater modeling tools are compared to aid in water management in urban and rural settings, which is crucial due to increasing storm intensity from climate change. The review debates the advantages and limitations of different modeling tools, particularly in modeling stormwater quantity and quality under different scenarios. It also examines tools used for predicting and analysing stormwater runoff during storm events in diverse locations. The assessment of modeling tools is centred on their support for Green Infrastructure (GI) practices, considering factors like modeling accuracy, data availability, and requirements. The study highlights the importance of these tools in managing water in urban areas and safeguarding water sources during stormwater events. Notably, the accuracy and efficacy of stormwater modeling tools are influenced by input data quality, calibration methods, and standardization metrics, with the widely used Stormwater Management Model (SWMM) being a common modeling tool.

Keywords Stormwater management · Modeling tools · Climate change · Green infrastructure

1 Introduction

Stormwater runoff is produced when rainwater flows over surfaces such as pavements and rooftops (Ghashghaie et al. 2022). During its occurrence, it collects different pollutants in its path and transports them into water bodies (Booth et al. 2002). The tendency of runoff

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to pick up contaminants, including sediment, chemicals, nutrients, heavy metals, and bacteria, from urban landscapes, construction sites, and agricultural regions is the root of the link between stormwater runoff and water pollution (Molla et al. 2022; Rabiei et al. 2022). Traditional ways of managing stormwater focus on controlling how much water flows but do not consider water quality. Green Infrastructure (GI) is a conventional stormwater management strategy that uses natural environments such as gardens, bio-swales, and pavements that allow water to flow through to manage rainwater (Javadinejad et al. 2019a; Haris et al. 2016).

Rodak et al. (2020) affirmed that detention and retention basins can be used as an alternative approach to stormwater management. These basins hold excess water from runoff for a short time, allowing pollutants to settle down for a moment at the bottom. The primary purpose of infiltration systems is to purify contaminated rainwater, which is regarded as a stormwater management approach (Nafchi et al. 2022; Jayasooriya and Ng 2014). Infiltration systems use sand and other materials to remove pollutants and other harmful contaminants before water enters lakes or rivers. Other practices that offer the best management for preventing stormwater pollution are called Best Management Practices (BMPs). These include cleaning streets, maintaining drains in good condition, and educating people on how to be more environmentally friendly (Mao et al. 2017).

The novelty of the review lies in its emphasis on addressing the limitations of traditional stormwater management practices by emphasizing the importance of water quality alongside quantity control. While conventional methods primarily control the flow of stormwater, they often overlook the crucial aspect of water quality. By highlighting the significance of GIs, which utilize natural elements like gardens, bio-swales, and permeable pavements to facilitate the flow of rainwater, this study contributes to a more holistic approach to stormwater management. Previous studies have identified a gap in stormwater management strategies, emphasizing the need to shift from solely managing water flow to considering the impact on water quality and ecosystems (Nafchi et al. 2022; Goulden et al. 2018). The study's emphasis on GI as a solution aligns with the evolving objectives in stormwater management, moving towards practices that not only manage stormwater but also enhance water quality and support ecosystems.

The application of AI modeling tools can help in the management of stormwater and contribute to improved water quality (Javadinejad et al. 2019b). These tools utilize computer programs that analyse vast amounts of information to model, differentiate situations, and make better decisions. AI tools can help predict stormwater flow and water quality. They require both old and new data to make these predictions. AI optimizes BMPs as a modeling tool to help decide where and how to construct stormwater management structures using information about land, rain, and pollution (Jeon et al. 2018).

Continuous water quality monitoring, including pollution concentration, pH levels, dissolved oxygen, and turbidity, can be achieved through AI-based sensors (Yang et al. 2019). This information can be used to understand how well current methods control rainwater runoff and to identify areas where improvements are needed. Decision support systems (DSS) are software applications that help users decide on water quality and quantity management. AI stormwater modeling tools can be used to develop DSS to predict the effects of different management approaches and assist users in choosing the best way to improve water quality (Gao et al. 2015).

Stormwater runoff modeling includes the simulation and prediction of the dynamics of water runoff throughout rainfall outbreaks (Jehanzaib et al. 2022). In urban locations, stormwater management constitutes a significant part of the abundance of impervious surfaces, including roads, pavements, and roofs, which preclude the natural infiltration of precipitation into the ground. Consequently, precipitation is redirected into stormwater management systems, which tend to become flooded during severe rainstorms, resulting in flooding, land degradation, and water purity degradation.

The analysis of stormwater quality in urban environments involves the application of mathematical models that enable the projection of the volume and characteristics of stormwater discharge stemming from a designated zone (Jayasooriya and Ng 2014). The stormwater runoff models employed in previous studies were based on fundamental physical principles, namely, the principles of conservation of mass and energy (Rodak et al. 2020). Examples of stormwater modeling tools include hydrological, hydraulic, and water quality models. These models accommodate a spectrum of essential factors such as land utilization, soil classification, degree of inclination, precipitation volume and intensity, and stormwater system attributes.

This study addresses a gap in existing research by proposing the integration of AI-based sensors with real-time control systems for dynamic stormwater management. While previous studies emphasize AI's role in analysis and planning, this study explores using deep learning algorithms to adjust stormwater infrastructure components in real-time based on sensor data. By enabling a responsive system that adapts to changing weather conditions, this approach aims to revolutionize stormwater management, moving away from static strategies towards dynamic, performance-optimized solutions. The novelty lies in leveraging AI for real-time control, offering a transformative perspective on stormwater management practices.

The main goals associated with stormwater modeling in urban areas include advancing the design and functionality of stormwater infrastructure, detecting regions with elevated potential for flooding, and evaluating the impact of urbanization on water quality and the health of aquatic ecosystems (Renouf et al. 2017). The acquisition of this information is of paramount significance in formulating efficacious strategies for managing stormwater (Rehman et al. 2019). These plans can effectively mitigate the negative repercussions of urbanization on the natural water cycle and safeguard public health and safety.

The use of mathematical and computational models to simulate water dynamics within a floodplain during a flood event is commonly identified as floodplain modeling (Neal et al. 2012). The core objective of floodplain modeling is to provide precise and dependable projections of flood inundation, water velocity, and other pertinent variables. These projections are commonly used to assess flood risks, develop mitigation strategies, and facilitate informed emergency management policies (Rehman et al. 2019).

Stormwater management models can be used to design and optimize stormwater operating systems, estimate the effectiveness of the systems, and assess the implicit impacts of new developments on stormwater runoff and water quality. These models are valuable tools for planners, masterminds, and policymakers working to cover the terrain and ensure the sustainability of water quality.

The novelty of the review lies in the integration of mathematical and computational models for floodplain modeling with stormwater management strategies. While floodplain modeling traditionally focuses on flood inundation projections and risk assessment, this study bridges the gap by applying similar modeling techniques to optimize stormwater operating systems and evaluate their impact on water quality (Neal et al. 2012; Rehman et al. 2019). By employing stormwater management models to design efficient systems, estimate effectiveness, and assess the implications of new developments on stormwater runoff and water quality, this study offers a comprehensive approach to sustainable water quality management. This innovative application of modeling tools not only enhances

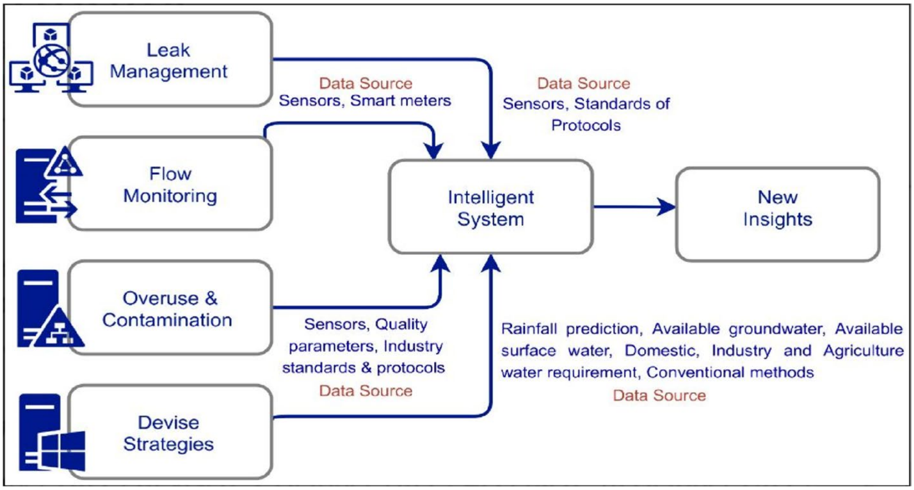


Fig. 1 Overview diagram of stormwater management with AI modeling tools (Krishnan et al. 2022)

stormwater management practices but also contributes to informed decision-making for policymakers and planners in ensuring water quality sustainability (Fig. 1).

2 Types of Stormwater Modeling

Stormwater operation models are computer programs designed to predict and simulate stormwater runoff in each area (Wanielista and Yousef 1992). These models are used to assess the impacts of stormwater runoff on terrain and to design stormwater operation systems that can effectively control and treat stormwater runoff. There are multiple distinctive stormwater operation models, each with unique features and capabilities. Standard stormwater operation models include hydrologic, hydraulic, water quality, and combined seamster overflow models (Ahyerre et al. 1998).

Two fundamental urban stormwater models are the rainfall–runoff model and the transport modeling approach (Haris et al. 2016). Rainfall-runoff modeling is related to the generation of surface and sub-surface runoff due to precipitation, coupled with the erosion of pollutants from the previous surface and the accumulation of impurities from impervious surfaces (Wanielista and Yousef 1992). Transport modeling involves the analysis of the movement of flows and contaminants within the stormwater infrastructure, which may comprise various components such as storage, open channels, and pipe networks.

Stormwater modeling involves the utilization of mathematical and computerized tools to simulate the hydrological behaviour of rainfall in urban drainage systems, both during and after precipitation events. Several stormwater modeling types exist, including hydraulic and hydrologic modeling, water quality modeling, floodplain modeling, green infrastructure modeling, and climate change modeling (Garcia-Cuerva et al. 2018).

2.1 Hydraulic/Hydrologic Modeling

Hydrologic models predict water movement through a drainage receptacle by considering factors such as rush, evaporation, infiltration, and runoff (Devia et al. 2015). Hydraulic models predict the water inflow through a drainage system by considering factors like pipe sizes, pitches, and obstructions (Rodríguez et al. 2012). The use of hydraulic models aids in the determination of water levels and flow rates within a given system. It allows for evaluating the efficacy of a range of stormwater management tactics.

2.2 Water Quality Modeling

Water quality models predict the flow and transportation of pollutants in stormwater runoff, considering factors such as the chemical and physical parcels of the contaminants and the entering water body (Devia et al. 2015). This type of modeling is used to predict the concentration of pollutants in stormwater runoff. It considers the sources and types of contaminants and the transport and fate of these pollutants in the drainage system. Combined seamster overflow models forecast the action of integrated seamster systems, which collect both stormwater and sewage in the same pipe and are designed to help overflow and minimize the impacts of these overflows on the terrain (Rodak et al. 2020).

2.3 Floodplain Modeling

Floodplain modeling creates computer simulations of how water behaves in areas prone to flooding (Devia et al. 2015). This model is used to assess flood tide threats, estimate the effectiveness of flood tide mitigation measures, and plan for exigency response in the event of a flood tide (Chomba et al. 2021). Floodplain modeling aims to anticipate the potential possibility and magnitude of inundation in the wake of a rainfall episode. This inquiry considers the watershed's morphology and attributes alongside the draining mechanism's ability and tendencies (Bulti and Abebe 2020).

2.4 Green Infrastructure Modeling

The concept of green infrastructure modeling entails the application of computational modeling approaches and methods. This method examines and blueprints environmentally friendly and natural infrastructure systems (Jayasooriya and Ng 2014). Yang et al. (2019) identified the use of green infrastructure modeling rainfall–runoff essential to support diverse ecological planning and management endeavours. As an illustration, it has the potential to identify regions where investments in green infrastructure can yield maximal advantages, notably diminishing urban heat islands or enhancing stormwater management. Furthermore, this tool may be employed to evaluate the effects of a range of land utilization scenarios on the provision of ecosystem services, including but not limited to carbon capture and water purity (Jayasooriya and Ng 2014).

2.5 Climate Change Modeling

Climate change modeling is a well-known tool employed to predict the potential impacts of climate variations on the stormwater management system in urban areas (Hijmans and

Graham 2006). This includes predicting significant changes in weather patterns, such as the intensification of rainfall, and analysing the resultant changes in the way of urban stormwater (Edwards 2011). The support presented by managers and engineers in their design procedures improves the application of resilient stormwater management systems (Figs. 2, 3, and 4).

3 Advantages and Disadvantages of Stormwater Modeling Tool

Stormwater modeling software and tools comprehensively describe the conditions and occurrence of stormwater runoff in a precise region (Huber et al. 2016). They analyse how water flows past various considered drainage systems, identify flood regions, and assess the overall performance of stormwater management approaches. These stormwater modeling tools help plan and predict stormwater management infrastructure, such as detention ponds, green roofs, and rain gardens (Haris et al. 2016). By simulating several conditions, designers can evaluate the effectiveness of various strategies and select the most efficient and cost-effective solutions.

Stormwater modeling software is a valuable predictive tool for foreseeing flood events by simulating precipitation patterns, surface runoff dynamics, and hydraulic flow within drainage systems (Kaykhosravi et al. 2018). This predictive capability, in turn, facilitates the formulation of complete flood mitigation strategies and allows the development of

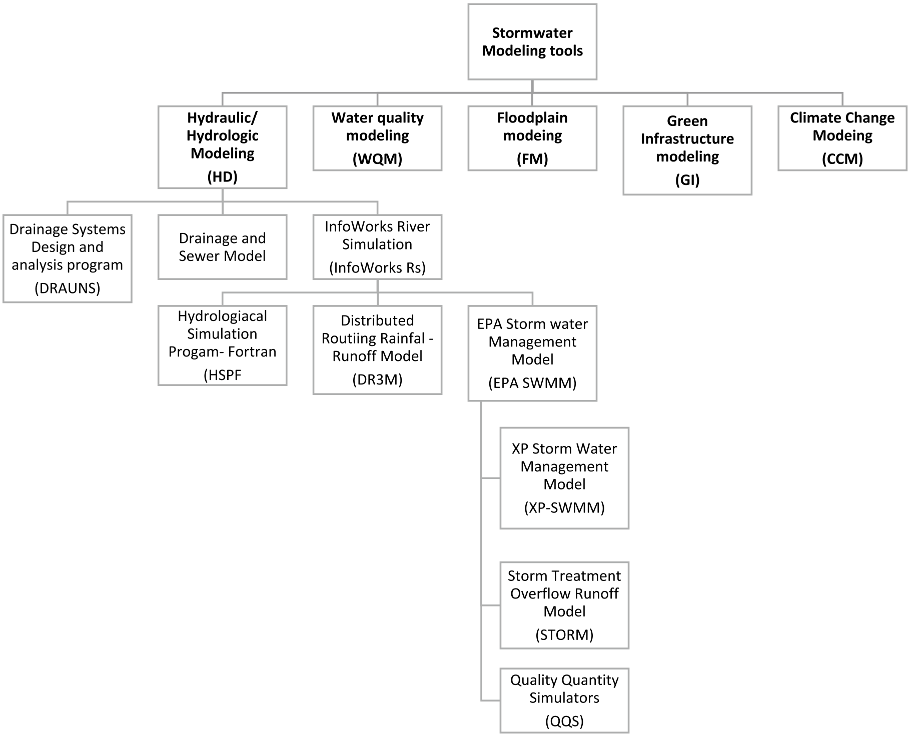


Fig. 2 Classification of Stormwater modeling tools (Haris et al. 2016)

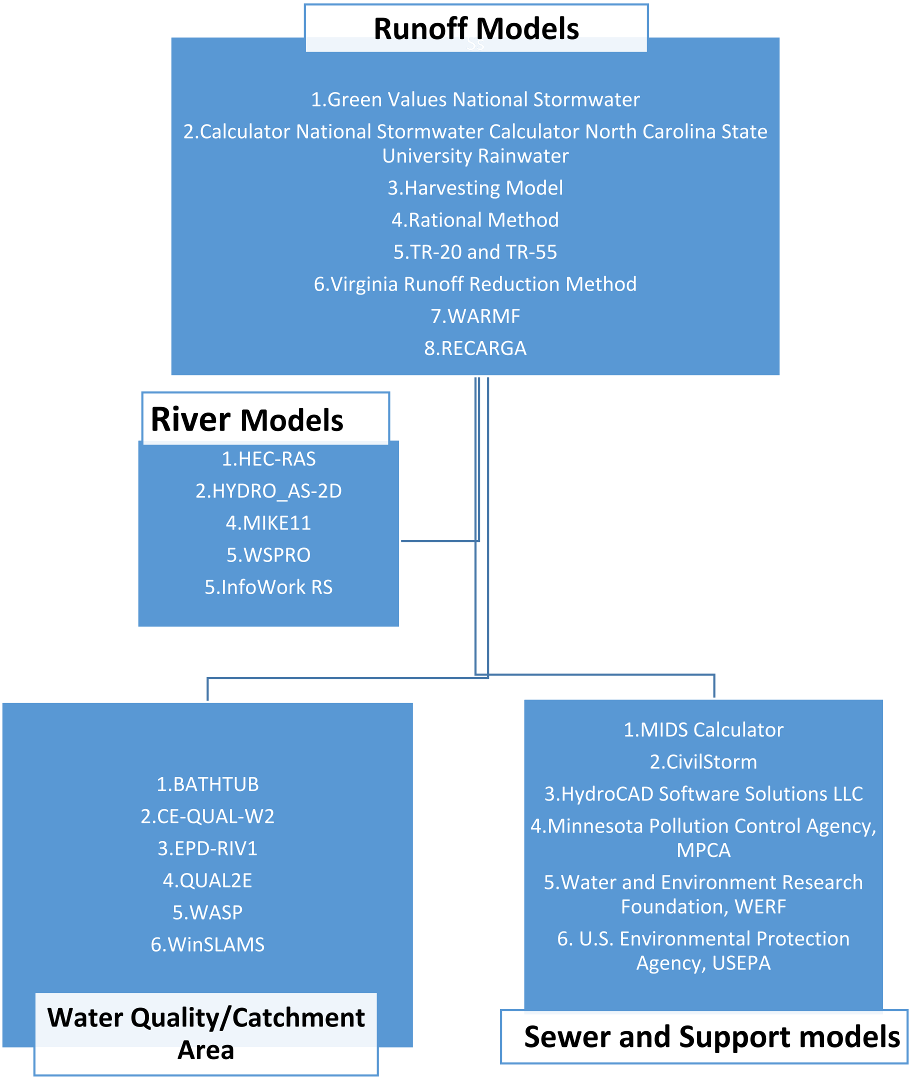
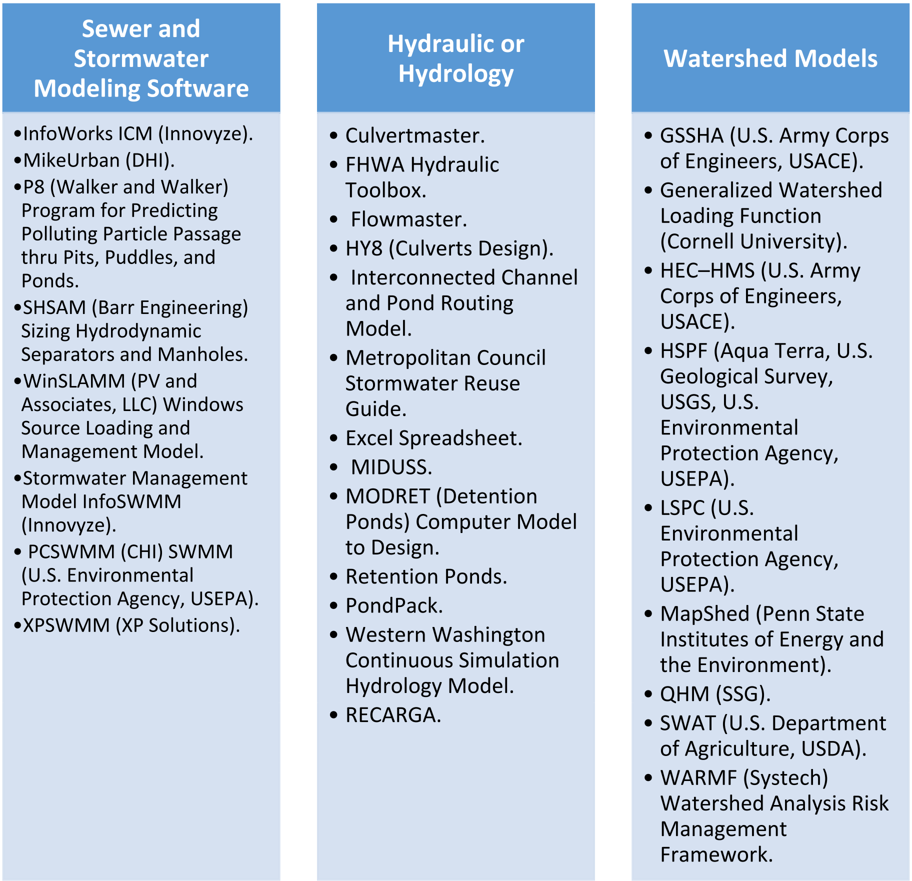


Fig. 3 Classification of Stormwater Modeling tools according to their types and Agency Support

effective emergency response plans. Furthermore, the use of stormwater modeling tools extends beyond flood prediction, including a necessary function in evaluating the ecological repercussions of developing initiatives on water quality, aquatic ecosystems, and different surface water reservoirs such as dams, rivers, and lakes (Jalaei and Jrade 2014). This complex modeling approach is essential to ensure informed decision-making procedures and implement well-suited mitigation practices.

Accurate modeling necessitates a significant quantity of data input, as Kumari et al. (2018) state, comprising topographic information, land-use datasets, rainfall datasets, and hydraulic properties of drainage infrastructure. Collecting and processing this data on a model can require more time and is expensive. It must be noted that the accuracy



Sewer and Stormwater Modeling Software

- InfoWorks ICM (Innovyze).
- MikeUrban (DHI).
- P8 (Walker and Walker) Program for Predicting Polluting Particle Passage thru Pits, Puddles, and Ponds.
- SHSAM (Barr Engineering) Sizing Hydrodynamic Separators and Manholes.
- WinSLAMM (PV and Associates, LLC) Windows Source Loading and Management Model.
- Stormwater Management Model InfoSWMM (Innovyze).
- PCSWMM (CHI) SWMM (U.S. Environmental Protection Agency, USEPA).
- XPSWMM (XP Solutions).

Hydraulic or Hydrology

- Culvertmaster.
- FHWA Hydraulic Toolbox.
- Flowmaster.
- HY8 (Culverts Design).
- Interconnected Channel and Pond Routing Model.
- Metropolitan Council Stormwater Reuse Guide.
- Excel Spreadsheet.
- MIDUSS.
- MODRET (Detention Ponds) Computer Model to Design.
- Retention Ponds.
- PondPack.
- Western Washington Continuous Simulation Hydrology Model.
- RECARGA.

Watershed Models

- GSSHA (U.S. Army Corps of Engineers, USACE).
- Generalized Watershed Loading Function (Cornell University).
- HEC–HMS (U.S. Army Corps of Engineers, USACE).
- HSPF (Aqua Terra, U.S. Geological Survey, USGS, U.S. Environmental Protection Agency, USEPA).
- LSPC (U.S. Environmental Protection Agency, USEPA).
- MapShed (Penn State Institutes of Energy and the Environment).
- QHM (SSG).
- SWAT (U.S. Department of Agriculture, USDA).
- WARMF (Systech) Watershed Analysis Risk Management Framework.

Fig. 4 Classification of Stormwater modeling tools according to their types (Jayasooriya and Ng 2014)

of the modeling tool relies on the quality of the input dataset and the validity of original predictions. Stormwater modeling tools produce helpful insights into stormwater management and risk assessment of flooding, as revealed by (Tuler et al. 2016). Still, they should be combined with other information sources and professional opinions to make informed decisions (Table 1).

4 Application of Stormwater Modeling Software that Models the Quantity and Quality of Stormwater Runoff

In recent years, there has been a significant advancement in utilizing data-driven models, artificial intelligence (AI), and machine learning (ML) based on satellite images and remote sensing for modeling water quality and quantity. Artificial neural networks (ANN), together with support vector machines (SVM), have been utilized by researchers to make precise predictions about water quality parameters using AI and ML techniques (Meshram et al. 2020; Krishnan et al. 2022. These models enable proactive planning for water resource

Table 1 Application of stormwater modeling tools and their advantages and disadvantages

	Application	Advantage	Disadvantage	Reference
Hydraulic/ hydrologic modeling	• Flood risk assessment. • Water resource management. • Stormwater management. • Dam safety analysis.	• It can be used to predict the potential impacts of floods. • It helps identify areas at risk of flooding, evaluate flood control measures, and develop emergency response plans. • Assess the effects of water withdrawals, evaluate water supply and demand, and optimize water allocation. • Helps evaluate the effectiveness of stormwater management systems in controlling stormwater runoff and reducing the risk of flooding.	• Models are complex and timeconsuming processes. • It relies on the quality and quantity of input data. • Modeling can be expensive in both terms of obtaining data and model execution. • We need continuing maintenance and updates to remain accurate and relevant.	(Akram et al. 2014; Haris et al. 2016; Palla et al. 2008)
Water Quality Modeling	• Management of drinking water supplies. • Management of wastewater treatment plants.	• It is commonly used to predict the impact of various human activities on water quality. • Identify sources of pollution and inform management strategies to protect and improve water quality. • It helps classify sources of pollutants upstream of the treatment system.	• Requires many data. • They are overly complex, and their accuracy relies on several assumptions. • Has limited spatial and temporal resolution. • It is not easy to interpret. • Limited in their ability to predict extreme events such as floods or droughts.	(Akram et al. 2014; Jayasooriya and Ng 2014; Rodak et al. 2020)
Climate change modeling	• Assessing the impacts of climate change • Mitigating greenhouse gas emissions • Planning for climate change. • Developing climate adaptation strategies.	• Predicts the impacts of climate change on water resources. • It helps identify the most effective strategies for reducing greenhouse gas emissions. • Informs long-term planning decisions for resource management.	• Based on many assumptions about how the Earth's climate system works. • It is highly complex and requires a lot of computing power to run. • Many details and calculations are made. • Models have limited scope.	(Edwards 2011; Hijmans and Graham 2006; Leavesley 1994)
Green infrastructure modeling	• Stormwater control. • Runoff reduction and flood alleviation. • Urban Landscape Analysis Tool.	• Enables users to assess the benefits and costs of different green infrastructure options for managing stormwater runoff. • Analyses the distribution and potential impacts of diverse types of green infrastructure.	• Depending on the precise and informed geospatial data. • Typically, it requires specific software, computational resources, and expertise. • Based on existing conditions and predictions about future needs.	(Jayasooriya and Ng 2014; Yang et al. 2019)

Table 1 (continued)

	Application	Advantage	Disadvantage	Reference
Floodplain modeling	• Flood risk assessment. • Floodplain mapping. • Floodplain management. • Emergency response planning.	• It can be used to assess the chances of flooding and the potential damage that could be caused in different areas. • Helps develop and evaluate different flood management strategies. • Floodplain models can be used to create detailed maps of flood-prone sites.	• The accuracy of floodplain modeling relies on the quality and accessibility of data. • It is an overly complex technical process that requires specified knowledge and abilities. • Based on several assumptions. • Building and maintaining floodplain models can be costly.	(Bulti and Abebe 2020; Chomba et al. 2021)

management, real-time monitoring, and informed decision-making. The integration of ML algorithms into decision support systems has improved water quality assessment, offering automation, efficiency, and enhanced accuracy in evaluating water quality for sustainable water management practices and environmental conservation.

There are several accessible stormwater modeling software that can be used to address the quantity of stormwater runoff. The trend of land use changes is significantly influencing the development of stormwater modeling, as evidenced by recent research findings. Studies highlight the critical impact of urbanization and climate change on hydrological processes, emphasizing the need for accurate modeling procedures to reflect these influences effectively (Fletcher et al. 2013; Stephens et al. 2020; Mensah et al. 2022). The convergence of urban expansion, deteriorating infrastructure, and a changing climate are projected to escalate stormwater pollution and urban flooding risks in the coming decades.

4.1 RECARGA Modeling

GI practices are commonly applied to replicate site improvement settings to reduce stormwater runoff quantity and improve runoff quality (Jayasooriya and Ng 2014). RECARGA is software established to alleviate the negative impact of stormwater runoff capacity on water quality (Sun et al. 2013). Through its application, RECARGA has been shown to have the potential to improve the state of water quality indirectly. Kaykhosravi et al. (2018) revealed that this modeling software can facilitate the simulation of water infiltration in three discrete soil layers with customizable climatic conditions specified by the user. The modeling software can reduce the simulation of water infiltration in three different soil layers, with customized climatic states identified by the user.

Atchison and Severson (2004) stated this to assess stormwater operational competence based on bioretention structures, rain gardens or parks, and infiltration basins. The RECARGA approach uses a temporary disaggregation technique to partition hourly precipitation data into 15-minute intervals to estimate the inflow of bioretention cells, soil moisture content within each stratum, ponding depth, and water balance components (Lisenbee et al. 2021). However, it is noted that the generated outcomes are solely displayed in hourly and aggregate formats.

Scientists used a modeling tool called RECARGA to check how bioretention affects the water balance in a service area by a highway in China. They found out which bioretention settings work best (Gao et al. 2015). As an example, the runoff profile from the green roof SWMM model was utilized as input to the RECARGA model of the bioretention cell, and the runoff from REGARGA was used as input to the detention basin in a study conducted by Kristvik et al. (2019). Sun et al. (2023) used RECARGA to simulate sub-catchment runoff series from 1968 to 1977. The runoff series was modified in the format required by RECARGA based on bioretention cells and sub-catchment characteristics. The water runoff in each bioretention cell was simulated using RECARGA, and the results of RECARGA were used to obtain the outflow series after the treatment of the bioretention cell.

4.2 EPA Stormwater Management Model (EPA-SWMM)

Advanced developments in stormwater management have contributed to the established Stormwater Management Model (SWMM) by the esteemed United States authorities (Rodak et al. 2020). Applying the Environmental Protection Agency (EPA) tool signifies a conventional method researchers use to model and predict the spread of stormwater within urban regions at the watershed level.

Jayasooriya and Ng (2014) stated that the Storm Water Management Model (SWMM) possesses the ability to evaluate the efficiency of several green infrastructure (GI) measures, including but not limited to vegetable swales, infiltration tunnels, street planting containers, rain gardens, green roofs, permeable road surfaces, and rainwater harvesting systems. The Stormwater Management Model (SWMM) is adaptable, extending across a broad spectrum of spatial scales ranging from site-specific applications to synoptic catchment-scale implementations (Paleg and Molnal 2019).

The study conducted by Hasan et al. (2019) employed the Storm Water Management Model (SWMM) to simulate flood events in an urbanized catchment covering approximately 3,978 hectares in Malaysia. Detecting catchment boundaries was performed using digital terrain models from LiDAR data, IKONOS satellite imagery, and on-site verification techniques.

Niyonkuru et al. (2018) studied stormwater runoff in Rwanda's Nyabugogo region, with a catchment area encompassing 1661.3 km^2. The study aimed to evaluate and assess stormwater quantities and floods in Nyabugogo drainage basins by applying EPA SWMM modeling tools for stormwater discharge simulations. Shamsi (2005) suggested two distinct categories of interfaces catering to GIS (Geographic Information System) applications in SWMM. The first interface, termed the input interface, functions as a pre-processor, facilitating the extraction of SWMM input from GIS layers. The second interface, referred to as the output interface, converts textual outputs of SWMM to GIS layers.

Meyer et al. (1993) recommended using a GIS program to prepare data and settings for an SWMM modeling tool that calculates water runoffs. They showed how to use computer programs to show model results on maps. Choi and Ball (2002) utilized GIS software to manage both spatial and non-spatial data and subsequently used the SWMM modeling tool to conduct urban stormwater modeling. The study was conducted in an urban basin covering an area of 463,132.

4.3 Personal Computer Stormwater Management Model (PCSWMM)

PCSWMM is an integrated modeling software capable of simulating the quantity and quality of stormwater runoff in metropolitan regions (Jayasooriya and Ng 2014). This modeling technique can create and assess different stormwater management methodologies. This modeling tool stands out for its versatility in creating and evaluating various stormwater management strategies, offering a comprehensive approach to addressing urban stormwater challenges. Azawi and Sachit (2018) conducted a study to determine the critical variables that depict the possible implementation of surfaces that are penetrable in Al-Huryai City utilizing the PCSWMM computer program and measuring the viability of this procedure on the hydrologic reaction of the case ponder by comparing the reenactment examinations.

Aparicio Uribe et al. (2022) conducted a comprehensive study to explore the impact of site-specific constraints on the efficacy of Urban Green Infrastructure (UGI) in mitigating flood-causing runoff at the watershed scale. Employing a hydrological simulation-based methodology, the research aimed to quantify the runoff reduction potential of UGI strategies using PCSWMM within the context of the Metropolitan Area of San José, Costa Rica. The findings highlighted the significant influence of urban fabric characteristics on the feasibility of UGI implementation, with diverse hydrological performance outcomes observed across various UGI implementation scenarios. Specifically, the study revealed that in residential zones, the implementation of permeable pavement, infiltration trenches, and street planters yielded the most substantial runoff reduction. In contrast, in industrial areas, solely permeable pavements demonstrated the highest efficacy in reducing runoff volumes.

In a recent study by Ben-Daoud et al. (2022), the hydrologic processes within Settat City, Morocco, were investigated with a focus on stormwater runoff generated by urban pavements. The researchers utilized the PCSWMM to simulate the urban hydrological cycle and assess the effectiveness of stormwater management infrastructure for the metropolitan area. The PCSWMM model was employed to evaluate stormwater runoff under four design rainfall events characterized by return periods of 50, 25, 10, and 5 years. This approach enabled the researchers to identify optimal stormwater management solutions for Settat City.

Abduljaleel et al. (2023) employed the PCSWMM modeling tool to simulate the hydrological behaviour of rainwater runoff. Utilizing historical rainfall data and incorporating projections of climate change impacts on future storm patterns, the study aimed to analyse the flow dynamics of rainwater within the studied area. Through the application of PCSWMM, the research quantified the volume of water discharged during storm events, examining both the total runoff and peak flow rates. The study utilized PCSWMM as a methodology to conduct a flood simulation of the Damansara catchment area, building upon the work of Sidek et al. (2021). The results revealed insights into the hydrological response of the catchment area to varying storm intensities. In conclusion, the study demonstrated the utility of PCSWMM in assessing and simulating stormwater dynamics, highlighting its significance in informing effective flood mitigation measures and urban water management practices.

An investigation to analyse the efficacy of SWMM models PCSWMM in a residential catchment area was conducted by Shaneyfelt et al. (2021), both before and after its retrofitting with Low Impact Development (LID) techniques. The results of the study led to the conclusion that all three calibrated pre-retrofit models of the PCSWMM software, the low, middle, and high-resolution models, exhibited a commendable extent of agreement between the observed and simulated outcomes regarding the parameters of runoff volume and peak flow.

The PCSWMM software was utilized to assess the likelihood of the current stormwater system flooding within the premises of Auburn University. The study performed by Molla et al. (2022) employed a PCSWMM methodology that utilizes maximum water velocity mapping to discern geospatial locations characterized by three distinct categories of stormwater flow speed, namely high, medium, and low velocities. The computational tool commonly known as PCSWMM was utilized in the study performed by Akhter and Hewa (2016) to examine the hydrological reactions in the Myponga catchment consequent to alterations in land use and exploring the potential of embracing Water Sensitive Urban Design (WSUD) apparatus, namely bio-retention cells, for storm runoff events.

4.4 Water Balance Model (WBM)

The hydrological modeling software, usually referred to as the Water Balance Model (WBM), is frequently used by scholars and technical writers to examine and understand the distribution and movement of water in small or large quantities within a specific environment or region (Fekete et al. 2006).

Hidayat et al. (2021) investigated WBM's potential effectiveness based on recharge zones by utilizing geographical information systems in compliance with Indonesia's regulatory framework. The study declares that rainfall creates a dynamic and sensitive cause in forming potential recharge zones. There is profound erraticism in the possible recharge areas when using four variables, and this variability can be credited to fluctuations in the yearly precipitation patterns. The validation of the WBM tool presented a level of accuracy with appropriate NSE values ranging from 0.52 to 0.61 and r values falling from 0.76 to 0.87.

4.5 Program for Predicting Polluting Particle Passage Through Pits, Puddles, and Ponds (P8 Urban Catchment Model)

The P8 Urban Catchment Modeling software is designed to predict the passage of rivers of polluting particles through pits, puddles, and ponds. It is a robust stormwater runoff and pollutant transport system for simulating and examining the pollutant movement in urban catchments (Jayasooriya and Ng 2014). It focuses on exploring the details around the transportation and critical disposition of little particle-based pollutants or contaminants within a stormwater management system, such as sediment and its associated contaminants.

P8 Urban Catchment Model software is used to assess design preconditions relating to Green Infrastructure (GI) to attain pollutant elimination of 70-85% for the entirety of suspended solids (Mok et al. 2019). The P8 software has been recognized as the optimal option for conducting the preliminary design of GI practices for catchment-level conceptualization (Jayasooriya and Ng 2014). The runoff modeling algorithms of P8 are founded on several catchment models, including SWMM, STORM, HSPF, and TR-20 (Palmstrom and Walker 1990).

Raine (1999) conducted a study to evaluate a trading initiative's efficacy in mitigating nonpoint phosphorus sources and the phosphorous point source originating from a wastewater treatment plant (WWTP) using P8 modeling software. P8 predicts that the pond is anticipated to exhibit the capability of eliminating 50% of the phosphorus from the fifty acres of forest and residential land that will undergo its treatment. However, empirical evidence derived from extant ponds leads to the inference that the actual efficiency of phosphorus removal is projected to be lower than the initially anticipated efficiency.

4.6 Delaware Urban Runoff Management Model (DURMM)

The Delaware Urban Runoff Management Model (DURMM) is a runoff modeling tool created to help manage urban runoff in Delaware, USA (Haris et al. 2016). It is intended to simulate and assess the influence of stormwater runoff from urban regions on water quality and quantity in receiving water sources. The modeling software considers numerous aspects, such as land use, soil types, and stormwater management practices, to estimate runoff volumes and contaminant loads (Lucas 2004).

The case study performed by Garza et al. (2016) emphasizes the importance of assessing native soils at a proposed site and using them again if their infiltration capacity is sufficient. The DURMM principles for on-site bioretention include residential rain gardens, bioretention cell variation 2-B, and the sub-category of infiltration the developers use to create the rain gardens. Balascio and Lucas (2009) used the curve numbers approach for the flooding events and the DURMM modeling method for the minor events up to the 2-year recurrence interval.

4.7 Stormwater Investment Strategy Evaluator (Storm WISE) Model

Stormwater Investment Strategy Evaluator (Storm WISE) modeling software used to evaluate and improve stormwater management approaches and investments. It helps inform people who participate in decision-making to assess the budget and benefits of numerous stormwater management practices and prioritize investments based on their efficiency in mitigating stormwater runoff and working on multiple objectives (Haris et al. 2016).

McGarity (2012) presented a study on stormwater management to address water quality. Storm WISE modeling software has effectively been utilized within the damaged Little Crum Creek catchment area in urban Philadelphia. The model revealed a solid ability to evaluate non-stationarity in factors formed from the changes in land-use patterns, as well as variations in climate that influence the occurrence of intense stormwater runoff.

4.8 Model for Urban Stormwater Improvement Conceptualization (MUSIC)

The Model for Urban Stormwater Improvement Conceptualization modeling software is extensively used for stormwater management and planning in urban areas. It is a theoretical modeling tool that helps design and assess stormwater management approaches and infrastructure for better water quality and minimized runoff in urban environments (Haris et al. 2016). MUSIC predicts the effectiveness of stormwater runoff and its relationship with numerous stormwater management approaches, like bioretention systems, rain gardens, infiltration trenches, and detention basins. The model considers variables such as land use, type of soil, patterns of precipitation, and stormwater runoff volumes (Fletcher et al. 2013).

4.9 InfoWorks River Simulation (InfoWorks RS)

InfoWorks River Simulation (InfoWorks RS) is a software modeling tool for simulating and evaluating river and open channel hydraulics (Haris et al. 2016). Planners and hydrological scientists extensively use it to plan and manage surface water resources, predict floods, and plan river systems. InfoWorks RS suggests a range of abilities to model and simulate the conditions of rivers, including flood dynamics, water levels, speeds, sediment erosion, and water quality. It uses progressive computational procedures and hydraulic models to precisely represent the complex hydraulic processes happening in river systems (Teng et al. 2017).

Adnan et al. (2016) conducted a study to evaluate flood patterns and create a comprehensive flood map for the Segamat River in Malaysia. The InfoWork River Simulation (RS) software was used to analyse and generate a flood map. Two experimental situations were conducted to examine the effect of hydraulic structures on water channels; in one case, one scenario involved the presence of a bridge and the other without it.

4.9.1 Distributed Routing Rainfall-Runoff Model (DR3M)

The Distributed Routing Rainfall-Runoff Model (DR3M) is a hydrological modeling tool to simulate and predict water movement in a river basin or watershed (Haris et al. 2016). It is developed to manage complex procedures for rainfall-runoff generation and flow movement spatially dispersedly. The modeling tool also simulates hydrological processes within each grid cell, such as precipitation, infiltration, evapotranspiration, and runoff generation (Du et al. 2007). It also allows the movement of flow between grid cells, which results in water flowing through the river system, including river channels, tributaries, and river catchments.

In research conducted by Du et al. (2007), the Distributed Routing Rainfall-Runoff Model (DR3M) was utilized to predict stormwater runoff in moist forested river catchments. The study was based on the Jiaokou watershed, which is a small basin of the Yongjiang River in China. The researchers examined a DR3M modeling tool utilizing data from nine stormwater runoff events in the study area.

4.9.2 Win-Source Loading and Management Model (Win-SLAMM)

The Win-Source Loading and Management Model (Win-SLAMM) is a complex software for stormwater management that assesses the simulation and detailed analysis of the effects of alteration in land use and stormwater control techniques on the quantity and quality of water (Kaykhosravi et al. 2018). This statement highlights the importance of assessing the effectiveness of diverse methods used in stormwater management and planning optimal systems for such reasons.

Win SLAMM software is a commonly used model as a planning tool that demonstrates its ability to be applied for hydrological analysis of different storm runoff types, incorporating small volume events. When a complete stormwater run is required, Win SLAMM can be integrated with other different stormwater runoff models (Jayasooriya and Ng 2014). Alam et al. (2019) evaluated the hydrologic performance of three kinds of permeable pavements under various rainfall events using the WinSLAMM model. The study revealed a 30% inaccuracy in the runoff projections made by the calibrated model.

4.9.3 Storage, Treatment, Overflow, Runoff Model (STORM)

The STORM model is a stormwater modeling tool developed by the US Corps of Engineers that allows stormwater runoff modeling in urban and rural catchment areas in response to rainfall (Haris et al. 2016). The modeling software helps evaluate and manage stormwater, considering storage, treatment, overflow, and runoff procedures within the catchment area. It offers a systematic approach to stormwater management by considering various components and processes in the urban water cycle (Park et al. 2013).

Kim and Han (2010) endeavoured to assess the water quality capture volume (WQCV) by using the initial abstraction method along with an evaporation velocity of 0.15 inches, which was commonly implemented, and this approach was executed in South Korea. The measurement of 0.38 cm was obtained using the Net STORM modeling software. The percentage capture approach was chosen to select STORM in Net STORM operational choices to achieve efficient and precise outcomes (Park et al. 2013).

Warwick and Wilson (1990) conducted a study aimed at analysing the possible varieties of predictions for STORM water quality, taking into consideration uncertainties in both water quantity and quality input parameters. The researchers successfully calibrated and verified the STORM program for the computation of runoff quantities within a residential community located in Dallas, Texas, as it was proven to be efficient (Haris et al. 2016). The assessment of the runoff quality, with a focus on evaluating the total suspended solids (TSS) values, revealed a significant underestimation when utilizing the suggested areal accumulation rates proposed by the STORM. This discrepancy was identified as an erroneous low estimation of the TSS values (Warwick and Wilson 1990).

4.9.4 MIKE - SWMM

MIKE-SWMM, also called the MIKE Stormwater Management Model, is extensively utilized as a hydrodynamic modeling tool developed by DHI. It is considered a global provider of solutions for water sources (Hidayat et al. 2021). MIKE-SWMM is designed to model urban stormwater runoff systems and their connections with surface water environments (Bisht et al. 2016). The modeling software uses active, combined strategies to model complex interactions concerning urban areas' rainfall, runoff, flow, and water quality.

Bisht et al. (2016) performed a study to plan and develop an applicable drainage system for the Kharagpur area. The MIKE URBAN model, which operates in two dimensions (2D), was utilized to address the limitation of the one-dimensional (1D) SWMM model in terms of its capacity for accurately predicting flood extent and runoff. The performance analysis of the polder system connected to coastal urban drainage used the MIKE URBAN and SWMM to determine the size of the polder system's effect on the Bank Indonesia Museum compartment (Arumsari and Setyandito 2018).

4.9.5 EPA System for Urban Stormwater Treatment Analysis and Integration (SUSTAIN)

SUSTAIN stormwater modeling software is an improved modeling tool designed by the United States Environmental Protection Agency (EPA) to help urban planners, engineers, and other stakeholders assess the occurrence and effectiveness of stormwater management practices (Haris et al. 2016). The modeling tool integrates hydrologic, hydraulic, and water quality models to simulate stormwater runoff and its interaction with different stormwater management practices.

SUSTAIN integrates water quality modeling tools to assess the effectiveness of several stormwater control approaches for pollutant removal. It evaluates ways to minimize polluting factors such as sediments, nutrients, heavy metals, PAHs, and other contaminants from stormwater runoff. The research was conducted by Mao et al. (2017) to evaluate the advantages of using the total Low Impact Development-Best Management Method (LID-BMPs) in managing stormwater runoff using the SUSTAIN stormwater modeling tool.

A case study was performed in Kansas City, Missouri, USA, to assess the efficiency of using SUSTAIN in examining possible green infrastructure management alternatives for mitigating the influences of integrated sewer runoffs (Lee et al. 2012). Gao et al. (2015) have conducted research intending to classify the most operative quantity and quality Best Management Practices (BMP) in industrial ability with a focus on reducing runoff volume and pollutant deposition in the drainage system of the study site.

4.9.6 Water Environment Research Foundation (WERF) Modeling Tool

The Water Environment Research Foundation (WERF) has produced modeling tools in Excel spreadsheets, which allows the evaluation of a cycle figure associated with Green Infrastructure (GI) in stormwater management. These modeling tools can articulate regulatory figures related to GI, considering expenditures associated with capital investment, daily running expenses, and upkeep costs (Jayasooriya and Ng 2014).

The modeling software developed by WERF offers nine distinctive GI practices that are frequently used for managing stormwater. These practices include Extended Detention Basins, Green Roof, Rain Garden, Bioretention, Planter Vault, Commercial Cisterns, Permeable Pavement, Swales, and Retention Ponds (Haris et al. 2016). This Excel modeling software allows a structured framework for evaluating the costs when implementing and maintaining these GI practices over their cycle.

4.9.7 Virginia Runoff Reduction Method (VRRM)

The Virginia Runoff Reduction Method (VRRM) is a stormwater modeling strategy used extensively in Virginia and the United States to evaluate and reduce the influence of stormwater runoff (Haris et al. 2016). VRRM was produced by the Virginia Department of Environmental Quality (DEQ) to meet terms with state environmental policies regarding stormwater management (Hodges 2016).

The main aim of VRRM is to measure the capacity of stormwater runoff and the consistent contaminant loads from development areas (Haris et al. 2016). The technique centres on reducing flow rates and runoff quantity and improving the stormwater quality of runoff discharged to catchment areas. Using effective stormwater GI practices such as retention ponds, biofiltration systems, and green roofs, VRRM targets to model pre-development hydrological environments and minimize the opposing influence of stormwater runoff on surface water bodies (Saby et al. 2021).

P value reduction necessities are calculated by applying the Virginia Runoff Reduction Method (VRRM). This technique reports for proposed land use and type adjustments to control suitable loads and related requirements (Saby et al. 2021). VRRM aims to quantify the volume of stormwater runoff and the corresponding pollutant loads from development sites.

4.9.8 Green Infrastructure Valuation Toolkit (GI Valuation Tool Kit)

The GI Valuation Toolkit, which is also known as the Green Infrastructure Valuation Toolkit, is a modeling tool designed to measure the economic value and benefits of green infrastructure (GI) predictions (Jayasooriya and Ng 2014). Green infrastructure signifies utilizing natural and engineered systems to control and predict stormwater occurrences and offer other environmental and social assistance. The main aim of this modeling tool is to manage and control complex assessments of the economic value of the environmental and economic advantages reduction from green infrastructure projects (Kim and Tran 2018).

4.9.9 Drainage System Design and Analysis Program (DRAINS)

A computer modeling tool called DRAINS was developed to plan and assess stormwater drainage systems in urban areas (Haris et al. 2016). The effectiveness of stormwater infrastructure in controlling rainfall runoff is regularly evaluated by civil engineers, urban planners, and hydrologists. DRAINS uses various techniques, such as the Probable Maximum Precipitation, Synthetic Unit Hydrograph, and Rational Method, to calculate design rainfall (Heppell et al. 2002). Users can enter local rainfall information or choose from preset settings based on regional standards. The software can model drainage systems of different sizes, from small areas to ten km^2, using sub-catchment with ILSAX hydrology and greater storage routing model hydrology (Jayasooriya and Ng 2014) (Table 2).

5 Comparison of Stormwater and Runoff Modeling Software

A comparative analysis of modeling software has been performed to evaluate and measure their competencies and limitations. This section aims to determine the extent to which each modeling software can provide for the improvement of applicable and efficient models.

5.1 Green Infrastructure (GI) Practices that the Model Tool Can Support

When comparing stormwater software models to the number of Green Infrastructure (GI) practices they can support, it is critical to consider that several modeling tools have varying abilities and features. The capability to support GI practices can rely on factors such as the model's design, underlying procedures, and the proposed aim of the software model (Kim and Tran 2018).

SWMM is a commonly utilized comprehensive hydrologic and hydraulic modeling tool (Rangari et al. 2015). It supports numerous GI practices, comprising permeable pavements, rain gardens, bioretention cells, green roofs, infiltration trenches, and more (Jayasooriya and Ng 2014). PCSWMM is another widespread stormwater modeling software developed on the EPA SWMM platform (Azawi and Sachit 2018). Jayasooriya and Ng (2014) revealed that SWMM supports several GI practices, including green roofs, rain gardens, permeable pavements, infiltration trenches, etc.

It was noted that RECARGA partially simulates bioretention, rain gardens, and infiltration trenches GI practices. P8 can only model a limited number of GIs, such as detention ponds, infiltration basins, swales, and buffer strips (Haris et al. 2016). XPSWMM is a hydrodynamic modeling tool that encompasses urban drainage and stormwater management. It can incorporate several GI practices, such as biofiltration systems, vegetated swales, infiltration basins, and others (Hidayat et al. 2021) (Table 3).

5.2 Data Availability and Input for Modeling Tools

Numerous aspects of data requirements are considered when relating to stormwater modeling tools. The data requirements may differ in the modeling tool's complexity and abilities. The modeling tools, namely MUSIC, WERF, SUSTAIN, LIDRA, and GI Valuation Toolkit, have in-built input databases that reduce the collection and cost of data for financial review and model are considered uncomplicated processes (Rangari et al. 2015).

In most stormwater modeling software tools, essential data prerequisites include climatic data, soil profile data, and land use data (Jayasooriya and Ng 2014). Modeling tools like RECARGA, P8, LIDRA, and Win SLAMM models only require a little input data or parameters compared to hydrologic and hydraulic modeling tools like the SWMM model (Haris et al. 2016). Therefore, it can be concluded that these models' tools are appropriate

Table 2 Application of stormwater modeling based on quantity modeling.

Model/ Developer/ Year	Capacity / Catchment Area (application)	The purpose of the investigation	Reference
RECARGA University of Wisconsin 2004	Cluj-Napoca, with a tributary area of 179.5 km^2	To classify appropriate bioretention cell models for the four types of urban locations in commercial, industrial, highdensity residential, and lowdensity residential regions.	(Boancă et al. 2018)
	The city of Novi Sad tributary area1= $865m^2$, tributary area2=$3,233m^2$, tributary area3= 3,456.64 m^2, and tributary area 4 2,182 m^2.	To evaluate the potential of bioretention systems for runoff reduction.	(Greksa et al. 2022)
	Norway in Scandinavia, Northern Europe.	To evaluate the performance of a bioretention facility.	(Kristvik et al. 2019)
	Xixian New Area, in Shaanxi Province.	To simulate the rain gardens in a sponge city pilot area in Northwest China.	(Zhang et al. 2020)
	Little Mill Creek Watershed in the United States of America, a catchment area of 0.36 km^2.	Modeling each sub-catchment runoff series between 1968 and 1977	(Sun et al. 2023)
EPA – SWMM U.S. EPA 2009	Malaysia Aur river, the total catchment area of 3978 ha.	To simulate urban flood events in the Aur River catchment.	(Hasan et al. 2019)
	The City of Adelaide catchment area is 122 km^2.	To compare how well the EPASWMM stormwater management model performs related to event-based and continuous simulation modeling when calculating total runoff.	(Hossain et al. 2019)
	Galleriano di Lestizza catchment is 36 ha.	To evaluate the efficiency of using a cutting-edge standard package for automatically c, an EPA-SWMM rainfall-runoff model was created for a small suburban catchment.	(Perin et al. 2020)
	In western Naples city, the total catchment area is 1760 ha.	Analyzing and calibrating rainfall runoff using EPASWMM and GA.	(Del Giudice and Padulano 2016)
	Rwanda, Nyabugogo, total Catchment area 1661.3 km^2.	Perform a study and analysis of stormwater quantities and floods in catchments.	(Niyonkuru et al. 2018)

Table 2 (continued)

Model/ Developer/ Year	Capacity / Catchment Area (application)	The purpose of the investigation	Reference
	Surat city in India, 24.88 km^2.	Using geo-informatics calibrating, estimate subcatchment area parameters for Storm Water Management Model (SWMM).	(Wang et al. 2016)
PCSWMM Computational Hydraulics International (CHI) 2019	Al-Huryai is i n the west of Baghdad, Iraq.	To investigate the critical factors that describe the possible Implementation of permeable pavement in Al-Huryai city via PCSWM.	(Azawi and Sachit 2018)
	Settat City in North-Western Parts of Morocco	To model the cycle of the hydrology process in the urban area of the Settat City.	(Ben-Daoud et al. 2022)
	Renton City, Washington, USA, With a catchment area of twelve km^2.	Perform an urban drainage model calibration to quantify stormwater runoff and associated pollutant loads.	(Abduljaleel et al. 2023)
Water Balance Model (WBM)	Cisadane watershed in Indonesia, the catchment area of 154547 ha.	The application of GIS restricts a recharge zone and relates it to water balance modeling.	(Hidayat et al. 2021)
British Columbia Inter-Governmental Partnership (BCIGP) 2003	Karaj River basin in Iran, with a catchment area of 847 km^2.	To understand how water moves in dry mountain areas,	(Tayefeh Neskili et al. 2017)
Storm WISE	Little Crum Creek in Delaware, a tributary that drains 8300000 m^2.	Scientists combined different modules of water balance models (WBM). Addressing the stream's water quality problems is impeded by municipal governance laws in Pennsylvania.	(McGarity 2012)
P8 Urban Catchment Model William W. Walker.	The Assabet River in Boston, Massachusetts, United States, has a catchment area of 34964.8395 ha.	To assess the functioning of a Phosphorus trading program between nonpoint sources and the point source reduced by the WWTP (P8 model).	(Raine 1999)
	Lake McKusick is a lake in Washington; the catchment area is eight km^2.	To create a design of an area that catches water and a proposed solution to control the water flow.	(STILLWATER 2013)

Table 2 (continued)

Model/ Developer/ Year	Capacity / Catchment Area (application)	The purpose of the investigation	Reference
RS InfoWorks Innovyze 2011	Malaysia by Segamat River, catchment area of 68,500 ha	To analyse the flood and develop the flood map for the Segamat River.	(Adnan et al. 2016)
	Muda River, Northern Peninsula Malaysia, catchment area of 4210 km^2.	This is to help determine the long-term behaviour of the Muda River and its flooding behaviour.	(Ghani et al. 2010)
	Sungai Johor basin, Malaysia, catchment of 2,636 km^2.	To perform river modeling and generate a flood map for Sungai Johor.	(Amin and Othman 2018)
	Malacca River, Malaysia.	To study the types of pollution and the tidal influences on river water quality.	(Che Osmi et al. 2018)
DR3M USGS 1991	China in Jiaokou Reservoir, Catchment area of 25900 ha.	To design some predictions of stormwater runoff from humid, afforested catchments.	(Du et al. 2007)
STORM US Corps	Bachman Branch in Dallas, Catchment area of 2,590 ha.	To determine probable ranges of STORM water quality predictions based on both water quantity and quality input variable uncertainties.	(Warwick and Wilson 1990)
MIKE - SWMM	Indian Institute of Technology (IIT) Kharagpur campus, West Bengal, India. The catchment area is 470 ha.	To design an efficient drainage system for the study of the Kharagpur campus.	(Bisht et al. 2016)
	Mashhad in Iran has a catchment area of seventy-one km^2.	To determine how much rainwater flows off and how a city's drains respond when it rains.	(Khodashenas and Tajbakhsh 2016)
	The powder system in Pluit.	To assess the Bank Indonesia Museum compartment's exposure to the impact of the polder system.	(Arumsari and Setyandito 2018)
SUSTAIN US EPA 2003	Foshan New City, China.	To assess the ecological Benefits of aggregate LID-BMPs for stormwater runoff control.	(Mao et al. 2017)

Table 2 (continued)

Model/ Developer/ Year	Capacity / Catchment Area (application)	The purpose of the investigation	Reference
Green Infrastructure Valuation Toolkit	Lake Michigan Watershed, Michigan, USA, 34 ha of drainage area.	Help owners and operators comply with the New York State Pollutant Discharge Elimination System (SPDES) planning requirements.	(Nordman et al. 2018)
Mersey Forest, UK 2015	Santa Clara Valley, in the City of Sunnyvale.	Used the GI valuation toolkit to classify the possible GI areas for Peery Park where redevelopment is planned.	(Wu et al. 2018)
HEC - HMS	In the city of Izmir in the west of Turkey, the catchment area is 29.6 km^2.	To examine the potential serviceability of the planned Bostanli Dam with the use of HEC-HMS and HEC-RAS modeling tools.	(Gül et al. 2010)
	Attanagalu Oya and Dee Eli Oya's study catchment area covers 337.06 km^2.	Produce long-term flow information for the Oya and the rivers to standardize and validate the HEC-HMS 3.4 model to the Attanagalu Oya (River) basin.	(Halwatura and Najim 2013)
	Klang River Basin in Malaysia, the catchment area is 159.7 km^2.	To produce outlines for the rainfall-runoff model by using the HEC-HMS program.	(Ramly and Tahir 2016)
Win - SLAMM	Sarawak River Sub-basin, Southeast Asia, catchment area of 657 km^2.	To understand a big flood one hundred years ago in this river area.	(Bustami et al. 2009)
Bob Pitt, University of Alabama 1998	The city of Brownsville's total drainage is 89.77 m^2. The City of La Feria's total drainage area is 789. 03 m^2. Cameron County Drainage District 619.17 m^2.	To produce a set of calibrated hydrologic models using WinSLAMM for three different regional permeable pavement types: permeable interlocking concrete pavement (PICP), interlocking block pavement with gravel (IBPG), and porous concrete pavement (PCP).	(Alam et al. 2019)

Table 3 **(GI) practices that the model tool can support**. Others include: (Bioswales, Urban Tree Canopy, Rainwater Harvesting, Green Walls, and Natural Drainage Systems)

Model	Permeable pavements	Rain gardens	Bioretention cells	Green roofs	Infiltration trenches	Others
EPA-SWMM	*	*	*	*	*	*
PCSWMM	*	*		*	*	*
RECARGA		*			*	*
P8					*	*
XPSWMM		*	*		*	*
Win-SLAM	*	*		*		*
SUSTAIN	*	*	*	*	*	*
MUSIC	*		*		*	*
Win-SLAMM	*		*		*	*
Storm WISE	*		*		*	*
DURMM			*			*
LIDRA						*
GI Valuation Tool Kit		*	*	*	*	*
VRRM	*		*	*	*	*
WERF Model	*		*			*
DR3M	*		*		*	
MIKE-SWMM	*		*	*	*	*

for planning future stormwater management strategies at the initial stage of runoff occurrence. SWMM and InfoWorks modeling tools require additional specified data inputs compared to other modeling tools. The data requirements involve catchment characteristics (area, slope, land use, soil type), rainfall data, hydraulic properties of pipes and channels, and additional data input on structures (Jehanzaib et al. 2022). Moreover, it necessitates data on the system layout and connectivity (Haris et al. 2016). Data requirements may differ based on the modeling tool version, configuration, and the level of detail anticipated in the evaluation.

5.3 Accuracy of the Modeling Tool

When evaluating stormwater modeling tools' efficiency, an essential factor to consider is the model's accuracy. The aspects that must be considered when doing a comparative evaluation involve the complexity of the modeling tool, the input data used, the standardization methods, and the validation metrics used and stated that the existence of unpredictability and irregularity in a modeling method is a natural characteristic that cannot be avoided and can significantly impact the accuracy of the outcome.

The accuracy of SWMM, PCSWMM, MIKE URBAN, RECARGA, Win SLAM, and HEC-HMS relies on the quality and utilization of the input data, as well as the calibration procedure applied to compare the outputs the model creates with observed data (Lucas 2004). Model accuracy can be improved through complex calibration and validation methods, utilizing an extensive range of observed data, such as rainfall, runoff rates, water quality assessments, and field observations. SWMM and Win SLAMM modeling software tools provide a high level of accuracy as extensive comprehensive design aids (Haris et al. 2016).

The models RECARGA, P8, CNT, and LIDRA have been recognized as intensely suited for activities at the GI planning. This is due to the presence of uncertainties and variations in input factors, which can influence the output of these models. MUSIC is also a tool that is accurate when operating as a conceptual modeling tool in the context of green infrastructure practices, as it does not necessitate algorithms for comprehensive sizing of such practices (Haris et al. 2016).

5.4 Stormwater Model Application and Limitations

When it comes to stormwater models, there are numerous possibilities of tools that are accessible, each modeling tool with its regional applications and limitations.

SWMM is extensively utilized in the United States and has been approved by many municipalities and organizations for stormwater management and evaluation. It is appropriate for urban and rural areas and can control complicated drainage systems involving integrated and separate sewer systems (Rodak et al. 2020). SWMM has comparatively extreme learning and involves some practical knowledge to set up and run efficiently. It might not be as appropriate for rural or agricultural areas with many drainage attributes. Moreover, the model's simulation abilities might be limited regarding enormous quantities and complicated drainage systems (Niyonkuru et al. 2018).

PCSWMM is an accessible desktop software used in different areas for stormwater management. It enables the evaluation and design of stormwater systems in both urban and rural areas (Ben-Daoud et al. 2022). It is commonly utilized in North America, the United States, and Canada. PCSWMM has limitations regarding large quantity systems, as it is primarily developed for small to medium catchment areas (Azawi and Sachit 2018). Modeling capabilities and functionality might differ based on specific versions and licensing preferences.

Applications of EPA-SWMM stormwater modeling are typical in the United States. These are often utilized for evaluating and developing stormwater management practices, including Best Management Practices (Rodak et al. 2020). It can be used in both urban and rural regions. EPA-SWMM necessitates an accurate level of practical knowledge to run effectively. There might be limitations in simulating extensive drainage systems, and model functioning can be affected by the quality and availability of data input. Although EPA-SWMM is commonly used in the United States, its regional applications may be more limited to other regions (Hasan et al. 2019).

RECARGA is a tool that utilizes input data from the Department of Natural Resources (DNR) conservation practice standards for Wisconsin, USA, and P8 is standardized with catchment input data from Rhode Island (Sidek et al. 2021). Therefore, RECARGA and P8 modeling tools have limited applications only for an area outside of those locations.

MUSIC has been recognized as the primary modeling tool in Australia for modeling GI, which integrates Australia's essential climate input data. The latest improvements have enabled the adaptation of the MUSIC tool to function efficiently within the region of the United Kingdom (Brimicombe and Li 2009). WERF, SUSTAIN, and LIDRA have been developed with integrated databases that cater to a particular context; however, these modeling tools offer users the flexibility to incorporate their data to meet specific modeling requirements (Jayasooriya and Ng 2014).

5.5 Spatial Resolution of Stormwater Modeling Tools

Several stormwater modeling tools are accessible for free, and each agency proposes unique features and modeling abilities. When comparing these tools based on spatial resolution, we refer to the level of aspect and granularity at which the modeling tool can simulate and evaluate stormwater procedures.

SWMM supports grouped and dispersed modeling methods, keeping the tool flexible for spatial representation (Rangari et al. 2015). People using this modeling tool can delineate sub-catchments, which can signify small locations in a few square meters or as big as the whole watershed. The PCSWMM modeling tool enables operators to draft sub-catchments and discretize them into smaller zones to capture spatial variability. PCSWMM supports high-resolution modeling, allowing it to be appropriate for the complete analysis of urban stormwater systems (Elliott and Trowsdale 2007). InfoWorks allows the application of comprehensive geographic information system (GIS) data, like digital elevation models (DEMs) and land use data, to represent the physical landform of the catchment accurately.

The modeling tool also performs dynamic linking of the 1D (pipe network) and 2D (overland flow) components, enabling simulation at various spatial resolutions (Elliott and Trowsdale 2007). MIKE SWMM integrates GIS modeling abilities, allowing users to import and use high-resolution spatial data for accurate feature output. The tool also allows dynamic integration between the 1D and 2D components for detailed modeling of complicated urban stormwater systems (Rangari et al. 2015).

5.6 Technical Support and Updates of the Modeling Tools

Stormwater modeling tools' technical support and updates are essential in ensuring that the stormwater models' accuracy and efficiency are presented. It is necessary to consider that the ease of use, technical support quality, and updates can vary over time as new versions are produced and software modeling tools organizations develop their assistance.

The U.S. Environmental Protection Agency (EPA) provides technical maintenance for SWMM over its website, which contains user guides, tutorials, and a given email contact for queries and reviews (Jayasooriya and Ng 2014). The SWMM modeling tool has undergone numerous versions and updates over the years, with the newest version, SWMM 5.1.014, developed in September 2021 (Jehanzaib et al. 2022). The EPA releases updates regularly to address bugs, add features, and improve functioning. PCSWMM gives technical support throughout its website, together with information about the model, tutorials, and user manuals. The PCSWMM inventors frequently produce model updates to solve model issues, enhance functionality, and include user reviews (Akhter and Hewa 2016).

The inventors of XP-SWMM offer technical support via their website, which contains user guides, FAQs, and a support permit system for assistance (Rangari et al. 2015). XP-SWMM has undergone updates and developments over the past years, but the frequency and capacity of updates may differ. DHI inventors of MIKE URBAN provide technical support to its tool users through the website (Bulti and Abebe 2020). This contains access information, tutorials, and contact for a support team for assistance. DHI frequently updates MIKE URBAN to solve functioning problems, present new features, and improve functioning (Bisht et al. 2016).

Innovyze, the organization that invented InfoWorks RS, offers support through its website (Ghani et al. 2010). It contains a user support portal, tool information, public interaction, and problem-solving tutorials. Innovyze is responsible for developing updates for InfoWorks RS to enhance its functionality, solve problems, and include user reviews (Amin and Othman 2018). The regularity of updates may differ, and users can evaluate the developer's website for the latest version. MUSIC offers complete software information containing user guides and tutorials. MUSIC is occasionally updated with new versions that address viruses, functioning enhancement, and additional features (Boancă et al. 2018).

5.7 Sensitivity and Calibration Process of Modeling Tools Base on Climatic Parameters

The stormwater modeling tools, such as EPA SWMM and PCSWMM, display high sensitivity to factors like rainfall patterns, catchment characteristics, and initial soil moisture levels. Calibration processes for these tools involve adjusting parameters based on observed streamflow and rainfall data to enhance accuracy in predicting stormwater behaviour (Jayasooriya and Ng 2014). RECARGA, on the other hand, focuses on rainfall and soil properties, with calibration involving observed infiltration rates and runoff volumes to fine-tune parameters related to soil moisture dynamics (Sun et al. 2013).

The P8 Urban Catchment Model is particularly sensitive to rainfall, pollutant loads, and stormwater practice design, with calibration targeting pollutant wash-off and removal processes within stormwater practices using observed pollutant concentrations (Devia et al. 2015). Win-SLAMM's predictions are influenced by rainfall patterns, land use changes, and stormwater management practices, with calibration involving observed runoff volumes to adjust parameters like runoff potential and pollutant loading rates from different land uses (Kaykhosravi et al. 2018).

SUSTAIN, which is like SWMM and PCSWMM, places additional emphasis on water quality. Calibration for SUSTAIN requires comprehensive data on flow, water quality, and BMP performance to fine-tune hydraulics, pollutant processes, and BMP removal efficiencies (Haris et al. 2016). MUSIC responds to rainfall, soil properties, and treatment practice design, with calibration focusing on observed runoff and pollutant data to adjust parameters related to infiltration and storage capacities of practices, as well as pollutant removal efficiency (Devia et al. 2015).

Storm WISE incorporates future climate scenarios into its modeling, with calibration aiming to capture the effects of changing rainfall patterns, land use modifications, and stormwater practice performance under various conditions (Haris et al. 2016). DURMM and VRRM are both sensitive to rainfall, land use, soil properties, and stormwater practice design (Lucas 2004; Haris et al. 2016). DURMM's calibration process involves adjusting runoff and pollutant load parameters based on observed data. At the same time, VRRM serves as a design tool with limited calibration, focusing on selecting appropriate stormwater management practices.

5.8 Hydrologic and Hydraulic Capability Modeling Tools

When comparing stormwater modeling tools, considering their hydrologic and hydraulic capabilities, there are several essential aspects to consider. Factors to check under hydrologics are rainfall data input, runoff calculation methods, solo types, land use, and subcatchment delineation. Aspects of hydraulics include pipe network modeling, trench and channel design, ponding, and overland flow.

SWMM, PCSWMM, RECARGA, XPSWMM, and MIKE URBAN present several hydrologic approaches, including the Rational Method, Green-Ampt, and Soil Conservation Service (SCS) methods, to predict stormwater runoff from various land uses and types of soil (Gül et al. 2010). SWMM and PCSWMM offer a complete hydraulic modeling approach, including open channel runoff, pipe runoff, infiltration, and stormwater routing through a system of transportation elements. MIKE URBAN offers hydraulic solid modeling features, including pipe flow, open channel flow, storage structures, and integrated 1D and 2D modeling abilities (Rodríguez et al. 2012).

HEC-HMS is a multipurpose modeling tool that provides different hydrologic modeling approaches, such as the SCS Curve Number method and unit hydrograph theory. It permits operators to delineate watershed characteristics, rainfall patterns, and runoff processes (Gül et al. 2010). HEC-HMS focuses on hydrologic modeling, which can produce critical hydraulic calculations by integrating hydrographs with channel routing procedures (Akram et al. 2014). Nevertheless, it is commonly used with other hydraulic modeling tools for complete analysis and evaluation.

MUSIC and P8 provide a full range of hydrologic models to simulate stormwater runoff from urban areas (Devia et al. 2015). The modeling tool permits the representation of different stormwater control methods (SCMs), such as rainwater tanks, bioretention systems, and detention basins. MUSIC offers a wider variety of pre-defined SCMs and enables operators to make custom SCMs. P8 has a restricted set of predefined SCMs but also provides flexibility in describing the practice of SCMs (Raine 1999).

When comparing stormwater modeling tools in terms of water quality modeling, it is crucial to consider software that includes water quality modules simulating pollutant transport and fate within the stormwater system, addressing factors like pollutant loads, settling processes, and BMPs for water quality improvement (Li et al. 2020). Tools like SWMM, PCSWMM, RECARGA, XPSWMM, and MIKE URBAN offer advanced capabilities in water quality modeling by enabling users to assess pollutant behaviour, model settling processes, and evaluate BMP effectiveness. In disparity, tools like HEC-HMS, MUSIC, SCMs, and P8 may have more limited water quality modeling functionalities but still contribute significantly to overall stormwater management by providing essential data for assessing water quantity aspects that indirectly impact water quality parameters, emphasizing the importance of a comprehensive approach to stormwater management.

Advanced models, as discussed by Alamdari et al. (2017), offer the ability to assess future stormwater behaviour under changing precipitation patterns and extreme weather events. These tools, such as SWMM, PCSWMM, EPA SWMM, MIKE URBAN, and InfoWorks ICM, provide valuable perspicuity into the potential effects of climate change on water quality within stormwater systems, aiding researchers and practitioners in understanding and addressing these challenges effectively.

6 Topics for Future Research

Even though there are considerable improvements in stormwater modeling tools, numerous areas still need further research. Future studies should focus on developing models that can use predictions about how the climate will change. This will help plan solid strategies for managing excess water during storm runoffs.

It is essential to add GI factors such as rain gardens and green roofs to modeling tools that predict how stormwater runoffs will flow during rainfall (Green et al. 2021). Researchers can assess how effectively they work, improve how they are created, and use modeling software to understand their effects in different areas. Improving stormwater modeling software that predicts how stormwater flows must include water quality so we can assess how dirty and waste travel is and develop plans to solve the problem. Research should be done to develop improved strategies to find out what happens to contaminants and strategies to have an idea of where pollutants originate from.

Using strategies to measure uncertainty in stormwater modeling can produce better predictions and assessments that can cater to a more trustworthy representation (Vezzaro and Mikkelsen 2012). Future research should investigate techniques to measure and distribute the uncertainties in related water measurements, model types, and input data. Producing modeling tools to predict stormwater in the long or short term is significant for managing it efficiently. Future scientists and researchers must work on integrating information from sensors that provide data in real-time, predictions of weather, and strategies for evaluating data into tools that can assist in making mitigation measures before runoff storms occur.

Studying how to manage stormwater to minimize the heat in urban areas is an essential field of research. More research must be done to see how well GIs and other strategies to cool urban areas work when integrated with tools for managing stormwater. Scientists must study ways to track how people and the environment affect city water systems over long periods. We are looking for procedures to improve stormwater models by integrating several data inputs, including satellite images, reports from regular people, and social media posts. This might make the models more precise and valuable. Scientists who wish to continue to study new ways of using data to learn and make predictions. This includes using computers to find patterns in the data and combining various data sources to improve our understanding.

7 Conclusion

Stormwater modeling tools are crucial for understanding and managing urban stormwater runoff. This study compared various modeling tools based on their functionalities, limitations, and applications. After reviewing modeling tools for stormwater management, the study can draw more than a few significant conclusions.

Different modeling tools cater to specific purposes when it comes to their application and limitations. SWMM, PCSWMM, XPSWMM, and MIKE URBAN are powerful for comprehensive simulations of both water movement (hydrology) and pipe flow (hydraulics) (Zölch et al. 2017). RECARGA, P8, and MUSIC excel at modeling how green infrastructure practices, like rain gardens and bioswales, impact stormwater management. For unimpeachably hydrologic modeling, HEC-HMS is a valuable option, as it can integrate with hydraulic tools for a more complete picture.

The complexity and functionalities of a tool influence the required data it needs to run and its accuracy (Kumari et al. 2018). SWMM and InfoWorks require a lot of detailed information, such as catchment area characteristics, rainfall patterns, and properties of the drainage system. In disparity, RECARGA and P8 are designed for the initial planning stages and require minimal data input. The accuracy of the outcomes relies on the quality of the data you provide in the model, along with how you calibrate and validate it. Tools like SWMM, PCSWMM, and WinSLAMM can be highly accurate when properly calibrated. However, RECARGA, P8, and LIDRA might have limitations due to uncertainties in some input factors.

Factors like the size and location of the area, the types of data available, and budget constraints all play a role (Welsh et al. 2013). For example, SWMM is popular in the US for both urban and rural areas, but it requires expertise to use effectively. PCSWMM offers a user-friendly interface but may not be suitable for exceptionally large systems. RECARGA and P8 have limitations in terms of where they can be applied geographically, while MUSIC, developed in Australia, has been adapted for use in the UK .

Modeling tools, like SWMM, PCSWMM, InfoWorks, and MIKE SWMM, allow for high-resolution modeling by enabling detailed breakdowns of drainage areas and incorporating data from Geographic Information Systems (GIS) (Kumari et al. 2018). Technical support and updates are crucial factors as well. The Environmental Protection Agency (EPA) for SWMM, PCSWMM from CH2M, DHI for MIKE URBAN, and Innovyze for InfoWorks all provide technical support and frequent updates, and updates may be different for other tools (Abbas et al. 2019).

Hydrologic and hydraulic capabilities are critical. SWMM, PCSWMM, XPSWMM, MIKE URBAN, and HEC-HMS offer a variety of hydrologic methods and can model pipe networks, channels, and overland flow. MUSIC and P8 focus on simulating urban runoff and the impact of different stormwater control measures. For water quality modeling, SWMM, PCSWMM, XPSWMM, and MIKE URBAN offer advanced functionalities. While HEC-HMS, MUSIC, and P8 have limited water quality modeling capabilities, they still contribute to overall management by providing water quantity data.

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References

Abbas A, Salloom G, Ruddock F, Alkhaddar R, Hammoudi S, Andoh R, Carnacina I (2019) Modelling data of an urban drainage design using a Geographic Information System (GIS) database. J Hydrol 574. https://doi.org/10.1016/j.jhydrol.2019.04.009

Abduljaleel Y, Salem A, Ul Haq F, Awad A, Amiri M (2023) Improving detention ponds for effective stormwater management and water quality enhancement under future climate change: a simulation study using the PCSWMM model. Scientific Reports 13(1):5555. https://doi.org/10.1038/s41598-023-32556-x

Adnan MS, Ali NC, Erfen Y, Rahmat SN, Razi MAM, Musa S (2016) Analysis of the Impact of Bridges Existence for the Segamat River Using Infowork RS. IOP Conference Series: Mat Sci Eng 136(1). https://doi.org/10.1088/1757-899X/136/1/012080

Ahyerre M, Chebbo G, Tassin B, Gaume E (1998) Stormwater quality modeling, an ambitious objective? Water Science and Technology 37(1):205–213. https://doi.org/10.1016/S0273-1223(97)00771-3

Akhter MS, Hewa GA (2016) The PCSWMM is used to assess the impacts of land use changes on hydrological responses and the performance of WSUD in managing the impacts at the Myponga catchment, South Australia. Water (Switzerland) 8(11). https://doi.org/10.3390/w8110511

Akram F, Rasul MG, Khan MMK, Amir MSII (2014) A Review on Stormwater Harvesting and Reuse. Intern J Environ Earth Sci Eng 8(3)

Alam T, Mahmoud A, Jones KD, Bezares-Cruz JC, Guerrero J (2019) WinSLAMM simulation of hydrologic performance of permeable pavements case study in the semi-arid lower Rio Grande Valley of South Texas, United States. Water (Switzerland) 11(9). https://doi.org/10.3390/w11091865

Alamdari N, Sample D, Steinberg P, Ross A and Easton Z (2017) Assessing the effects of climate change on water quantity and quality in an urban watershed using a calibrated stormwater model, water. Water 9(7):464. https://www.mdpi.com/2073-4441/9/7/464

Amin NFM, Othman F (2018) Generation of flood map using infoworks for Sungai Johor. Int J Int Eng 10(2):142–145. https://doi.org/10.30880/ijie.2018.10.02.026

Aparicio Uribe CH, Bonilla Brenes R, Hack J (2022) Potential of retrofitted urban green infrastructure to reduce runoff - A model implementation with site-specific constraints at neighborhood scale. Urban Forestry & Urban Greening 69. https://doi.org/10.1016/j.ufug.2022.127499

Arumsari P, Setyandito O (2018) Spatial Data and Catchment Discretization for Assessment Coastal Urban Drainage Performance Using GIS and MIKE URBAN-SWMM. IOP Conference Series: Earth Environ Sci 195(1). https://doi.org/10.1088/1755-1315/195/1/012018

Atchison D, Severson L (2004). RECARGA User's Manual

Azawi HKS, Sachit DE (2018) Investigation of Permeable Pavement Implementation in Baghdad Using PCSWMM Model. Environment and Natural Resources Research 8(3):117. https://doi.org/10.5539/enrr.v8n3p117

Balascio CC, Lucas WC (2009) A survey of storm-water management water quality regulations in four Mid-Atlantic States. Journal of Environmental Management 90(1):1–7. https://doi.org/10.1016/j.jenvman.2007.10.006

Ben-Daoud A, Ben-Daoud M, Moroșanu GA, M'Rabet S (2022) The use of low-impact development technologies in the attenuation of flood flows in an urban area: Settat City (Morocco) as a case. Environ Chall 6. https://doi.org/10.1016/j.envc.2021.100403

Bisht DS, Chatterjee C, Kalakoti S, Upadhyay P, Sahoo M, Panda A (2016) Modeling urban floods and drainage using SWMM and MIKE URBAN: a case study. Natural Hazards 84(2):749–776. https://doi.org/10.1007/s11069-016-2455-1

Boancă P, Dumitraş A, Luca L, Bors-Oprişa S, Laczi E (2018) Analysing bioretention hydraulics and runoff retention through numerical modeling using RECARGA: A case study in a Romanian urban area. Polish J Environ Stud 27(5):1965–1973. https://doi.org/10.15244/pjoes/79271

Booth DB, Hartley D, Jackson R (2002) Forest cover, impervious surface area, and the mitigation of stormwater impacts. Journal of the American Water Resources Association 38(3):835–845. https://doi.org/10.1111/j.1752-1688.2002.tb01000.x

Brimicombe A, Li C (2009) Location-based services and geo-informaion engineering. John Wiley and Sons

Bulti DT, Abebe BG (2020) A review of flood modeling methods for urban pluvial flood application. Modeling Earth Systems and Environment 6(3):1293–1302. https://doi.org/10.1007/s40808-020-00803-z

Bustami R, Bong C, Mah D, Hamzah A, Patrick M (2009) Modeling of Flood Mitigating Structures for Sarawak River Sub-basin Using InfoWorks River Simulalation (RS). International Journal of Civil and Environmental Engineering 3(6):248–252

Che Osmi SA, Wan Ishak WF, Azman MA, Ismail AS, Samah NA (2018) Development of water quality modeling using InfoWork river simulation in Malacca River, Malaysia, and contribution towards Total Maximum Daily Load approach. IOP Conference Series: Earth Environ Sci 169(1). https://doi.org/10.1088/1755-1315/169/1/012073

Choi KS, Ball JE (2002) Parameter estimation for urban runoff modelling. Urban Water 4(1):31–41. https://doi.org/10.1016/S1462-0758(01)00072-3

Chomba IC, Banda KE, Winsemius HC, Chomba MJ, Mataa M, Ngwenya V, Sichingabula HM, Nyambe IA, Ellender B (2021) A review of coupled hydrologic-hydraulic models for floodplain assessments in Africa: Opportunities and challenges for floodplain wetland management. Hydrology 8(1). https://doi.org/10.3390/hydrology8010044

Del Giudice G, Padulano R (2016) Sensitivity Analysis and Calibration of a Rainfall-runoff Model with the Combined Use of EPA-SWMM and Genetic Algorithm. Acta Geophysica 64(5):1755–1778. https://doi.org/10.1515/acgeo-2016-0062

Devia GK, Ganasri BP, Dwarakish GS (2015) A Review of Hydrological Models. Aquatic Procedia 4:1001–1007. https://doi.org/10.1016/j.aqpro.2015.02.126

Du J, Xie S, Xu Y, Xu CY, Singh VP (2007) Development and testing of a simple physically based distributed rainfall-runoff model for storm runoff simulation in humid forested basins. Journal of Hydrology 336(3–4):334–346. https://doi.org/10.1016/j.jhydrol.2007.01.015

Edwards PN (2011) History of climate modeling. Wiley Interdisciplinary Reviews: Climate Change 2(1):128–139. https://doi.org/10.1002/wcc.95

Elliott AH, Trowsdale SA (2007) A review of models for low-impact urban stormwater drainage. Environmental Modelling and Software 22(3):394–405. https://doi.org/10.1016/j.envsoft.2005.12.005

Fekete BM, Gibson JJ, Aggarwal P, Vörösmarty CJ (2006) Application of isotope tracers in continental scale hydrological modeling. Journal of Hydrology 330(3–4):444–456. https://doi.org/10.1016/j.jhydrol.2006.04.029

Fletcher TD, Andrieu H, Hamel P (2013) Understanding, management, and modeling of urban hydrology and its consequences for receiving waters: A state of the art. Advances in Water Resources 51:261–279. https://doi.org/10.1016/j.advwatres.2012.09.001

Gao J, Wang R, Huang J, Liu M (2015) Application of BMP to urban runoff control using SUSTAIN model: A case study in an industrial area. Ecological Modelling 318:177–183. https://doi.org/10.1016/j.ecolmodel.2015.06.018

Garcia-Cuerva L, Berglund EZ, Rivers L (2018) An integrated approach to place Green Infrastructure strategies in marginalized communities and evaluate stormwater mitigation. Journal of Hydrology 559:648–660. https://doi.org/10.1016/j.jhydrol.2018.02.066

Garza PR, Welker A, ASCE M, Rife S (2016) Forensic Analyses of Two Failed Rain Gardens in a Tract Development in Glasgow, Delaware. Geoenviron Eng

Ghani AA, Ali R, Zakaria NA, Hasan ZA, Chang CK, Ahamad MSS (2010) A temporal change study of the Muda River system over 22 years. International Journal of River Basin Management 8(1):25–37. https://doi.org/10.1080/15715121003715040

Ghashghaie M, Eslami H, Ostad-Ali-Askari K (2022) Applications of time series analysis to investigate components of Madiyan-rood River water quality. Applied Water Science 12(8):202. https://doi.org/10.1007/s13201-022-01693-5

Goulden S, Portman ME, Carmon N, Alon-Mozes T (2018) From conventional drainage to sustainable stormwater management: Beyond the technical challenges. Journal of Environmental Management 219:37–45. https://doi.org/10.1016/j.jenvman.2018.04.066

Green D, O'Donnell E, Johnson M, Slater L, Thorne C, Zheng S, Stirling R, Chan FKS, Li L, Boothroyd RJ (2021) Green infrastructure: The future of urban flood risk management? Wiley Interdisciplinary Reviews: Water 8(6):1–18. https://doi.org/10.1002/wat2.1560

Greksa A, Grabić J, Blagojević B (2022) Contribution of low impact development practices-bioretention systems towards urban flood resilience: a case study of Novi Sad, Serbia. Environ Eng Res 27(4). https://doi.org/10.4491/eer.2021.125

Gül GO, Harmancioğlu N, Gül A (2010) A combined hydrologic and hydraulic modeling approach for testing efficiency of structural flood control measures. Natural Hazards 54(2):245–260. https://doi.org/10.1007/s11069-009-9464-2

Halwatura D, Najim MMM (2013) Application of the HEC-HMS model for runoff simulation in a tropical catchment. Environmental Modelling and Software 46:155–162. https://doi.org/10.1016/j.envsoft.2013.03.006

Haris H, Chow MF, Usman F, Sidek LM, Roseli ZA, Norlida MD (2016) Urban Stormwater Management Model and Tools for Designing Stormwater Management of Green Infrastructure Practices. IOP Conf Series: Earth Environ Sci 32(1). https://doi.org/10.1088/1755-1315/32/1/012022

Hasan HH, Razali SFM, Zaki AZIA, Hamzah FM (2019) Integrated hydrological-hydraulic model for flood simulation in tropical urban catchment. Sustainability (Switzerland) 11(23). https://doi.org/10.3390/su11236700

Heppell CM, Worrall F, Burt TP, Williams RJ (2002) A classification of drainage and macrospore flow in an agricultural catchment. Hydrological Processes 16(1):27–46. https://doi.org/10.1002/hyp.282

Hidayat DPA, Darsono SLW, Farid M (2021) Modelling of Potential Recharge Zone Using Geographical Information System Based on Indonesia Regulation and Water Balance Model. Int J Geomate 20(79):147–154. https://doi.org/10.21660/2021.79.j2037

Hijmans RJ, Graham CH (2006) The ability of climate envelope models to predict the effect of climate change on species distributions. Global Change Biology 12(12):2272–2281. https://doi.org/10.1111/j.1365-2486.2006.01256.x

Hodges CC (2016) Optimization of BMP Selection for Distributed Stormwater Treatment Networks

Hossain S, Hewa GA, Wella-Hewage S (2019) A comparison of continuous and event-based rainfall-runoff (RR) modeling using EPA-SWMM. Water (Switzerland) 11(3). https://doi.org/10.3390/w11030611

Huber M, Welker A, Helmreich B (2016) A critical review of heavy metal pollution of traffic area runoff: Occurrence, influencing factors, and partitioning. Science of the Total Environment 541:895–919. https://doi.org/10.1016/j.scitotenv.2015.09.033

Jalaei F, Jrade A (2014) Integrating building information modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings. J Inf Technol Constr 19:494–519

Javadinejad S, Hannah D, Ostad-Ali-Askari K, Krause S, Zalewski M, Boogaard F (2019a) The Impact of Future Climate Change and Human Activities on Hydro-climatological Drought, Analysis and Projections: Using CMIP5 Climate Model Simulations. Water Conservation Science and Engineering 4:71–88. https://doi.org/10.1007/s41101-019-00069-2

Javadinejad S, Ostad-Ali-Askari K, Eslamian S (2019b) Application of Multi-Index Decision Analysis to Management Scenarios Considering Climate Change Prediction in the Zayandeh Rud River Basin. Water Conservation Science and Engineering 4:53–70. https://doi.org/10.1007/s41101-019-00068-3

Jayasooriya VM, Ng AWM (2014) Tools for modeling of stormwater management and economics of green infrastructure practices: A review. In *Water, Air, and Soil Pollution* (Vol. 225, Issue 8). Kluwer Academic Publishers. https://doi.org/10.1007/s11270-014-2055-1

Jehanzaib M, Ajmal M, Achite M, Kim TW (2022) Comprehensive Review: Advancements in Rainfall-Runoff Modelling for Flood Mitigation. Climate 10(10). https://doi.org/10.3390/cli10100147

Jeon DJ, Ki SJ, Cha YK, Park Y, Kim JH (2018) New methodology of evaluation of best management practices performances for an agricultural watershed according to the climate change scenarios: A hybrid use of deterministic and decision support models. Ecol Eng 119. https://doi.org/10.1016/j.ecoleng.2018.05.006

Kaykhosravi S, Khan UT, Jadidi A (2018) A comprehensive review of low-impact development models for research, conceptual, preliminary, and detailed design applications. Water (Switzerland) 10(11). https://doi.org/10.3390/w10111541

Khodashenas SR, Tajbakhsh M (2016) Management of Urban Drainage System Using Integrated MIKE SWMM and GIS. Journal of Water Resource and Hydraulic Engineering 5(1):36–45. https://doi.org/10.5963/jwrhe0501004

Kim HW, Tran T (2018) An evaluation of local comprehensive plans toward sustainable green infrastructure in the US. Sustainability (Switzerland) 10(11):1–21. https://doi.org/10.3390/su10114143

Kim S, Han S (2010) Urban Stormwater Capture Curve Using Three-Parameter Mixed Exponential Probability Density Function and NRCS Runoff Curve Number Method. Water Environment Research 82(1):43–50. https://doi.org/10.1002/j.1554-7531.2010.tb00255.x

Krishnan SR, Nallakaruppan MK, Chengoden R, Koppu S, Iyapparaja M, Sadhasivam J, Sethuraman S (2022) Smart Water Resource Management Using Artificial Intelligence—A Review. Sustainability (Switzerland) 14(20):1–28. https://doi.org/10.3390/su142013384

Kristvik E, Johannessen BG, Muthanna TM (2019) Temporal downscaling of IDF curves applied to future performance of local stormwater measures. *S*ustainability (Switzerland) 11(5). https://doi.org/10.3390/su11051231

Kumari A, Tanwar S, Tyagi S, Kumar N, Maasberg M, Choo KKR (2018) Multimedia big data computing and Internet of Things applications: A taxonomy and process model. Journal of Network and Computer Applications 124(May):169–195. https://doi.org/10.1016/j.jnca.2018.09.014

Leavesley GH (1994) Modeling the effects of climate change on water resources - a review. Climatic Change 28(1–2):159–177. https://doi.org/10.1007/BF01094105

Lee JG, Selvakumar A, Alvi K, Riverson J, Zhen JX, Shoemaker L, Lai FH (2012) A watershed-scale design optimization model for stormwater best management practices. Environmental Modelling and Software 37:6–18. https://doi.org/10.1016/j.envsoft.2012.04.011

Lisenbee WA, Hathaway JM, Burns MJ, Fletcher TD (2021) Modeling bioretention stormwater systems: Current models and future research needs. In *Environmental Modelling and Software* (Vol. 144). Elsevier Ltd. https://doi.org/10.1016/j.envsoft.2021.105146

Li H, Xu Y, Yin Z, Liu J (2020) A review of stormwater management models for urban areas. Environ Sci Poll Res 27(18):23519–23539. https://doi.org/10.1007/978-3-030-11818-1

Lucas WC (2004) Delaware Urban Runoff Management Model-Hydrology and Hydraulics

Mao X, Jia H, Yu SL (2017) Assessing the ecological benefits of aggregate LID-BMPs through modeling. Ecological Modelling 353:139–149. https://doi.org/10.1016/j.ecolmodel.2016.10.018

McGarity AE (2012) Storm-Water Investment Strategy Evaluation Model for Impaired Urban Watersheds. Journal of Water Resources Planning and Management 138(2):111–124. https://doi.org/10.1061/(ASCE)wr.1943-5452.0000157

Mensah JK, Ofosu EA, Yidana SM, Akpoti K, Kabo-bah AT (2022) Integrated modeling of hydrological processes and groundwater recharge based on land use land cover, and climate changes: A systematic review. Environ Adv 8:100224. https://doi.org/10.1016/j.envadv.2022.100224

Meshram SG, Singh VP, Kisi O, Karimi V, Meshram C (2020) Application of Artificial Neural Networks, Support Vector Machine, and Multiple Models to Sediment Yield Prediction. Water Resources Management 34:4561–4575. https://doi.org/10.1007/s11269-020-02672-8(2020)

Meyer SP, Salem TH, Labadie JW (1993) Geographic Information Systems in Urban Storm-Water Management. J Water Resources Plan Manag 119(2). https://doi.org/10.1061/(ASCE)0733-9496(1993)119:2(206)

Mok S, Hawxwell T, Kramer M, Maciulyte E (2019) NBS Value Model: D6.4 Deliverable. Urban Nature Labs 730052:26–62

Molla A, Mitra C, Vasconcelos J (2022) Assessment of and Solutions to the Stormwater Management System of Auburn University Campus in Auburn, Alabama. J Water Manag Model 30(June). https://doi.org/10.14796/JWMM.C488

Nafchi RF, Pardis Y, Vanani HR, Ostad-Ali-Askari K, Jafar N, Bizhan M (2022) Correction to: Eco-hydrologic stability zonation of dams and power plants using the combined models of SMCE and CEQUALW2. Appl Water Sci 12(4). https://doi.org/10.1007/s13201-021-01563-6

Neal J, Schumann G, Bates P (2012) A subgrid channel model for simulating river hydraulics and floodplain inundation over large and data-sparse areas. Water Resour Res 48(11). https://doi.org/10.1029/2012WR012514

Niyonkuru P, Sang JK, Nyadawa MO, Munyaneza O (2018) Calibration and validation of EPA SWMM for stormwater runoff modelling in Nyabugogo catchment, Rwanda. Open Access Journal of Sustainable Research in Engineering 4(4):152–159

Nordman EE, Isely E, Isely P, Denning R (2018) Benefit-cost analysis of stormwater green infrastructure practices for Grand Rapids, Michigan, USA. Journal of Cleaner Production 200:501–510. https://doi.org/10.1016/j.jclepro.2018.07.152

Paleg N, Molnal P (2019) Rainfall monitoring, modeling, and forecasting in urban environments. UrbanRain18: 11th International Workshop on Precipitation in Urban Areas. Conference Nadav Peleg & Peter Molnar. Inst Environ Eng ETH Zurich, Switzerland. https://doi.org/10.3929/ethz-b-000347485

Palla A, Berretta C, Lanza LG, La Barbera P (2008) Modeling stormwater control operated by green roofs at the urban catchment scale. 1–10

Palmstrom N, Walker WW (1990) The P8 Urban Catchment Model for Evaluating Nonpoint Source Controls at the Local Level. In Enhancing States' Lake Management Programs

Park D, Song Y-I, Roesner LA (2013) Effect of the Seasonal Rainfall Distribution on Storm-Water Quality Capture Volume Estimation. Journal of Water Resources Planning and Management 139(1):45–52. https://doi.org/10.1061/(ASCE)wr.1943-5452.0000204

Perin R, Trigatti M, Nicolini M, Campolo M, Goi D (2020) Automated calibration of the EPA-SWMM model for a small suburban catchment using PEST: a case study. Environ Monit Assessment 192(6). https://doi.org/10.1007/s10661-020-08338-7

Rabiei J, Khademi MS, Bagherpour S, Ebadi N, Karimi A, Ostad-Ali-Askari K (2022) Investigation of fire risk zones using heat–humidity time series data and vegetation. Appl Water Sci 12. https://doi.org/10.1007/s13201-022-01742-z

Raine TJ (1999) Modeling and Analysis of Non-point Source Runoff and Best Management Practice Devices in Acton, MA Department of Civil and Environmental Engineering Modeling and Analysis of Non-point Source Runoff and Best Management Practice Devices in Acton, MA

Ramly S, Tahir W (2016) Application of HEC-GeoHMS and HEC-HMS as Rainfall-Runoff Model for Flood Simulation. ISFRAM 2015:181–192

Rangari VA, Kumar Patel A, Umamahesh NV (2015) Review of urban stormwater models. Water Resources and River Engineering 16:37

Rehman J, Sohaib O, Asif M, Pradhan B (2019) Applying systems thinking to flood disaster management for sustainable development. International Journal of Disaster Risk Reduction 36:669–677. https://doi.org/10.1016/j.ijdrr.2019.101101

Renouf MA, Serrao-Neumann S, Kenway SJ, Morgan EA, Low Choy D (2017) Urban water metabolism indicators derived from a water mass balance – Bridging the gap between visions and performance assessment of urban water resource management. Water Research 122:669–677. https://doi.org/10.1016/j.watres.2017.05.060

Rodak CM, Jayakaran AD, Moore TL, David R, Rhodes ER, Vogel JR (2020) Urban stormwater characterization, control, and treatment. Water Environment Research 92(10):1552–1586. https://doi.org/10.1002/wer.1403

Rodríguez JP, McIntyre N, Díaz-Granados M, Maksimović Č (2012) A database and model to support proactive management of sediment-related sewer blockages. Water Research 46(15):4571–4586. https://doi.org/10.1016/j.watres.2012.06.037

Saby L, Nelson JD, Band LE, Goodall JL (2021) Nonpoint Source Water Quality Trading outcomes: Landscape-scale patterns and integration with watershed management priorities. J Environ Manag 294. https://doi.org/10.1016/j.jenvman.2021.112914

Shamsi UM (2005) GIS application for water, wastewater, and stormwater systems. Taylor and Francis

Shaneyfelt KM, Johnson JP, Hunt WF (2021) Hydrologic Modeling of Distributed Stormwater Control Measure Retrofit and Examination of Impact of Sub catchment Discretization in PCSWMM. Journal of Sustainable Water in the Built Environment 7(3):1–13. https://doi.org/10.1061/jswbay.0000938

Sidek LM, Chua LHC, Azizi ASM, Basri H, Jaafar AS, Moon WC (2021) Application of pcswmm for the 1-d and 1-d–2-d modeling of urban flooding in Damansara catchment. Malaysia. Applied Sciences (Switzerland) 11(19):1–16. https://doi.org/10.3390/app11199300

Stephens C, Lall U, Johnson F, Marshall L (2020) Landscape changes and their hydrologic effects: Interactions and feedback across scales. Earth-Science Reviews 212. https://doi.org/10.1016/j.earscirev.2020.103466

STILLWATER CO (2013) Mckusick Lake Aquatic Plant Management Plan

Sun T, Bou-Zeid E, Wang ZH, Zerba E, Ni GH (2013) Hydrometeorological determinants of green roof performance via a vertically resolved model for heat and water transport. Building and Environment 60:211–224. https://doi.org/10.1016/j.buildenv.2012.10.018

Sun Y, Li Q, Yu F, Ma M, Xu C (2023) Assessing Hydrological Performances of Bioretention Cells to Meet the LID Goals. Sustainability (Switzerland) 15(5). https://doi.org/10.3390/su15054204

Tayefeh Neskili N, Zahraie B, Saghafian B (2017) Coupling snow accumulation and melt rate modules of monthly water balance models with the Jazim monthly water balance model. Hydrological Sciences Journal 62(14):2348–2368. https://doi.org/10.1080/02626667.2017.1373778

Teng J, Jakeman AJ, Vaze J, Croke BFW, Dutta D, Kim S (2017) Flood inundation modelling: A review of methods, recent advances, and uncertainty analysis. Environmental Modelling and Software 90:201–216. https://doi.org/10.1016/j.envsoft.2017.01.006

Tuler SP, Webler T, Rhoades JL (2016) Stormwater management in a time of climate change: Insights from a series of scenario-building dialogues. Weather, Climate, and Society 8(2):163–175. https://doi.org/10.1175/WCAS-D-15-0048.1

Vezzaro L, Mikkelsen PS (2012) Application of global sensitivity analysis and uncertainty quantification in dynamic modelling of micro-pollutants in stormwater runoff. Environmental Modelling and Software 27–28:40–51. https://doi.org/10.1016/j.envsoft.2011.09.012

Wang J, Zhang P, Yang L, Huang T (2016) Cadmium removal from urban stormwater runoff via bioretention technology and effluent risk assessment for discharge to surface water. Journal of Contaminant Hydrology 185–186:42–50. https://doi.org/10.1016/j.jconhyd.2016.01.002

Wanielista MP, Yousef YA (1992) Stormwater management. John Wiley and Sons

Warwick JJ, Wilson JS (1990) Estimating Uncertainty of Stormwater Runoff Computations. Journal of Water Resources Planning and Management 116:187–204

Welsh WD, Vaze J, Dutta D, Rassam D, Rahman JM, Jolly ID, Wallbrink P, Podger GM, Bethune M, Hardy MJ, Teng J, Lerat J (2013) An integrated modeling framework for regulated river systems. Environ Model Software 39. https://doi.org/10.1016/j.envsoft.2012.02.022

Wu J, Pete K, Hunt J, McKee L (2018) Green Infrastructure Planning for the City of Sunnyvale with GreenPlan-IT (Issue 881)

Yang SN, Chang LC, Chang FJ (2019) AI-based design of urban stormwater detention facilities accounting for carryover storage. J Hydrol 575. https://doi.org/10.1016/j.jhydrol.2019.06.009

Zhang B, Li J, Li Y (2020) Simulation and optimization of rain gardens via DRAINMOD model and response surface methodology. Ecohydrol Hydrobiol 20(3). https://doi.org/10.1016/j.ecohyd.2020.03.002

Zölch T, Henze L, Keilholz P, Pauleit S (2017) Regulating urban surface runoff through nature-based solutions – An assessment at the micro-scale. Environ Res 157. https://doi.org/10.1016/j.envres.2017.05.023