AN URBAN DENSITY-BASED RUNOFF SIMULATION FRAMEWORK TO ENVISAGE FLOOD RESILIENCE OF CITIES.

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Degree of Master Science by Research

Department of Town & Country Planning

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Declaration

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The supervisor/s should certify the thesis/dissertation with the following declaration.

The above candidate has carried out research for the Masters/~~MPhil/PhD~~ thesis/ Dissertation under my supervision.

Name of the supervisor: Supervisor1 : Dr.(Ms) Chethika Abenayake
Supervisor2 : Dr. Amila Jayasinghe

Signature of the supervisor:………………… Date : 03.07.2023
Dr.(Ms) Chethika Abenayake

Signature of the supervisor:………………… Date : 03.07.2023
(Dr. Amila Jayasinghe)

Abstract

Urban form densities play a decisive role in complex urban form scenarios. Therefore, learning to ‘live with the floods’; has become a challenging issue to practice in most urban planning approaches. Several simulation studies have been conducted to examine the influence of urbanization scenarios on urban flood risk management. Yet, there is a gap remaining to optimize every component of flood hydrodynamics across a distinct urban form density. As a result, the economic loss to the urban system is hard to minimize. But planning an intervention with a proper quantification approach for a long-term flood management strategy is useful for making cities resilience to floods. The primary aim of this research is to create a spatial simulation framework that can evaluate how urban density(UD) affects surface runoff (SR) in urban watersheds in various urban form scenarios. First, examine the potential quantification indicators of urban form density. Second, develop a framework to quantify urban form density at the urban watershed scale, which applies to spatial structure. The third step involves creating an SR simulation model that utilizes the 13 selected UD indicators to verify and validate the previously developed framework with real-world data, with the main three categories (3Ds') as per the developed framework. The model evaluates itself with AI-based Decision Tree Analysis incorporated with correlation and experts’ opinions. The model results indicate that the UD indicators including impervious coverage (accuracy level 98.7%), OSR (accuracy level 94.8%), and road density (accuracy level 93.5%) are the key indicators combined with the population density, accessibility, and built_up coverage to regulate SR in urban catchments. The ground verification of model results indicates an R2 value greater than 0.88. The ultimate goal of this study is to create a method of quantitatively evaluating the effects of physical UD as an independent variable, allowing for a more location specific manner. This study contributes a novel framework incorporating 3Ds (density, diversity, design) to quantify UD, which will aid subsequent processes of decision-making in the realm of urban flood mitigation and planning techniques.

Keywords: Urban flood, Urban density (UD), Surface runoff (SR), planning & decision-making, resilience

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Acknowledgment

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List of Abbreviations

2D RRI	Two-Dimensional Rainfall-Runoff-Inundation
3Di	Three-dimensional flood model
3Ds	Density, Diversity, Design
AI	Artificial Intelligence
ARW	Access Road Width
BD	Building Density
BEATS	Biophysical Environments and Technologies Simulator
BH	Building Height
CD	Colombo District
DD	Derange Density
DE	Design Elements
DEM	Digital Elevation Model
DS	Digital Simulation
DTA	Decision Tree Analysis
EPA	Environmental Protection Agency
FAR	Floor Area Ratio
FSI	Floor Space Index
GI	Green Infrastructure
GIS	Geographic Information System
GSI	Ground Space Index
HEC-RAS	Horologic Engineering Center’s River Analysis System
IC	Impervious Coverage
KD	Kalutara District
L	Local
LID	Low Impact Development
ML	Machine Learning
NBS	Nature based solution
OSR	Opens space ratio
PCSWMM	Personal Computer Storm Water Management Model
PD	population density
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
R	Regional
RD	Road density
RS	Remote Sensing based
SD	Spatial Density
SR	Surface Runoff
SUDS	sustainable urban drainage system
SWMM	Storm Water Management Model
UD	Urban Density
UNDP	United Nations Development Programme
UNDRR	United Nations Office for Disaster Risk Reduction
USD	United States Dollar
USMS	Urban water management system/techniques
WSUD	water sensitive urban design

CHAPTER 1: INTRODUCTION

1.1 Introduction

Urbanization often results in a rise in the severity and frequency of flooding , making communities more susceptible to increasingly serious flood dangers. Flooding is a frequent risk that affects urban areas and may result in significant harm to the environment, society and property. The high population density, the close proximity of services, and the existence of impermeable surfaces in metropolitan areas are the main causes of this. Urban flooding is a problem since more than half of the world's population lives in urbanized regions (Ashley et al., 2007; World Bank, 2017). Over the last two decades (2000-2019), there has been a significant increase in the number of reported flooding incidents, more than twice the amount observed during the previous decade (UNDRR, 2020; United Nations et al., 2019). The number of recorded events, rose from 1,389 to 3,254, whereas the quantity of incidents related to weather and flood damage increased from 1,457 to 2,034 events. The total economic loss recorded due to these events was 2.97 trillion USD (UNDRR, 2020). Consequently, many countries are prioritizing measures to increase the resilience of cities to flooding.

While flooding considers a naturally occurring event, the risk associated with it is amplified by the exposition and susceptibility of the community (Feng et al., 2021). The threat of flooding is increasing with rapid urbanization, particularly with the agglomeration of communities into urban areas (Kang et al., 2021). As a result, built-up areas have emerged as susceptible hot points for severe flooding incidents caused by intense development. The urban morphological features, such as layout, design, and structure of buildings, streets, and transportation systems can substantially affect the flow of flooding. (Ferrari & Viero, 2020; Kang et al., 2021). Urban areas experience increased the highest flow rates during a flood event due to human activities, resulting in a reduction of their capacity to store water in comparison to rural areas. Urban density (UD) is a key factor with significant implications in altering the natural flow patterns of water, leading to sudden inundations (Feng et al., 2021; Ferrari & Viero, 2020; Kang et al., 2021). This study will evaluate how UD affects the damage caused by flooding. Urban planners, architects, engineers, and government organizations can use UD as a tool for making decisions to mitigate urban flood hazards since it is a basic component that impacts anthropogenic activities.

The primary studies indicate that there are several factors responsible for the increase in peak discharge of urban catchments (Gupta & Nair, 2011) (T. T. Nguyen et al., 2019). Compared to other elements that cause urban flooding, such as high precipitation, watershed terrain, geological characteristics, types of plant canopy, and hydrologic issues in urban areas, the degree of UD has the biggest influence on the peak discharge of flood occurrences (Alexander, 1993). The UD regulates how much rainfall and Surface Runoff (SR) are discharged into the urban setting over paving, lodging, and construction, during a particular flood event (Hoyer & Dickhaut, 2010; Park & Lee, 2019). Recent literature has extensively investigated the natural factors associated with SR in urban environments. However, our understanding of the complex and dynamic relationship between UD and SR remains limited due to a lack of comprehensive evaluation frameworks (Madusanka et al., 2022; Sharifi, 2019).

1.2 Research Problem

Thousands of people throughout the world deal with flood catastrophes each year. The disruption of natural flood defense systems caused by the significant development of built-up environments increases flood vulnerability and damage (Pregnolato et al., 2017) . It has become very difficult for decision-makers to quantify the change of SR with dynamic urban form density because to the limited availability and accuracy of applicable approaches. The rapid-unplanned urban expansion and the high land demand in urban areas trigger urban flooding, which challenges the entire urban system. It has had a number of negative effects, including as the loss of livelihoods, economic damage, ecological degradation, and considerable decline in property values and road congestion in urban catchment regions (UNDRR, 2020). In the absence of a comprehensive framework to assess the relationship between US on SR level is significant to reduce the risk. This can help to reduce human and economic losses in urban environments, both directly and indirectly. Although forecasting and managing floods is challenging, it is possible with the appropriate quantitative frameworks and assessment approaches.

Consequently, it is impossible to eliminate urban flood hazards, damage can be reduced by using a solid flood evaluation methodology and a thorough understanding of urban form dynamics. The level of SR that can be managed by planning intervention at the initial stage is strongly influenced by UD. To regulate SR by modifications to UD, which may be used as a long-term flood management technique at the micro-urban watersheds (i.e., local level), however, there is just a small amount of material available in the literature. It results in less flood damage and increases the flood resiliency of metropolitan areas.

In order to reduce the negative impacts of urbanisation on hydrological processes and to encourage sustainable and resilient urban development, this research has been done on focusing the relationship between UD and SR.

1.3 Research Need

Human activities, including the recycling of water-logged areas, constructions in low-lying zones, urban sprawl, infrastructural challenges, economic and social factors, have a substantial influence on high SR in urban watersheds. These factors challenge the global efforts to build flood- resilience cities and contribute to the occurrence of urban flooding (Talbot, et al., 2018) (UNDP, 2017) (Crandell, 2011). Improving the flood resilience of urban areas has emerged as a more effective flood management strategy. Numerous studies have demonstrated that the UD, including built-up density, density of road network, land use features, and built form topographies, has a substantial impact on increasing SR in urban watersheds (Ferrari & Viero, 2020; Kändler et al., 2020; O'Donnell & Thorne, 2020). Several proxies or indicators have been used to measure UD in various studies. However, there is no consensus on which indicator best represents the level of SR. In addition, many UD indicators are used in various models and many urban morphological features are interrelated, there may be overlap, leading to multicollinearity, which could weaken the conceptual framework of current models (Wright, 2007) (Dempsey et al., 2008). Therefore, it is necessary to create an effective quantification technique to determine how UD has an influence on the change of SR.

High-density urban patterns imply the existence of large areas covered by impermeable surfaces, which reduces the natural infiltration process. Due to a decrease in the hydraulic reaction time and an increase in the level of risk of floods, this causes the rate of peak runoff in urban areas(Kang et al., 2021). In various urbanization scenarios, (Eini et al., 2020) analyses how urban expansion affects the rate of natural penetration. According to the proportion of the total impermeable surface areas, across various land uses in urban watersheds is closely correlated with UD. Land use with variation in geography may make flash floods more severe with similar average impervious surface area percentages compared to land use and UD that are spatially consistent (Feng et al., 2021). Therefore, the concept of UD needs to be analysed comprehensively in the complex and dynamic reality of urban watersheds in order to understand its impact on SR (Afifi et al., 2019; C. Chen et al., 2008). In a dynamic urban environment, the influence of UD on flash flooding and overflow in a considerable manner.

Although previous studies have assessed the urban flood using environmental-based parameters such as topography, geological, soil, precipitation, land use changes, and hydrology various spatial scales. But the impact of density in urban area (UD) not considers as an isolated determinant on flash floods in existing research (Cea & Costabile, 2022; Rezaei et al., 2019). The connection between UD and flood risk is not fully understood, and the research on this topic is currently restricted to the scale of urban watersheds. Additionally, there is a lack of specific techniques for predicting and reducing floods in metropolitan areas. This presents a significant challenge for those in charge of making decisions, including urban planners, the government, local governments, and NGOs. Therefore, to address this issue, it is essential to provide a thorough, theory-driven methodology to assess the impact of UD on urban flooding. This strategy will give decision-makers and urban planners a useful tool for controlling flood risk in urban settings, enabling them to make more strategic decisions to safeguard communities from the detrimental effects of floods.

1.4 Research Aim and Objectives

In this study, aim to develop a holistic framework that can assess the impact of UD on SR levels in different urban watersheds located in Sri Lanka. To understand how varying levels of UD affect SR and to provide insights for sustainable urban planning and development. Under this aim, three objectives are going to be achieved.

1. To determine urban form based indicators for quantifying SR that are associated with UD.
2. To create a theory-based conceptual framework that identifies how changes in UD impact the quantity of SR within urban micro-watersheds.

3. To assess the effectiveness of the developed framework as a planning aid and decision-making tool through validation with real-world data and planning practitioners.

1.5 Significance of the Study

Developing such a simulation framework can be useful in envisioning the flood resilience of cities by providing a tool to assess and understand the complex interactions, between urban development, land use, and hydrological processes. The proposed framework can be simulated runoff behaviour in an urban environment. This provides insights into how different urban development scenarios, such as the use of green infrastructure or the implementation of zoning regulations, can impact the water cycle in urban areas. In addition, research on UD and SR can help city planners and engineers to understand and model the complex interactions, to make planning and design decisions, to create more sustainable and resilience cities. Identifying areas of high flood risk and developing appropriate strategies to manage stormwater runoff, in urban areas can reduce the impact of flooding and water pollution on both humans and the natural environment. Further, this could include measures such as increasing green infrastructure (open spaces), improving drainage systems, or implementing zoning regulations that limit the number of impervious surfaces in certain urban areas in a strategic manner. That would utilize by urban regulatory bodies in their planning practices.

1.6 Scope of the Study and Limitations

The scope of the study was narrowed down from analysis of flood disasters to the urban floods that occurred due to urban agglomeration. Here identified three limitations under the literature survey which going to be addressed through this study. First, there is not any specific measuring indicator of UD. Second, the available flood modelling methods have time-consuming and required vast numbers of data or are simulated under commercial platforms. Third, flood mitigation through urban form variations experiences yet to be identified as climate change adaptation research and policy (Aalst et al, 2008). Hence this study fulfils the above three areas by creating a framework to evaluate the impact of UD modifications on SR levels within micro-watersheds in urban areas.

The limited availability of data access is one of the main limitations of this study. Here utilised a combination of open access data and real-time flood data in free and open-source modelling applications.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter provides a basic idea of how the urban flood differs from the natural flood phenomenon and how UD influences the SR under different urban scenarios. A systematic literature review was conducted to achieve the first and second objectives of this study. Next narrative' synthesis is utilized to develop the conceptual framework and define variables. The final section of this chapter examines the existing possibilities and practical examples of managing urban floods by utilizing UD related mechanisms in different scenarios. The more detailed literature review and the narrative literature reviews are used to develop the research methodology, which is represented in the next chapter (chapter 3 -methodology and proposed conceptual framework).

2.2 Urban Density(UD) impact on Urban Flood

UD can have a significant impact on urban floods. When cities become more densely populated, there is often a corresponding increase in the amount of impervious surfaces, such as buildings and paved roads, which can reduce the capacity of the urban landscape to absorb and store rainwater (Kirshen et al., 2008). This, in turn, can lead to more frequent and severe urban flooding. High UD can also lead to a greater demand for urban infrastructure, including stormwater drainage systems (Ashley et al., 2007; Cea & Costabile, 2022). However, these systems may not be able to cope with the increased volume of SR generated by dense urban catchments, which can result in flooding.

The urban areas where there is a high concentration of people and infrastructure. Hence the urban flooding has become increasingly problematic for regional and local flood management. Human actors exacerbate the situation by altering land use, occupying the flood plain, maintaining drainage systems insufficiently, and obstructing drainage channels through poor solid waste disposal at urban environment. The high-density urban areas are more vulnerable to flooding due to impervious areas, the structure of the buildings, and the lack of green/open spaces (Lee & Brody, 2018). As a result, urban morphological features have a significant impact on changing SR in dense urban watersheds. The following sections define and examine how UD influences on the urban flood (to increase SR). UD indicates the physical or urban morphological configuration in an urban area which shapes urban space (Berling-Wolff & Wu, 2004). According to

(Hitchcock, 1994) density appears to be a simple concept in land use planning, but the complex reality of applying it to a three-dimensional city cannot be fully reflected by one density measure. However UD is a key element of urban morphology (urban form) among street network, land use, building types and urban layout (Dempsey et al., 2008). UD is an outcome of anthropogenic activities and land use policy or regulations which may change with time series. It refers to the number of inhabitants, buildings, roads, and streets in a particular urban area in a given period (Batty, M, 2019).

The severity of urban flood can be changed with UD parameters such as building density, the density of open space, population density, land use density, drainage density etc (Zevenbergen, 2011). The rapid urbanization the water movement pattern in an urban environment getting more complex. Urban floods happen when the system cannot handle the volume or intensity of precipitation, or when certain components of the system aren't working effectively.

2.2.1 Urban flood

Urban flooding occurs with heavy precipitation overwhelm the capacity of urban drainage systems, leading to the inundation of streets, buildings, and other urban infrastructure. Urban flooding can also occur as a result of rapid sprawl, coastal storm surge, or the failure of water management infrastructure (World Bank, 2017). But the most frequent type of urban flood occurs with densely populated areas with a high percentage of impervious surfaces, such as concrete and asphalt, which reduce the ability of the landscape to absorb and store water (Zevenbergen, 2011)   (Fernández & Lutz, 2010). It occur during extreme weather events, such as hurricanes or severe storms (Atta-ur-Rahman et al., 2016; Cook et al., 2019). In some cases, urban flooding can occur as a result of man-made factors, such as inadequate drainage systems or poor urban planning. Hence the urban floods can have a significant impact on urban areas, causing damage to buildings and infrastructure, disrupting transportation systems, and posing a threat to public health and safety (Rezaei et al., 2019). As a result, there is a growing need for strategies to mitigate the impact of urban floods and promote more sustainable and resilience urban development.

Considering the factors to distinguish urban flooding from rural flooding are the distinctive qualities of urban areas; in its most basic form, urbanization involves removing flora and land cover to make space for impervious constructions like parking lots, buildings, and highways (Eini et al., 2020; Li et al., 2022). The local soil's inherent ability to store water is reduced or even gone. Construction-related (and unintentional) drainage canals change the hydrology and flow regimes so that rainwater moves quickly over the surface in brief bursts of high intensity and volume get quick inundations (Campana & Tucci, 2001) (Hoyer, et al., 2006). When the UD is high in urban areas, which directly increases the SR in adverse rainfall events refer Figure 1 and 2.

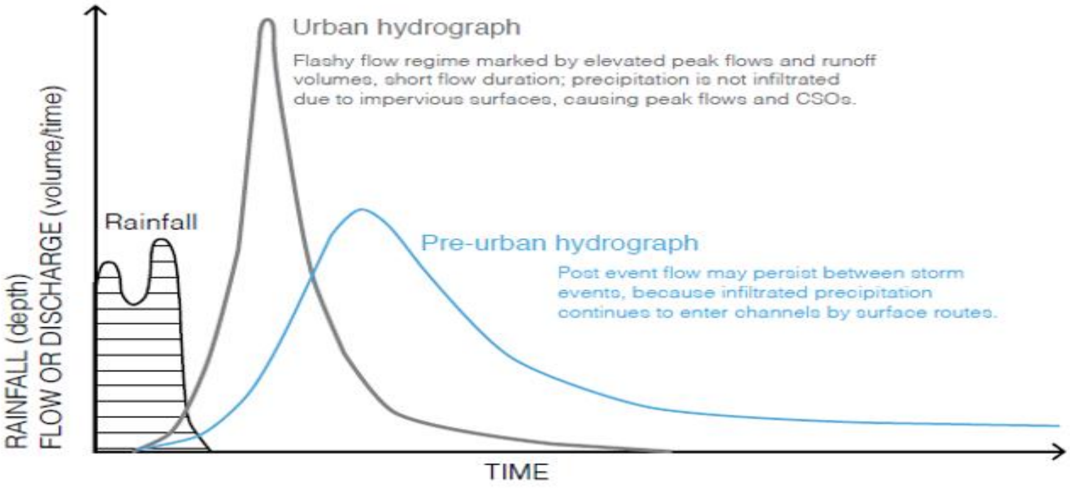


Figure 1:Difference between natural and urban hydrographs

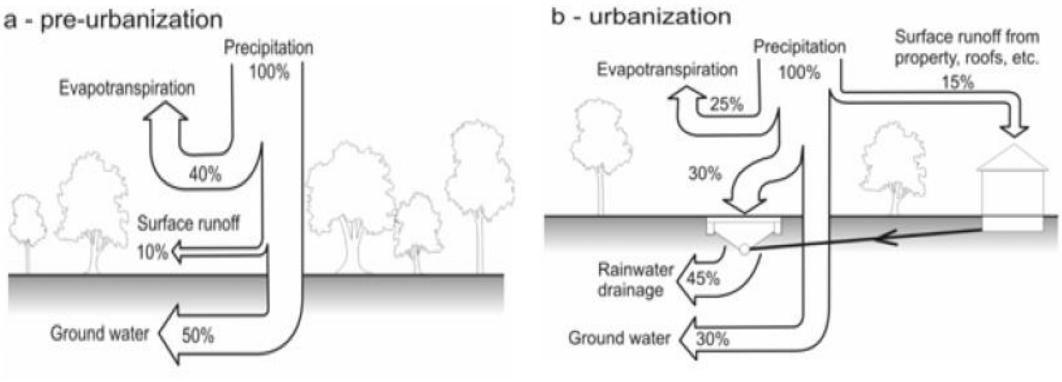


Figure 2: Water balance characteristics in a natural (a) and urban watershed(b)

The Figure 3 indicates how the UD saviour flood related problems in urban environment. Urban flooding has obvious and visible immediate effects, including flooding of homes and buildings, structural damage, washing away of possessions and automobiles, destruction of public infrastructure, and widespread muck and mould. But the indirect aspects of the urban flood are unable to disappear which takes a long term to recover

(Berling-Wolff & Wu, 2004; H. D. Nguyen et al., 2021; United Nations et al., 2019). As a result, that the UD play a significant role in cumulative SR at the urban micro-watershed scale.

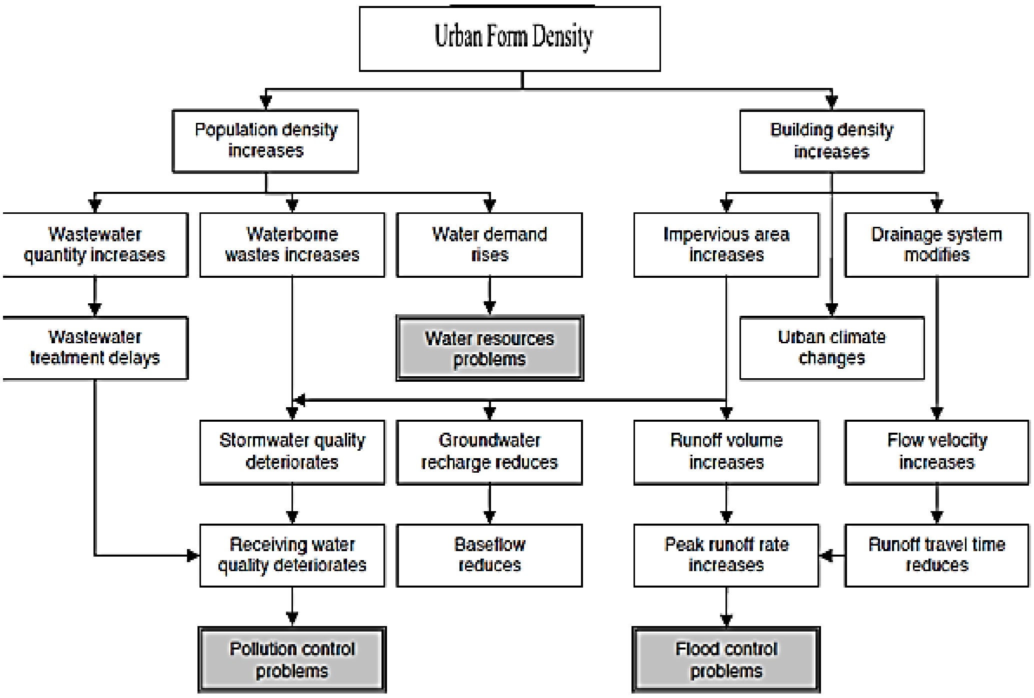


Figure 3: How urban form density increase runoff and make flood-related urban problems.

2.3 Summary of the Systematic Review

A systematic review of literature carryout to identify the impact of UD on SR would typically include the following sections.

2.3.1 Search strategy

A systematic review was carried out as per the objectives of this study using Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) analysis protocols checklist. This study used SCOPUS scientific database using the advanced search options Title – Abstract – Keyword (TITLE-ABS-KEY) and additional open access articles. The search query is built under two purposes; the first to understand the concept of urban density-based urban form factors on urban flooding and to find the various measures and parameters developed in this field. The second query was built to find the simulation type of models, usage, limitations, and model application in different urban contexts utilized in urban flood modelling. The search was conducted up to the 21st of August in 2021. The below depicts the search queries. The result of the first query selected 207 articles and the second query selected 224 articles respectively.

```
TITLE-ABS-KEY ( urban  AND flood  AND  density )  AND  ( building  OR  morphology )  AND  ( LIMIT-TO (
PUBYEAR ,  2021 )  OR  LIMIT-TO ( PUBYEAR ,  2020 )  OR  LIMIT-TO ( PUBYEAR ,  2019 )  OR  LIMIT-TO
( PUBYEAR ,  2018 )  OR  LIMIT-TO ( PUBYEAR ,  2017 )  OR  LIMIT-TO ( PUBYEAR ,  2016 )  OR  LIMIT-
TO ( PUBYEAR ,  2015 )  OR  LIMIT-TO ( PUBYEAR ,  2014 )  OR  LIMIT-TO ( PUBYEAR ,  2013 )  OR  LIMIT-
TO ( PUBYEAR ,  2012 )  OR  LIMIT-TO ( PUBYEAR ,  2011 ) )  AND  ( LIMIT-TO ( LANGUAGE ,  "English"
) )
```

```
TITLE-ABS-KEY ( urban  AND flood  AND model* )  AND  ( density )  AND  ( LIMIT-TO ( PUBYEAR ,  2021 )
OR  LIMIT-TO ( PUBYEAR ,  2020 )  OR  LIMIT-TO ( PUBYEAR ,  2019 )  OR  LIMIT-TO ( PUBYEAR ,  2018
)  OR  LIMIT-TO ( PUBYEAR ,  2017 )  OR  LIMIT-TO ( PUBYEAR ,  2016 )  OR  LIMIT-TO ( PUBYEAR ,
2015 )  OR  LIMIT-TO ( PUBYEAR ,  2014 )  OR  LIMIT-TO ( PUBYEAR ,  2013 )  OR  LIMIT-TO ( PUBYEAR
,  2012 )  OR  LIMIT-TO ( PUBYEAR ,  2011 ) )  AND  ( LIMIT-TO ( LANGUAGE ,  "English" ) )  AND  ( LIMIT-
TO ( OA ,  "all" ) )
```

2.3.2 Eligibility Criteria

This study followed explicitly stated objectives with a set of pre-defined eligibility criteria, as well as a systematic search to discover all eligible papers to ensure that the approach was explicit and reproducible. Below Table 1 depicts the inclusion and exclusion criteria of the abstract screening process.

Table 1: Criteria included or excluded from the systematic review.

Inclusion Criteria	Exclusion Criteria
• The articles should include urban form density factor with the urban flood. • The articles should include urban flood modelling applications. • The article should relate to the urban planning subject field.	1. Articles that do not include urban flood, as a disaster or urban form density factor. 2. Articles that do not include urban flood modelling applications. 3. Articles that do not match with the urban planning subject field. 4. Articles which Socio-economic considerations or disaster/ flood evacuation. 5. Articles that focused on coastal flooding, sea-level rise flooding, or flooding amongst other natural hazards. 6. Articles that focused only on the hydraulic perspective.

2.3.3 Study selection and data extraction

As depicted in Figure 4 all the articles screening the title and abstract as per the above-defined eligibility criteria as the first step under the data extraction. After screening the title and abstract 314 articles are excluded from a total of 441 articles. Secondly, the remaining 127 of articles were selected for full-text reading and it was carried outflowing the same eligibility criteria. After the full-text reading, 85 articles are excluded after the full-text reading. The remaining 42 articles area selected for future analysis.

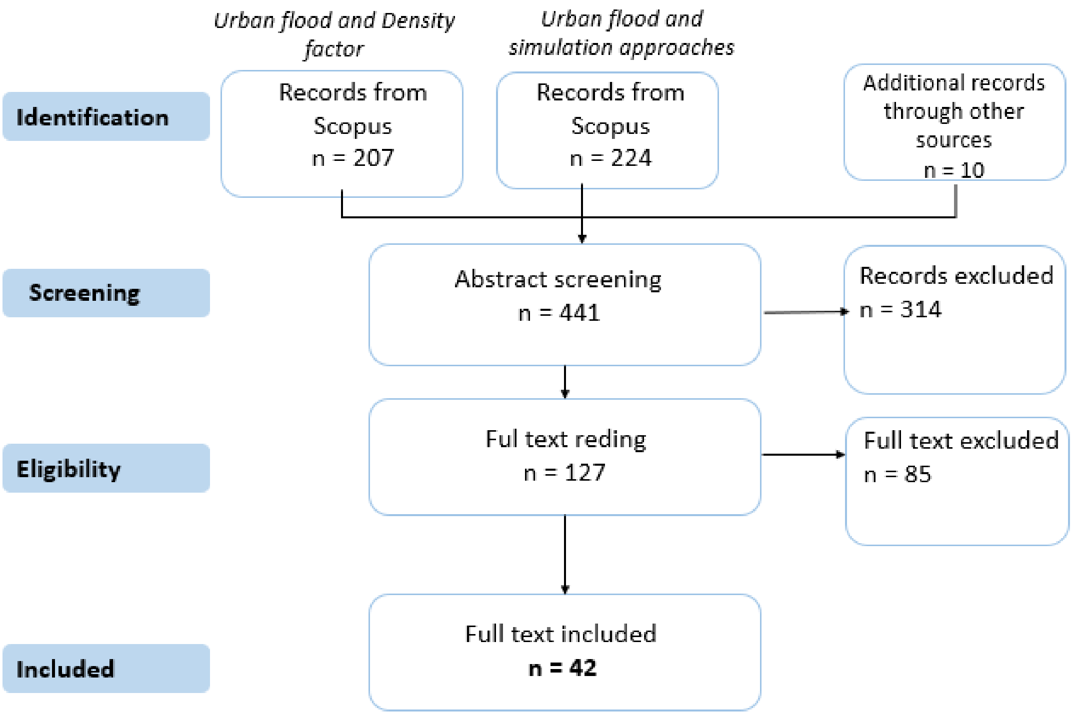


Figure 4: Systematic literature review framework using PRISMA protocol

2.3.4 Findings for Systematic Review

This systematic review was carid out to as per the first and second objectives of the study. Dense urbanization, urban floods, and human activities have been the focus of many studies in recent years. The following is a brief overview of some of the findings from the literature.

- Studies have shown that UD can lead to a higher risk of urban flooding due to increased impervious surfaces and a reduced capacity for water retention.
- UD can also lead to the degradation of natural environments, including loss of green spaces, habitat fragmentation, and decreased biodiversity with quick inundations cooperate with anthropogenic activities.
- Anthropogenic activities, including land use changes, urbanization, and deforestation, can increase the risk of urban floods by altering the natural hydrological cycle.

- The degradation of natural environments resulting from human activities can also lead to decreased resilience to extreme weather events (such as floods) and other natural disasters.
- Urban floods can have significant negative impacts on the quality of life of city communities, including damage to buildings and infrastructure, disruptions to transportation systems, and risks to public health and safety.

With this it can be reached to a compromise the dense urbanization, urban floods, and human activities are interlinked factors that contribute to the occurrence of flash floods in urban areas(Feng et al., 2021; King & Simonovic, 2020; H. D. Nguyen et al., 2021). To mitigate the impacts of flash floods, it is essential to adopt an environmental approach that takes into account the interconnected nature of these factors. This approach includes the development of sustainable urban planning and design strategies that incorporate green infrastructure, such as rain gardens and green roofs, to reduce runoff and improve water infiltration(Cook et al., 2019). It also involves improving drainage systems, promoting sustainable land use practices, and increasing community awareness about the impacts of urbanization on flood risk.

The UD measures are often used in urban planning, urban design, and environmental studies to quantify the impact of UD on various aspects of urban life(Rodrigues & Antunes, 2021). Different studies used several parameters to quantify UD, but it unable to identify clear-cut definitions of UD with their measuring variables. Some parameters are overlapping with different case study applications (i.e., site level, city level and regional level). Hence it is required to develop a proper quantification mechanism for UD. This requirement is detailly described in the next chapter (under section 3.2).

Next, identify some flood simulation models from selected articles. As a summery, the urban flood modelling is an essential tool for predicting and mitigating the impacts of floods in urban areas. There are various types of simulation models used for urban flood modelling, including hydraulic models, hydrologic models, and coupled hydrodynamic models. These models simulate the movement of water in the urban environment, allowing for the analysis of flood risk and the assessment of the effectiveness of flood mitigation measures. The models used to measure different UD indicators are attached in ‘Appendix E’.

Hydraulic models are commonly used to simulate the flow of water through urban drainage systems, such as pipes and channels. Hydrologic models, on the other hand, simulate the movement of water on the land surface, including the effects of precipitation, evapotranspiration, and infiltration (Cheng et al., 2020; Souza et al., 2020). Coupled hydrodynamic models combine both hydraulic and hydrologic models to simulate the complex interactions between water flow in urban drainage systems and overland flow.

Despite their usefulness, these models have limitations. For instance, hydraulic models can be computationally intensive and require significant amounts of input data, while hydrologic models may not account for the effects of urbanization on the hydrological cycle(Bruno et al., 2022). Coupled hydrodynamic models require significant computational resources and can be challenging to calibrate and validate. Nevertheless, these models have wide applications in different urban contexts. They can be used to develop flood risk maps, evaluate flood mitigation measures, and inform flood emergency management plans. Additionally, they can be used to analyse the impacts of land-use changes, climate change, and urbanization on flood risk in urban areas.

When comes to the urban watershed scale the selection of an accurate simulation approach is essential for the accuracy of the results. Hence this study separately defines limitations and required data with validation accuracy of each modelling framework (Refer Appendix E). The model selection process is described in section 3.6 in the next chapter.

As per the narrative review conducted to find out the ability to reduce urban flood damage with UD changing approaches under above systematic review; it has been identified some practical examples applied by some developing countries as their urban planning regulations to manage urban SR. Those measures and guidelines are applicable for different urban scales such as regional level, local level, and small site/neighbourhood levels (Sharifi, 2019). It has become clear that most economically developed countries have realized flood water issues must be addressed easily and have begun integrating solutions with new urban water management strategies and techniques based on "Sustainable Development," "Biodiversity," "Ecosystem Services," or " Ecosystem-Based Solutions," and, most recently, "Nature-Based Solutions" (NBS) (Hoyer & Dickhaut, 2010). Recently conventional flood mitigation strategies (i.e., dams, reservoirs, flood walls, levees) shifted to modern urban water management strategies focusing on to seeking safer urban flood management utilizing nature-based solutions. This approach follows more greener and sustainable direction while managing UD in a more strategic way (Cook et al., 2019; Sharifi, 2019; Zevenbergen, 2011). Those approaches are cost effective and have longer term vision to reduce future urban flood damage via most environmental friendly approach delivering environmental, social, and economic benefits.

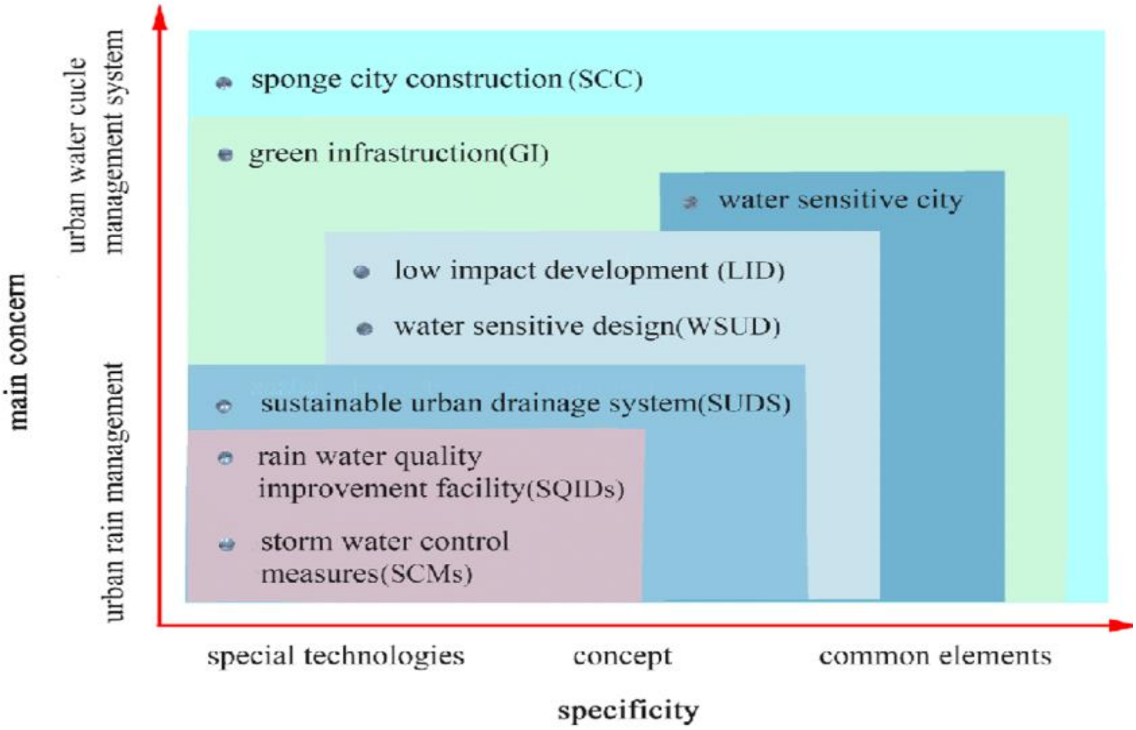


Figure 5: New urban water management strategies and techniques based on "Sustainable Development

Source: (Ma et al., 2017)

2.4 Existing Possibilities and Practical Examples of Managing Urban Floods.

The existing possibilities and practical examples of managing urban floods involve a range of strategies and techniques that aim to mitigate the impacts of floods in urban areas. An urban water mass balance is a method used to quantify the movement of water in urban areas, including the various inputs, outputs, and storage components of the urban water cycle. It involves tracking the flow of water through different pathways, such as rainfall, runoff, infiltration, evapotranspiration, and water consumption by humans and vegetation. It is often used as a tool for water resource management (Cook et al., 2019; Peng et al., 2018).

The notion of water balance (as shown in Figure 6) describes how water enters, moves through, and leaves urban areas. It also explains how urbanization affects these flows and how they must be modified to imitate a more natural hydrological water balance. The "natural" water cycle takes place in the urban context, where it is altered by urbanization and is connected to the "urban" (man-made) water system (Rodrigues & Antunes, 2021)(Essery, 1995). The "whole water cycle" is made up of "natural" and "urban" channels. Exchanges of flow between system components along each of these pathways may be investigated using the "water balance technique." Additionally, it enables the examination of flow exchanges through linkages between components of the "urban" pathway (urban water system) and components of the "natural" pathway.

Assessments of water balance in "water sensitive" (and more climate resilience) urban landscapes are often more difficult than similar evaluations in "natural," "rural," and "conventional" urban landscapes due to the related various water flow channels which applied by developed countries(Hoyer & Dickhaut, 2010). The water balance technique has nonetheless been used to research urban water systems or to help create sustainable urban water management solutions. However, the locally appropriate urban water balance framework must include a number of characteristics and capacities that allow it to fulfil a variety of functions. These include the following: the ability to accommodate the diversity and varying complexity of urban water systems; the capacity to offer a guiding tool to streamline data collection and interpretation; the capacity to facilitate consistent and accurate water balance evaluations of water systems at various scales (within a region as well as across regions); and the suitability to offer a platform for transparent and defendable reporting. So, in summary, this technic helps to manage the water within the urban environment even though the UD is high or less.

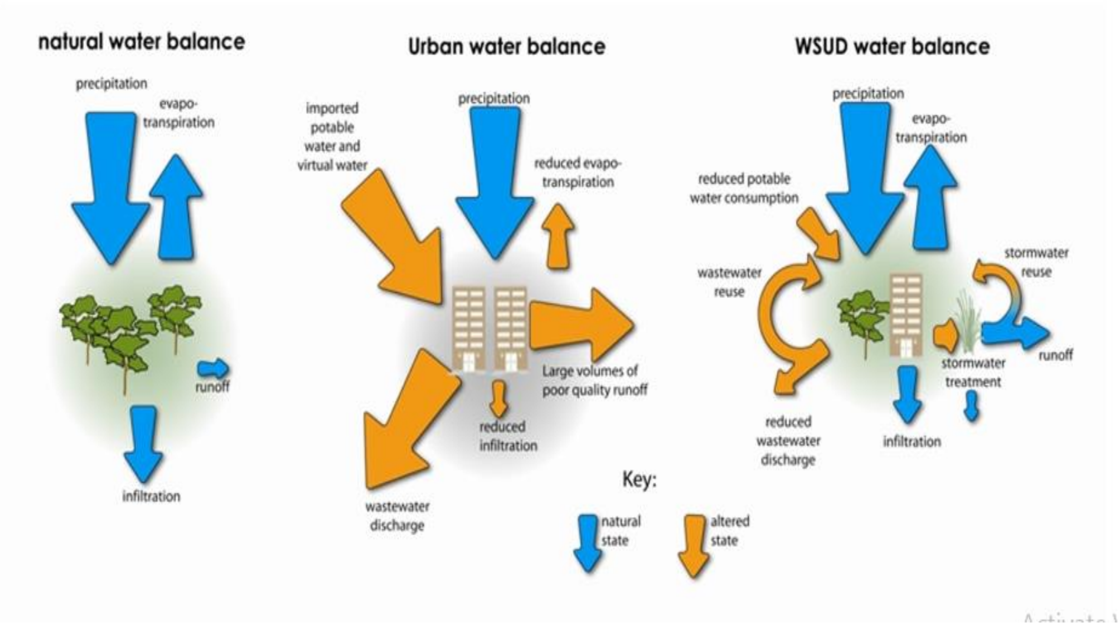
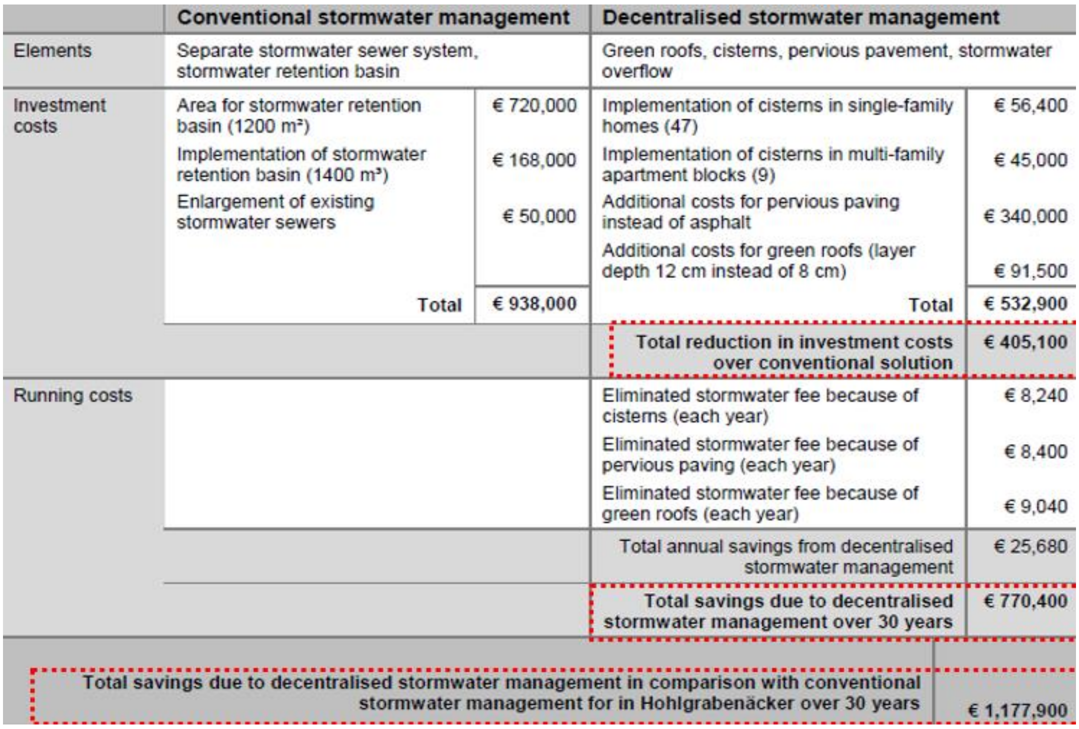


Figure 6: Increasing built form density of the water balance through Urban Water Mass Balance

(Kubin, 1992) asserts that urban morphology is useful and that both physical structure and UD relations are incorporated into the city structure. According to Batty (2001), urban morphology is the study of structure and processes, growth, shape, form and urban function through the analysis of its urban density. It can be identified as some practical examples to reduce the impact of floods by urban form features (refer Figure7 and 8)(C. D. Nguyen et al., 2021) (Hoyer & Dickhaut, 2010). The below graphs in Figure 8 illustrate the way to reduce flood damage by applying urban water management strategies.



	Conventional stormwater management		Decentralised stormwater management	
Elements	Separate stormwater sewer system, stormwater retention basin		Green roofs, cisterns, pervious pavement, stormwater overflow	
Investment costs	Area for stormwater retention basin (1200 m^2)	€ 720,000	Implementation of cisterns in single-family homes (47)	€ 56,400
	Implementation of stormwater retention basin (1400 m^3)	€ 168,000	Implementation of cisterns in multi-family apartment blocks (9)	€ 45,000
	Enlargement of existing stormwater sewers	€ 50,000	Additional costs for pervious paving instead of asphalt	€ 340,000
			Additional costs for green roofs (layer depth 12 cm instead of 8 cm)	€ 91,500
	Total	€ 938,000	Total	€ 532,900
			Total reduction in investment costs over conventional solution	**€ 405,100**
Running costs			Eliminated stormwater fee because of cisterns (each year)	€ 8,240
			Eliminated stormwater fee because of pervious paving (each year)	€ 8,400
			Eliminated stormwater fee because of green roofs (each year)	€ 9,040
			Total annual savings from decentralised stormwater management	€ 25,680
			Total savings due to decentralised stormwater management over 30 years	**€ 770,400**
	Total savings due to decentralised stormwater management in comparison with conventional stormwater management for in Hohlgrabenäcker over 30 years			**€ 1,177,900**

Figure 7: Example case, implementing Sustainable Strategies for Urban Stormwater Management in Germany

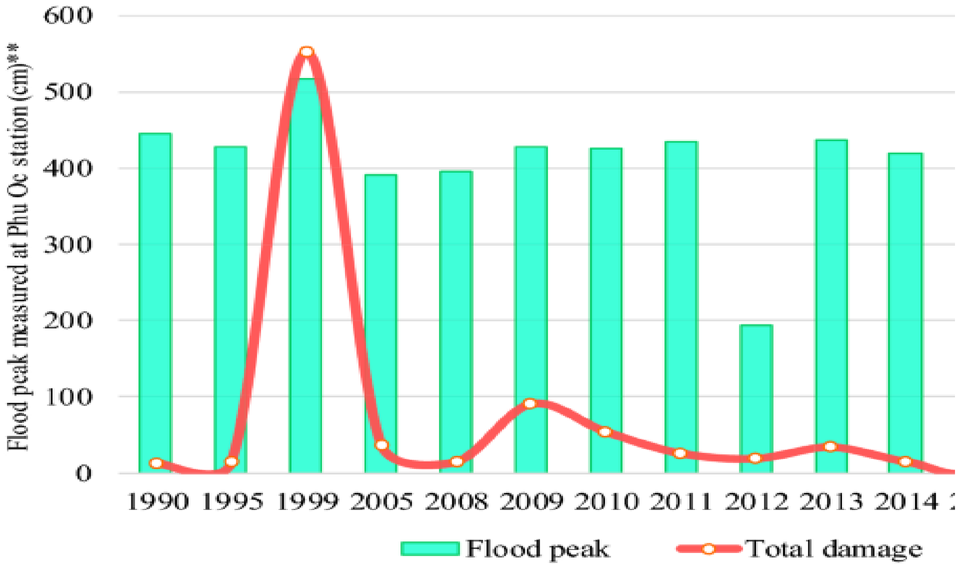


Figure 8: Example , Improvement urban flood Mitigation in long term - Vietnam

Urban floods are becoming increasingly common in many parts of the world due to urbanization, climate change, and other factors. Managing these floods is essential to minimize their impact on people's lives and the environment. Above discuss some existing possibilities and practical examples of managing urban floods with practical examples. By implementing a combination of these solutions, urban areas can effectively manage and mitigate the risks of floods caused by urbanization and climate change.

2.5 Flood Resilience City

Flood resilience of cities refers to the ability of urban areas to withstand, adapt to, and recover from flood events while minimizing their social, economic, and environmental impacts (Refer Figure 9). It involves a comprehensive approach that integrates strategies, policies, and actions to reduce vulnerability, enhance preparedness, and improve the ability of cities to absorb, recover, and bounce back from flooding (Wijayawardana et al., 2023). Flood resilience focuses on minimizing damage to infrastructure, protecting human lives, safeguarding property, preserving natural resources, and maintaining the overall functionality and well-being of urban communities in the face of flood-related challenges. It encompasses measures such as effective flood risk management, robust infrastructure, land-use planning, emergency response, community engagement, and long-term adaptation strategies(O’Donnell & Thorne, 2020). The goal is to build cities that can anticipate, withstand, and adapt to flood events, ultimately reducing the risks and improving the overall resilience of urban areas to flooding.

Urban density has significant implications for the flood resilience of cities, with both positive and negative impacts. One key benefit of higher urban density is efficient land use. Compact development helps preserve natural floodplains, reducing the need for urban expansion into flood-prone areas (Tabibian & Rezapour, 2016). By minimizing encroachment on vulnerable zones, cities can preserve open spaces that aid in floodwater absorption, enhancing their resilience to flooding.

Another advantage of higher urban density is reduced exposure to flood hazards. Concentrating development in denser areas helps protect critical infrastructure and valuable assets from the risks associated with flooding. By strategically locating buildings and infrastructure away from flood-prone areas, cities can minimize potential damages and disruptions caused by flood events.

Additionally, higher-density areas often have better access to infrastructure, including improved stormwater management systems. This enables the implementation of effective drainage systems, flood control measures, and resilient infrastructure capable of handling increased runoff during flood events. The availability of such infrastructure contributes to the flood resilience of cities by efficiently managing excess water and reducing the impacts of flooding.

However, challenges may arise due to limited space in densely populated areas. The compact nature of high-density urban environments can make it more difficult to implement certain flood resilience measures(O’Donnell & Thorne, 2020). Innovative solutions, such as stormwater storage systems and green infrastructure, may be necessary to mitigate flood risks in these constrained spaces.

Furthermore, UD can foster collaboration and community engagement. Denser neighborhoods often have stronger social networks, which facilitate collective action in flood preparedness, response, and recovery efforts. This sense of community can contribute to a more resilient urban fabric, as residents work together to address flood-related challenges(Tabibian & Rezapour, 2016).

The UD plays a significant role in shaping the flood resilience of cities. Efficient land use, reduced exposure to flood hazards, improved infrastructure, community collaboration, and innovation are among the factors that contribute to flood resilience in densely populated areas(T. T. Nguyen et al., 2019). However, challenges related to limited space and stressed infrastructure must be carefully addressed to ensure effective flood risk management in high-density urban environments.

This study achieves resilience by developing a comprehensive framework that assesses the impact of urban development on stormwater runoff in urban watersheds. It aims to identify indicators for quantifying stormwater runoff associated with urban development, create a conceptual framework for understanding the relationship between urban development and stormwater runoff, and validate the framework as a planning aid. By integrating these objectives, the study contributes to resilience by guiding sustainable urban planning and decision-making, ensuring effective stormwater management, and promoting adaptive strategies for urban development.

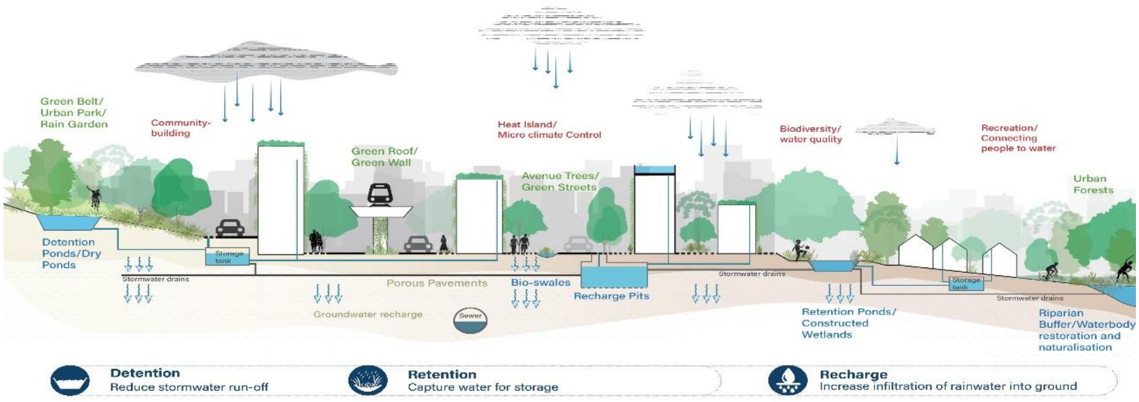


Figure 9: Flood-resilient city with a diverse urban setting

Source: S. Janakiraman, 2021 - Water Sensitive Urban Design

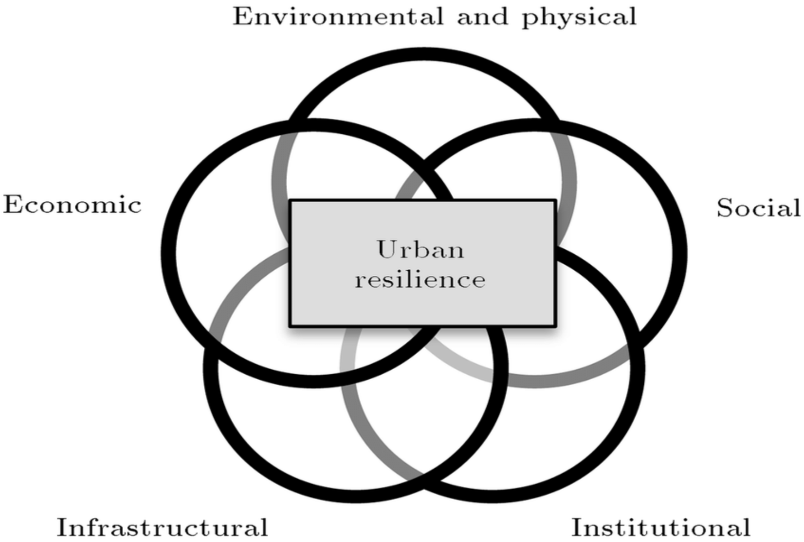


Figure 10: Dimensions of flood resilience city

CHAPTER 3: METHODOLOGY AND PROPOSED CONCEPTUAL FRAMEWORK

3.1 Introduction

The first section of this chapter identifies the UD indicators used for the quantification process as per the first sub-objective of this study. Next, evaluate the existing theories and concepts used to develop a conceptual framework for this research as per the second objective. The latter section indicates the selection of the simulation tool of SR and the case study area selection based on UD and the preparation of data base in a detailed manner.

Methodology as a Summery

This study was conducted in three phases according to the objectives.

In the first phase, a systematic review was performed to define the variables that quantify urban form density. Thirteen (13) density measuring variables were identified through this review process.

The second phase involved the development of a conceptual framework to measure overall urban form density. Thirteen variables were selected and categorized under the three main categories known as the "3Ds of Urban Form," which were derived from three theoretical frameworks: Patterns of Natural Movements, Model of the Urban Maturing Procedure, and Rational Formula of Runoff.

The third phase focused on selecting a runoff simulation model for model formulation and validation, using both systematic and narrative reviews. The SWMM model selected to simulate surface runoff. Model formulation and validation were carried out, incorporating statistical analysis and decision tree analysis. The prediction probability and level of accuracy of the pre-developed theoretical framework were measured through real ground verifications and expert opinions.

By following these three phases, the study aimed to achieve its objectives and provide a comprehensive understanding of urban form density and its implications for urban water management and runoff.

3.2 Identifying the most influencing Indicators

It is important to build a spatial simulation approach in order to assess the influence of UD on the changing severity of SR at the micro urban watershed scale. It is essential for deciding the urban planning sector as per the main objective of this study. As a result of the multifaceted nature of the urban environment, the UD has a significant impact on the intensify the level of SR in a specific location (Li et al., 2022; Madusanka et al., 2022). Nevertheless, it is not known about the most critical indicator/s that have the greatest impact on SR are as per the literature survey. Most of the research focusing on the intensity of rainfall suggested that the main cause of the degree of SR change has become the influence of climate change (Li et al., 2022). The effects of climate change will persist for a significant period of time. Variations in infrastructure growth, building density, type of land use, and climatic patterns, combined with the long lifespan of urban systems, contribute to increased SR resulting from human activities (Madusanka et al., 2022; Piyumi et al., 2021). Urban floods result from a combination of hydrological and meteorological situations, exacerbated by anthropological actions in urban areas with high population/ building densities. Thus, the exploration of crucial indicators that contribute to the intensity of SR remains a topic of inquiry in the literature.

In the early stage of this study, a systematic review was conducted to discover the UD indicators that can quantify the SR level. The results of the review indicate that there is a lack of consensus regarding the most influential UD indicators that contribute to SR (C. Chen et al., 2008; Hoyer & Dickhaut, 2010; Sharifi, 2019). However, scholars have acknowledged that UD is a well-established factor in studies related to urban floods and its role in triggering SR (C. Chen et al., 2008; Sharifi, 2019).

The Appendix A presented the derived indicators associated with UD that were found in studies related to SR. These indicators were identified through a systematic review that focused on articles published within the last ten years. To ensure comprehensive coverage of overall UD indicators, a set of predefined criteria were followed.

- These criteria included selecting articles with open access.
- Ensuring that data on density parameters were available for the local context.
- Verifying that the articles were related to the subject field of urban planning.

The UD indicators obtained earlier were applied assess the intensity of SR incorporating environmental-based elements like changes in precipitation, soil properties, terrain settings, vegetation cover type, and drainage status. However, no research has exclusively examined the effect of alterations in density in urban form as a quantification benchmark of SR variation.

While assessing UD indicators impact on SR, this research has identified three limitations. First, different studies use various indicators to measure UD, but there is no agreement on which indicator precisely represents the SR level. Second, most studies about SR focus on the effect of riverine floods vicinity of urban centres, and not on unexpected urban flash floods resulting from adverse and high-intensity weather events (Buitelaar & Segeren, 2011). In addition, they did not take into account the continuous expansion of impervious surfaces with dense elements on urban floods. Urban flooding happens due to the surge in SR caused by development activities within UD, such as paving Gray infrastructure, which has lower infiltration capacity compared to natural fields. Consequently, the volume of rainfall runoff in urban watersheds can surge greater than six times compared to the natural environments. Third, the indicators that were identified through the literature review interact with other indicators of UD, that requires robust conceptual framework is necessary to identify the most significant UD indicators that influence SR. Thus, this study aims to review the indicators of UD, used in existing research. Further this identifies the significant indicator/s that can properly depict the impact of UD on SR , predominantly in micro -urban watersheds.

By developing a methodology that allows for measuring the effect of UD on runoff from the surface (SR) at the size of micro-urban watersheds, this study seeks to solve the constraints identified above. Existing ideas, concepts, and models will be used to construct the conceptual framework in order to successfully achieve this aim of the study.

3.3 Identifying the Theories and Concepts

As second objective in the present study is to create a framework for determining the way the amount of SR at the level of micro-urban watershed changes by UD. A theoretical and narrative review was carried out to examine appropriate theoretical ideas, concepts, and models in order to accomplish this objective. Three philosophical models were discovered by the review: the Patterns of Natural Movements, Model of the Urban Maturing procedure, and the Rational Formula of runoff.

How economic activity impacts the alteration of space is explained by the **Patterns of Natural Movements**(Hillier et al., 1993). The pattern of roadway networks is one of the key elements influencing on urban configuration and building density. Under the first stage of urban expansion, which was triggered by concentrations of economic activity, built form density was originally created (Buitelaar & Segeren, 2011). The second phase was defined by an improvement in the demand for real estate close to economic hubs, where ownership rights play a critical role here (Bobkova, 2019). Third, long-term urban expansion has been forecast to be driven by the rise of built form density, activity diversity, and economic concentration (Batty, M, 2019). In this stage, the land subdivides into smaller plots and is filled with dense built-form elements.

Urban morphological investigations indicate that this tendency larger segmentation of natural environment urban land into tiny parcels. The segregation of land parcels depends significantly on urban transportation systems, which encourage accessibility and increase density (Bobkova, 2019). As a result of that, the penetration rates are reduced, and impermeable structures grow over the natural environment imposing sudden floods. Urban watersheds ecosystem with tiny plots of land, dense building density, and rising imperviousness are common places for this phenomenon to occur.

According to the **Theory of Urban Maturation procedure**, spatial integration and a diverse mix of land use lead to higher UD (Buitelaar & Segeren, 2011; Marcus & Colding, 2014). According to this theory, there are three levels of growth for urban forms, each of level facilitated by an amalgamation of UD, unique amalgamation with physical structure, and a variety of land use types. The relationship between spatial arrangement, UD, and level of functional diversity in a typical urban setting is defined by the spatial configuration idea in combination with aspects of the urban form (Nes, 2013). The functional mix reveals the structure and land use zoning densities (Hillier et al., 1993). As a city grows more and more developed, the overall density inside the urban form rises as a result of its high degree of availability and the variety of land uses, which can cause flooding or a boom in runoff from the surface owing to the accumulating of activities in high-density urban areas and the transition of natural open space to the construction of structures (Nes, 2013). In order to make cities flood-resistant and control SR, the planning procedure for new town formation should incorporate UD, city services, and distinctive layout into consideration. Refer to Figure 12 for a better understanding of this concept.

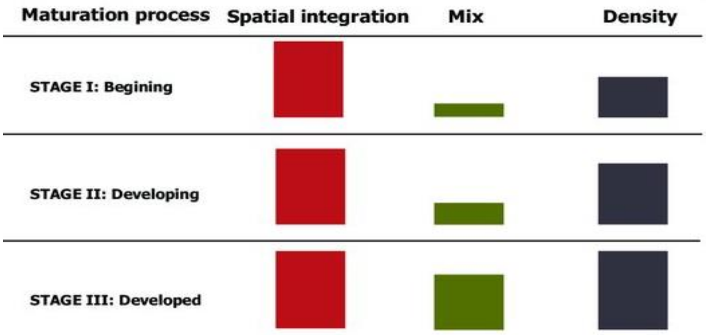
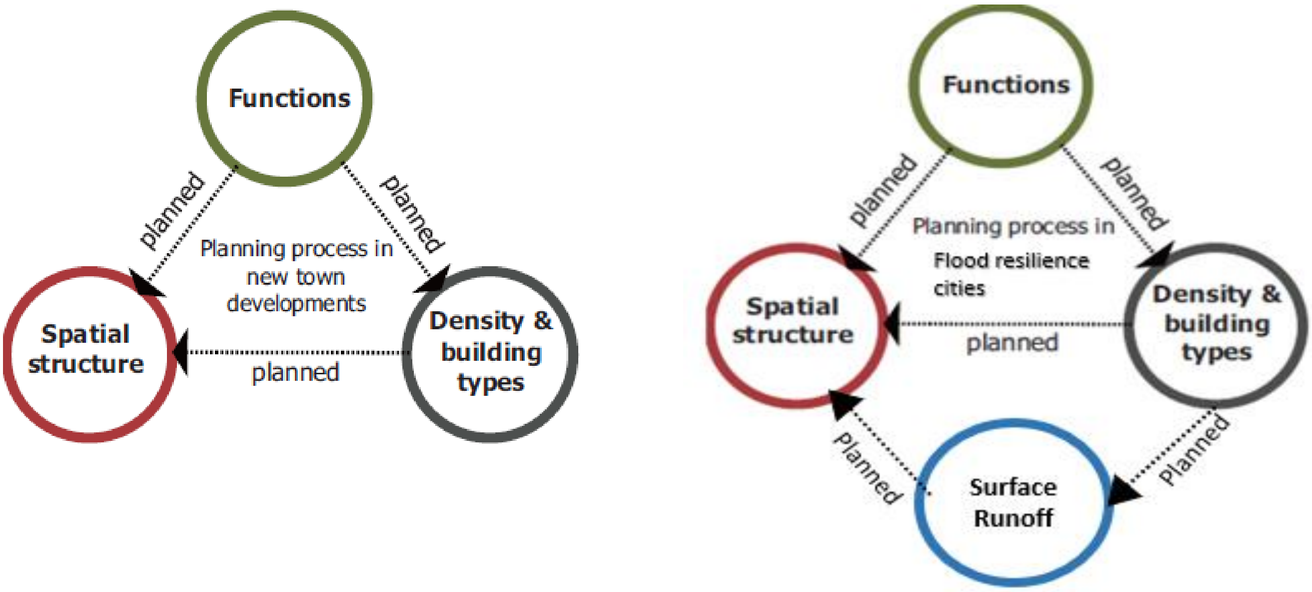


Figure 11: Process of urban maturation - different stages



(**a**) (**b**)

Figure 12: New town development, incorporating urban density, city functions, special structures, and surface runoff

New town development in Theory of Urban Maturation procedure (a) | how SR link with New town development (b)

The **Rational Formula of runoff** describes the way ecological systems, taking into consideration the amount of precipitation and the catchment region's characteristics, equilibrium water (rainfall) in a region with water runoff (Grimaldi & Petroselli, 2015). This Rational Formula of runoff technique makes the assumption that the coefficient of runoff is uniform, and changes depending on the density of built forms and the nature of land use in a region. In recent research argues challenged this concept, contending that the coefficient of runoff cannot be a fixed value and should vary depending on the regional land use and density in populated areas. The purpose of this study is to assess how different urban densities affect runoff coefficients (Grimaldi & Petroselli, 2015; Marcus & Colding, 2014). According to the researchers, changes in the runoff coefficients due to urban density characteristics, which are connected to the Patterns of Natural Movements and the Model of the Urban Maturation procedure, would have an impact on SR.

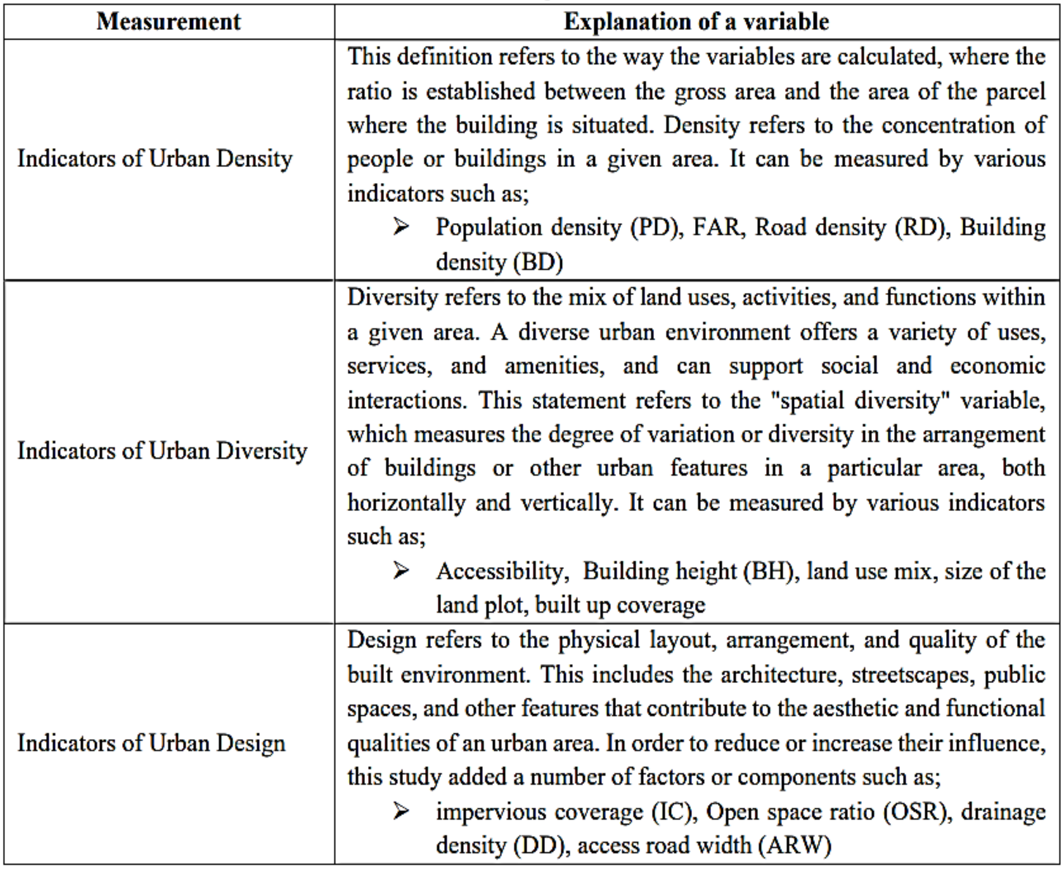
3.4 Concepts

Two different sorts of concepts were used in this study to build the theoretical framework. The first concept accounted for variations in spatial patterns by categorizing UD. The second category of ideas concentrated on municipal strategies that may be employed to reduce or control the amount SR in a local or micro-urban watershed. Through a narrative review of urban water management tactics used in various urban contexts, these city-level concepts were discovered.

Density can be measured using a variety of techniques (i.e., Floor area ratio (FAR), Building coverage, Impervious surface area, building density and spaciousness (Alexander, 1993; Dempsey et al., 2008) . However, no single measure can adequately capture by UD at the local or micro-urban watershed scale can be challenging with intricate nature of urban form (Dempsey et al., 2008; Sharifi, 2019). Most academics agree Density is a crucial factor among overall urban form that is subject to changes brought about by anthropogenic activities. Density is a broad notion that includes several interrelated elements. While it is possible to physically and geographically quantify the components of a given area, it is also possible to assess them based on specific traits of an individual or a group (Churchman, 2000). Furthermore, UD is closely linked to various other dimensions of urban form, such as accessibility, Road and transportation infrastructure, land use mix, green/open spaces, Drainage infrastructure and neighbourhood characteristics. UD can be viewed as a composition of physical elements in this context. UD can be employed as a tool in planning to evaluate UD, spatial diversity (SD), and design elements_(DE).

This study utilizes the **"3D"** paradigm established by Cervero and Kockelman (1997) to capture the transformations of urban configurations) (Cervero & Kockelman, 1997). The paradigm represents Density, Diversity, and Design, and is used to understand the impact of UD on various urban processes, including SR (Kim & Hipp, 2021). This is a broad notion that pertains to studies on travel demand and transportation. But nowadays this 3D concept used in many urban planning studies (Carpio-Pinedo et al., 2020; Ye et al., 2017. The three variables, which serve as indicators for urban density(UD), spatial diversity(SD), and design elements(DE) can be combined, according to the authors, to create the total amount of UD. The three dimensions of the built environment, or the 3Ds should be changed in order to accomplish these aims, according to designers who are modern urbanists, neo-traditionalists (Ye et al., 2017). The study's main objective is to use the component analysis approach to determine the relative significance of each UD indicators, urban diversity, and design and their combined effects. The table 2 contains descriptions of each dimension.

Table 2: Variable explanation for 3D s



Measurement	Explanation of a variable
Indicators of Urban Density	This definition refers to the way the variables are calculated, where the ratio is established between the gross area and the area of the parcel where the building is situated. Density refers to the concentration of people or buildings in a given area. It can be measured by various indicators such as; ➢ Population density (PD), FAR, Road density (RD), Building density (BD)
Indicators of Urban Diversity	Diversity refers to the mix of land uses, activities, and functions within a given area. A diverse urban environment offers a variety of uses, services, and amenities, and can support social and economic interactions. This statement refers to the "spatial diversity" variable, which measures the degree of variation or diversity in the arrangement of buildings or other urban features in a particular area, both horizontally and vertically. It can be measured by various indicators such as; ➢ Accessibility, Building height (BH), land use mix, size of the land plot, built up coverage
Indicators of Urban Design	Design refers to the physical layout, arrangement, and quality of the built environment. This includes the architecture, streetscapes, public spaces, and other features that contribute to the aesthetic and functional qualities of an urban area. In order to reduce or increase their influence, this study added a number of factors or components such as; ➢ impervious coverage (IC), Open space ratio (OSR), drainage density (DD), access road width (ARW)

Source: Compiled by author

SR have been introduced throughout the past few decades, and the idea of urban water management techniques (UWMS) has shown to be effective in reducing their effects. The management of constructed form elements is the main emphasis of a new paradigm in urban planning and design, which includes this strategy. The UWMS idea is strongly related to the 3D urban forms that were covered in the prior section on "indicators of urban design." The major goal of these methods is to use technological, urban planning, and engineering solutions to control and minimize the problems caused by urbanization and climatic variability while maintaining the ecological and social balance. UWMS has been referred to by a variety of terms in different nations. For instance, the phrase "sustainable urban drainage systems" (SUDS) is favoured in the United Kingdom, whereas the word "water sensitive urban design" (WSUD) is used in Australia. The phrases low impact development (LID) and stormwater best management practices (BMPs) are frequently used in the US, whereas green infrastructure (GI), blue-green infrastructure, nature-based solutions, and sponge city idea are used in China to define UWMS (Cook et al., 2019; T. T. Nguyen et al., 2019; Sarkar et al., 2021). There are still many difficulties associated with the practice of implementing UWMS in poor nations, which call for additional investigation and pilot projects. Considerations like financial capacity, execution tactics, and accuracy must be given great thought. In nations with different urban density and uncontrolled urban expansion, the problem is especially difficult. A lack of knowledge exists regarding how effectively planning and building density based on UWMS contribute to community flood resilience, despite several research evaluating how well building regulations are compatible with UWMS projects. The best flood protection method should be chosen after decision-makers analyse their options, help build a long-term flood-resistant metropolitan system, and reduce risk.

3.5 Conceptual Framework

This study aims to investigate the relationship between UD and SR by exploring the impact of three different density clustering approaches (3Ds) falling under the paradigm: indicators of urban density, indicators of urban diversity, and indicators of urban design. The study aims to identify the most critical indicator that trigger surface runoff at the urban macro -watershed scale, with the ultimate goal of providing a tool for decision-making and planning flood- resilience cities in the future. The framework presented below Figure 13 is built upon the theories and concepts discussed earlier.

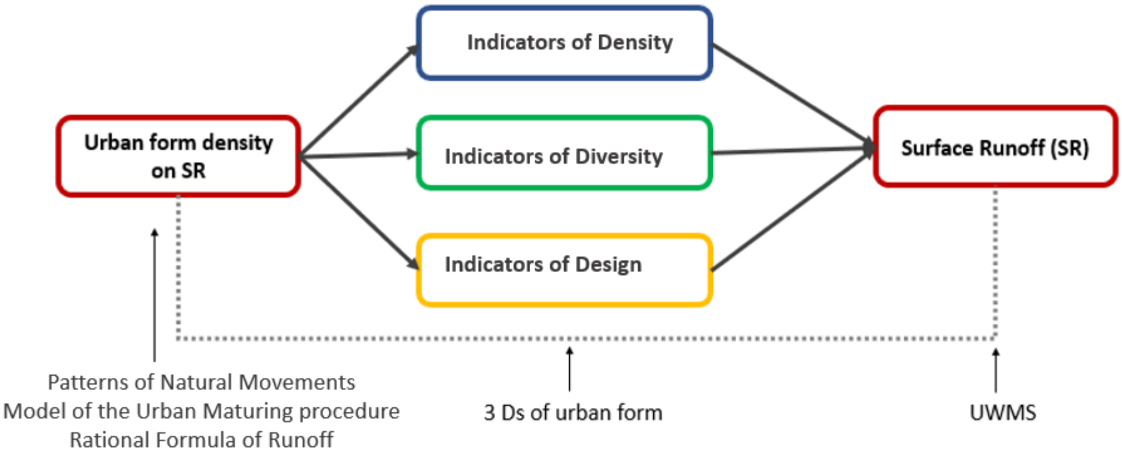


Figure 13: Conceptual Framework of this study

Source: Compiled by author

3.6 Model the surface runoff and identify the relative importance.

To identify a simulation tool to model the SR, using previous systematic review. Here analyses the existing modelling frameworks under different spatial scales such as local level, site-specific level or regional level with their model accuracy. Further, analyzed the existing limitations of each model in practical usage and data requirements in the Sri Lankan context. The below table 3 despite a comprehensive summary of existing simulation approaches utilizing density-based factors in different urban scales.

Table 3: Overview of urban flood simulation approaches applied in different urban scales, input data and model limitations.

Simulation Model	Scale	Data required	Limitations cited	Reference
HEC-RAS	R, L, S	Topographic data, river crossing data, the river bank line, flood amount and the flood level, land-use area	Mainly used for river-based floods not for urban-flood. Cannot simulate flood inundation from the subsurface drainage systems in a study area.	(Khalaj et al., 2021)
SWMM	L, S	Rainfall, drainage details, imperviousness, topographic data, LID details	This is 2D simulation application.	(Abenayake et al., 2020)
PC- SWMM	L, S	Permeable Surface, Impervious Surface, Pipeline, infiltration parameter, drainage system, rainfall	This is a commercial model used for flood simulation and which is unable to capture the spatial dynamics of the urban environment.	(Peng et al., 2018)

Urban BEATS	L	elevation, soil type, land use and population	does not take into account long-term system dynamics such as changes in rainfall patterns or water demands.	(Bruno et al., 2022)
MIKE flood	R, L, S	Precipitation, drainage details, flow velocities topographic data	This model is not open-source model which most suitable for hydraulic simulations.	(Sarkar et al., 2021) (H. D. Nguyen et al., 2021)
City Drain3	L	catchment, inner-river, storage facilities, pumping stations, outer-river, wastewater treatment plant	This is free and open-source C++/Python environment application which used to evaluate performance evaluation of UWMS. But it needs some modifications on catchment characteristics.	(Schmitt et al., 2004)
3Di Model	R	high-resolution DEM, Precipitation, urban areas, levees, population density, flood depth	This is most suitable for residential buildings smaller in size or dispersed distribution.	(Afifi et al., 2019)
2D RRI[1]	L	Land Cover Types, precipitation, topographic_data, Building_Height, Building_Conditions, Building_Materials, Land_Value,_Total Population	This method developed for flood risk evaluation and need to improve this model with more case studies on a local scale to take more accurate result.	(Abdrabo et al., 2020)
DS[2] Model	L	Elevation, ground slope and impermeability, runoff coefficients of the land types, Building density, POI density	This model simulates the risk and uncertainty of rainfall scenarios in urban areas. But not considered the urban form dynamics.	(Cai et al., 2019)
DEM based	R, L, S	Topographic data, precipitation, population density, land use/ cover types	Most studies use to risk evaluation of urban character using topological features. All reviewed case studies analysis the urban flood related to riverine.	(Fahy et al., 2019) (Walczykiewicz & Skonieczna, 2020) (Y. Liu et al., 2021)
Remote sensing (RS)	R, L	Landcover, population density, distribution, Topographic data, precipitation	The visualization of flood risk with remote sensing most prominent in reviewed case studies, but quantification of the impact is somewhat challenging	(X. Liu et al., 2021) (Mwangi et al., 2020)

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[1] Rainfall runoff inundation city model

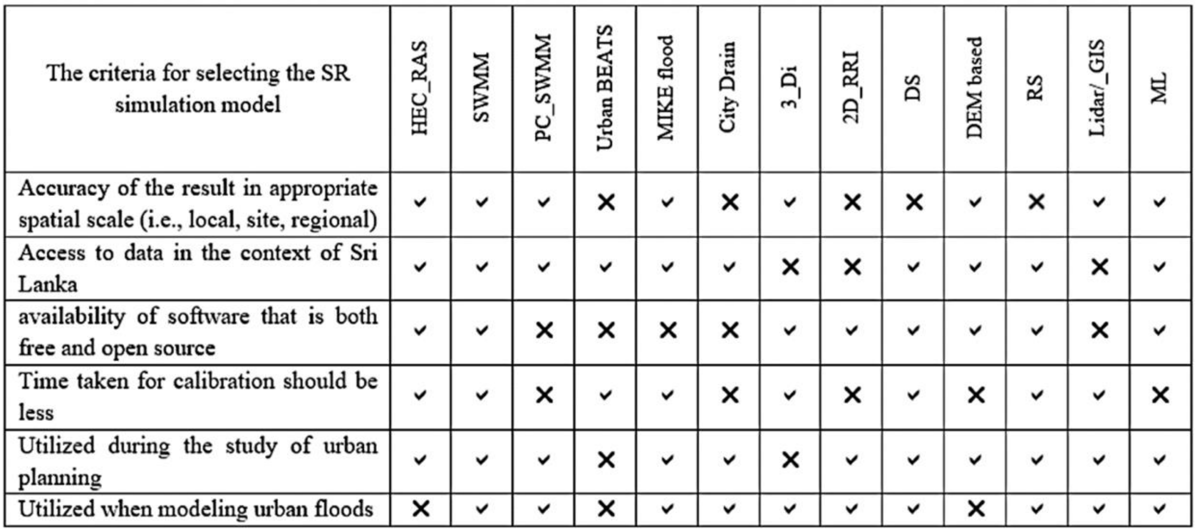
[2] Digital Water Simulation hydrodynamic model

			with distinct urban contexts.	
LIDAR image + GIS	R, L	LIDAR point cloud, land use	It requires high-performance computers, and cost for data acquisition. The simulation takes more time to give an accurate result.	(Albano, 2019)
ML	N, R, L, S	Topographic data, land use, population density, building details, drainage details, flood depth	Urban flood is a complex system depend on various selected factors.	(J. Chen et al., 2019) (Papilloud et al., 2020) (Lin et al., 2021)

Note: N- National scale | R- Regional Scale | L – Local Scale | S – Site or neighborhood level

Source: Compiled by author

Table 4: Selection of simulation model for SR



The criteria for selecting the SR simulation model	HEC_RAS	SWMM	PC_SWMM	Urban BEATS	MIKE flood	City Drain	3_Di	2D_RRI	DS	DEM based	RS	Lidar/_GIS	ML
Accuracy of the result in appropriate spatial scale (i.e., local, site, regional)	✓	✓	✓	✗	✓	✗	✓	✗	✗	✓	✗	✓	✓
Access to data in the context of Sri Lanka	✓	✓	✓	✓	✓	✓	✗	✗	✓	✓	✓	✗	✓
availability of software that is both free and open source	✓	✓	✗	✗	✗	✗	✓	✓	✓	✓	✓	✗	✓
Time taken for calibration should be less	✓	✓	✗	✓	✓	✗	✓	✗	✓	✗	✓	✓	✗
Utilized during the study of urban planning	✓	✓	✓	✗	✓	✓	✗	✓	✓	✓	✓	✓	✓
Utilized when modeling urban floods	✗	✓	✓	✗	✓	✓	✓	✓	✓	✗	✓	✓	✓

Abbreviations for each model- [3]

Source: Compiled by author

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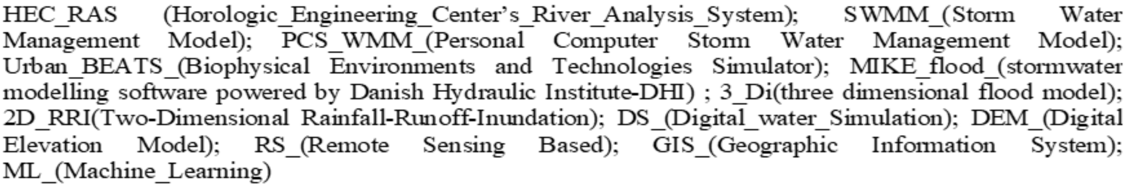
[3]



HEC_RAS (Horologic_Engineering_Center's_River_Analysis_System); SWMM_(Storm Water Management Model); PCS_WMM_(Personal Computer Storm Water Management Model); Urban_BEATS_(Biophysical Environments and Technologies Simulator); MIKE_flood_(stormwater modelling software powered by Danish Hydraulic Institute-DHI) ; 3_Di(three dimensional flood model); 2D_RRI(Two-Dimensional Rainfall-Runoff-Inundation); DS_(Digital_water_Simulation); DEM_(Digital Elevation Model); RS_(Remote Sensing Based); GIS_(Geographic Information System); ML_(Machine_Learning)

After conducting a thorough analysis of various flood simulation models, this study has determined that the SWMM modelling platform is the most suitable for modelling SR based on the predefined criteria (refer Table 4).

3.7 Identification of simulation tool

The researchers in this study chose the EPA_SWMM model for their examination of SR in urban-micro watersheds in order to overcome existing limitations of SR simulation models . This choice was reached after weighing the pros and disadvantages of other surface runoff simulation techniques and taking into account the EPA_SWMM as a flood inundation model (Moravej et al., 2021). Under different modeling scenarios, the EPA SWMM model can forecasting of storage, outflows, and inflows inside a single sub_catchment area. At various spatial scales, including local, sub-watershed, neighborhood, and site scales, it delivers accurate results. By including various land-use types, urban density's physical and nature potentials can determine with runoff components for sub-catchment areas with this model. The EPA SWMM 5.1, which is capable of delivering accurate results for model calibration and verification, has been used successfully for urban stormwater modelling (Abenayake et al., 2020; Moravej et al., 2021). The EPA SWMM model is utilized in a site-specific manner for urban planning and urban flood assessments across the globe. CSO-LTC plans in cities like Philadelphia, Cincinnati, Indianapolis, Seattle, and New Haven are a few examples (Chrysochoou et al., 2012; Jang et al., 2007. In these situations, this technology has demonstrated the effectiveness of the model.

$$\frac{\partial Q}{\partial t} + gAS_f - 2V\frac{\partial A}{\partial t} - V^2\frac{\partial A}{\partial x} + gA\frac{\partial H}{\partial x} = 0 \qquad \text{…………………………(Equation 1)}$$

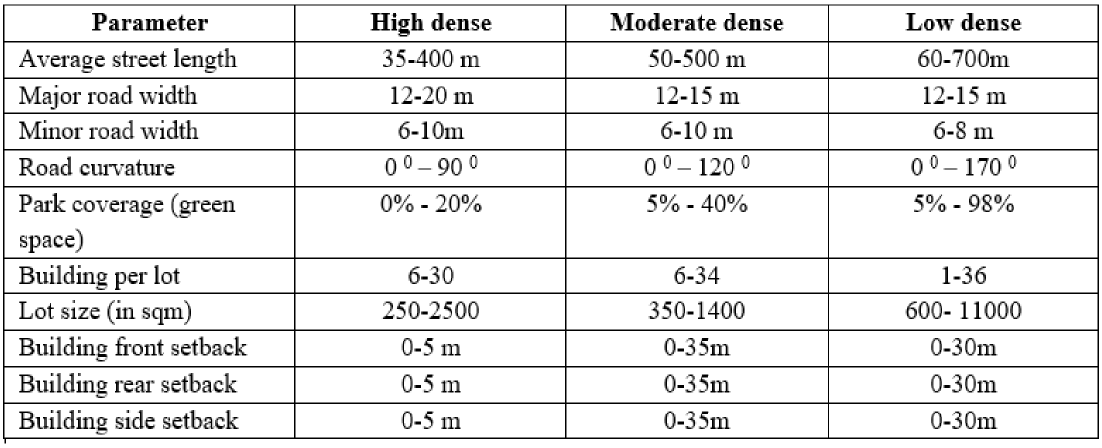
Where,
Q = Discharge through the conduit
V= Velocity in the conduit
A= Cross sectional area of the flow
H= Hydraulic head (invert elevation plus water depth)
S_f = Friction slope
g = Gravity
t = Time (USEPA, 2015)

3.7.1 Selection of case study area/s

The study areas were selected based on the range of urban densities found within the micro-urban watershed scale. The Spacemate density categorization approach, which measures urban form densities using the Floor_Space_Index (FSI), Ground_Space_Index (GSI), and Open_Space_Ratio (OSR), was used to determine the three primary categories of density (Nes, 2013). The nine density categories in the Spacemate approach, as shown in Figure 15, can be used to divide regions into high-, mid-, and low-density groupings. The three primary density categories were modified for this study in order to support the suggested theoretical framework.

The pattern of the urban watershed's UD was determined before case study regions were chosen in the first stage of selection of case study area. To generate urban layouts, a Procedural Urban Generation System was utilized (Bruwier et al., 2018). This system operates autonomously by following a set of parameter. This system's objective is to automatically design urban layouts by accounting for geometric urban features including accesses road width, direction a building faces (building-orientation), the degree of curvature or bending of a road or street, size of the land parcel and the orientation of open space in a land with building (setback). The study employed an open_source visual computation tool that helps urban planners quickly assess how different urban design patterns affect flood risk. The AI technology utilized to create UD based Procedural Urban Forms with the "Probabletrain Procedural City Generator" program. Table 5 displays a catalogue of the parameters employed in generating the urban density form.

Table 5: Parameter – AI based Procedural City Generator



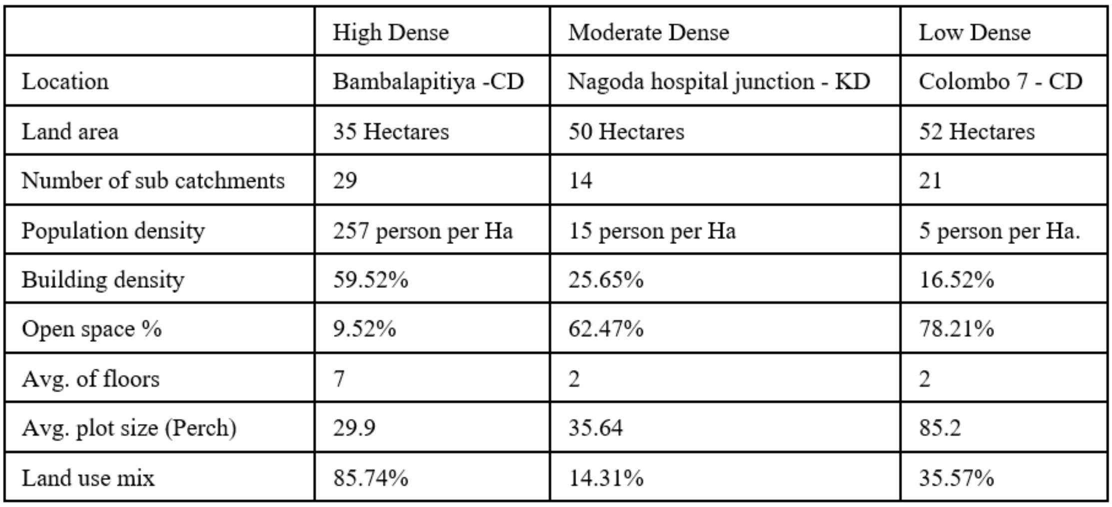
Parameter	High dense	Moderate dense	Low dense
Average street length	35-400 m	50-500 m	60-700m
Major road width	12-20 m	12-15 m	12-15 m
Minor road width	6-10m	6-10 m	6-8 m
Road curvature	$0^{0} – 90^{0}$	$0^{0} – 120^{0}$	$0^{0} – 170^{0}$
Park coverage (green space)	0% - 20%	5% - 40%	5% - 98%
Building per lot	6-30	6-34	1-36
Lot size (in sqm)	250-2500	350-1400	600- 11000
Building front setback	0-5 m	0-35m	0-30m
Building rear setback	0-5 m	0-35m	0-30m
Building side setback	0-5 m	0-35m	0-30m

The case study locations were selected for the second step based on predetermined urban form density categories for complete urban watersheds. Hydrological analysis employing a 12.5m DEM on the Arc GIS platform was used to identify the chosen watersheds. The urban watersheds were divided to sub-catchment regions considering prevailing drainage and typical water flow. To investigate relationship among UD and SR distinct densities in Sri Lanka. The case studies of real-world layouts and procedural system layouts were selected, as depicted in Figure 14.

Figure 14: The layout of procedural systems compared to that of real-world systems

The features of each case study site, which were selected based on their density, are outlined in Table 6.

Table 6: Unique features of the selected case study areas based on UD



	High Dense	Moderate Dense	Low Dense
Location	Bambalapitiya -CD	Nagoda hospital junction - KD	Colombo 7 - CD
Land area	35 Hectares	50 Hectares	52 Hectares
Number of sub catchments	29	14	21
Population density	257 person per Ha	15 person per Ha	5 person per Ha.
Building density	59.52%	25.65%	16.52%
Open space %	9.52%	62.47%	78.21%
Avg. of floors	7	2	2
Avg. plot size (Perch)	29.9	35.64	85.2
Land use mix	85.74%	14.31%	35.57%

The surface runoff amounts for the chosen case study areas are shown in Figure 16. The SWMM platform's heaviest rainfall occurrences from the last year (2021), between June 20 and June 25, served as the basis for the simulations. 15-minute interval rainfall values were recorded at 4_ONSE meteorological station locates in the University of Moratuwa and Kalutara- Nagoda meteorological station from the Department of Meteorological database and taken as input rainfall data for the simulations because the extreme rainfall event produced 160-250 mm of rain per day (24_hours).

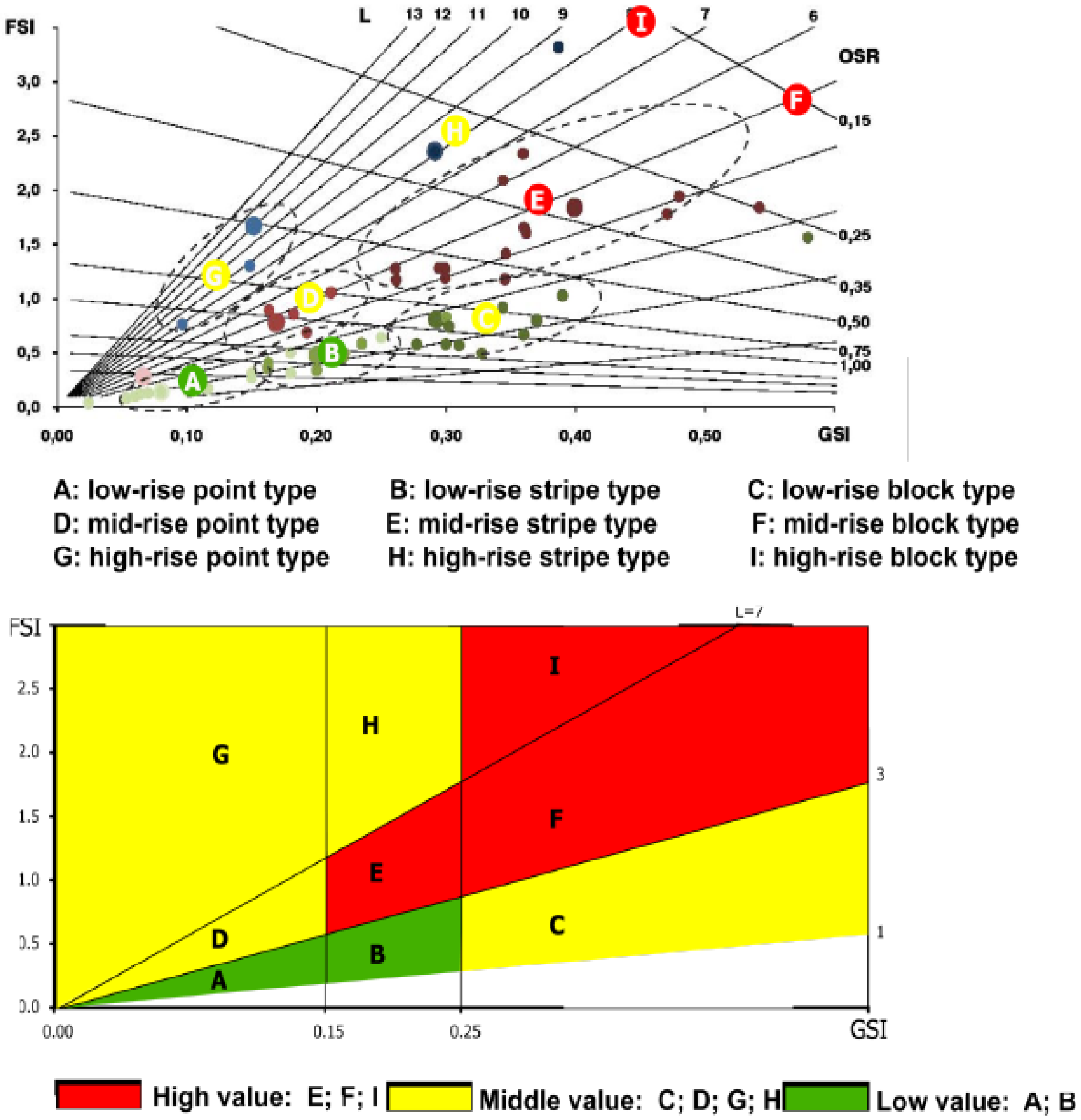


Figure 15: density classification in Spacemate

Note: FSI – Floor Space Index | GSI - Ground Space Index

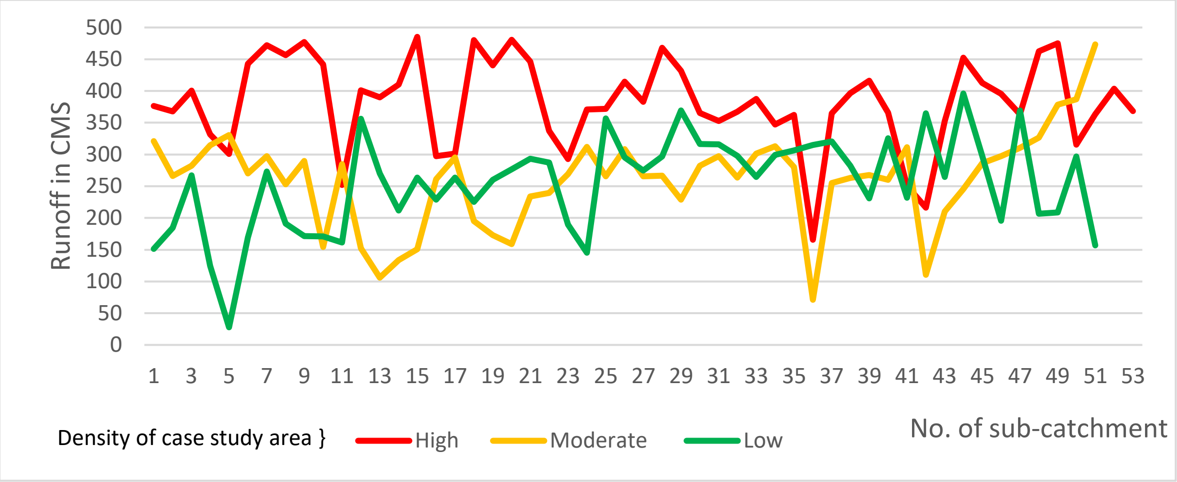


Figure 16: SR in catchments generated with SWMM

3.8 Data collection and modeling

Table 7 presents the main variables and thirteen sub-variables that were utilized to measure UD in each study area, along with the measurement methods and data sources .

Table 7: Measurement of variables

Density based Key variable	Measuring variable	Equation / method of measure	Source
Indicators of Density	Population density (PD)	$\mathrm{PD_x} = \frac{\mathrm{Population_x}}{\mathrm{Area_x}}$	Capitulate by author
	Building density	*Building dentist of buildings in a particular land plot/ area*	*JICA database*
	Road density	$\mathrm{RD} = \frac{\sum(\text{Gress road area})}{\text{land area}}$	*JICA database /* Capitulate by author
	FSI (FAR)	$\mathrm{FSI} = \frac{\text{Gross Floor Area}}{\text{land area}}$	*JICA database*
Indicators of diversity	Building height	*Sum of floors in in selected land plot/ area* $S_n = (a1 + a2 + a3 + \cdots, a_n)$	Capitulate by author
	Level of accessibility	*CCi=* (*N*−1)/ Σ*dij* (Closeness centrality of road segment)	*JICA database /* Capitulate by author
	Land use mix (Mixed Use Index)	$\mathrm{MUI} = -\sum_i \mathrm{P_i}\left(\frac{\ln(\mathrm{P_j})}{\ln(\mathrm{J})}\right)$	*JICA database*
	Plot size	*Extracted as mean plot size from survey department data*	*JICA database /* survey dept. data
	Built-up coverage (BC)	$\mathrm{BC} = \frac{\text{Ground Floor Plinth Area}}{\text{land area}} \text{x100}$	Capitulate by author
Indicators of Urban design	Open space ratio (OSR)	$\mathrm{OSR} = \frac{\text{open space area}}{\text{land area}} \text{x100}$	Capitulate by author
	Access Road width	*Extracted with google earth*	OSM data / google earth measure
	Impervious surface coverage	*The % of impervious area of the catchment*	Capitulate by author
	Drainage density	$\mathrm{DD} = \frac{\sum(\text{dranage area})}{\text{land area}}$	*Drainage data of the area – WSDB and GN level/* Capitulate by author

3.9 Model Validation

The model's accuracy was confirmed by contrasting the model's predictions with real flood events analysed in the field and historical flood records. To assess the prediction accuracy of the model, spatial-statistical analytical techniques were used, including geographical analysis in GIS, correlation, and AI based- decision tree analysis (DTA). The effectiveness of the techniques was managing surface runoff to maximize urban density. To ensure sustainable usage of urban water management systems was assessed by applying to individual case studies. To verify the model result, the flood level is checked against with ground observations. At the end, conducted a focus group discussion to check the applicability of the model with planning experts. This aids in determining the most important indicators, or groupings of indicators, in urban density that may be controlled through planning procedures to develop cities that are robust to flooding in the future.

3.10 Overall methodology

The methodology of this study is comprised of three phases aligned with the research objectives. In the first phase, urban form-based indicators of UD were identified to quantify SR. The second phase involved the development of a conceptual framework using existing theories, concepts, and modelling approaches. Finally, in the third phase, data was prepared to model the proposed conceptual framework using the SWMM modelling approach and real ground flood data. Figure 17 illustrates the key phases of this study.

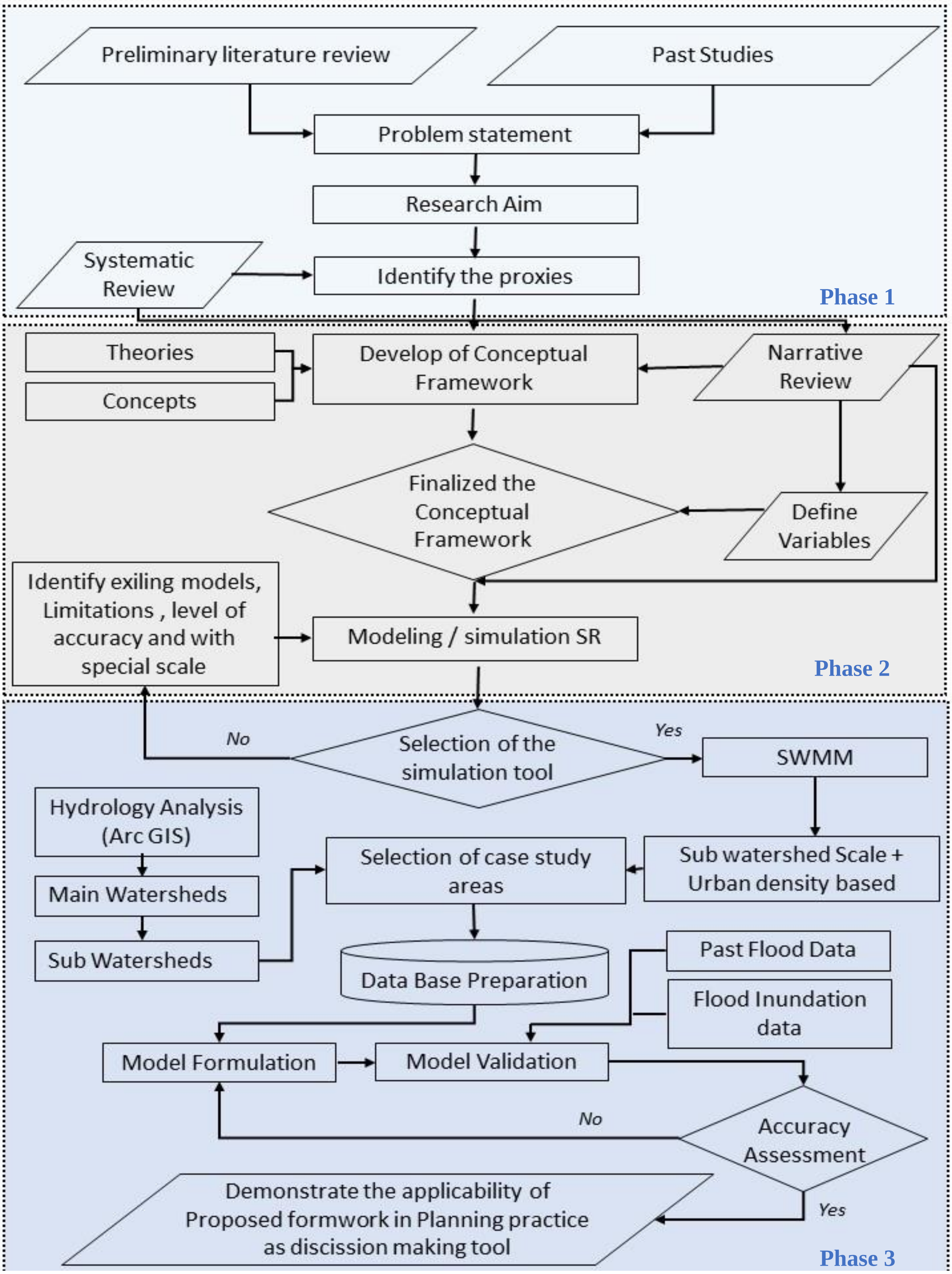


Figure 17: Overall Methodology

CHAPTER 4: ANALYSIS AND RESULTS

4.1 Introduction

To accomplish the primary objective of this study, a spatial simulation framework was created to assess the impact of UD on SR at the micro-urban watershed scale. To validate the framework, selected case study areas were utilized. The first step involved performing Pearson correlation analysis to determine the correlation among the chosen UD indicators. Next, an AI-based decision tree analysis (DTA) was employed to establish a model that would identify the most significant UD parameter affecting SR. In the third stage, regression analysis was utilized to verify the accuracy of the developed framework by comparing it with actual ground flood data. Lastly, to assess the applicability of the proposed modelling framework as a planning and decision-making tool for planning practices, a focus group discussion was held. The outcomes of each stage are summarized in Table 8.

Table 8: Analysis types carryout

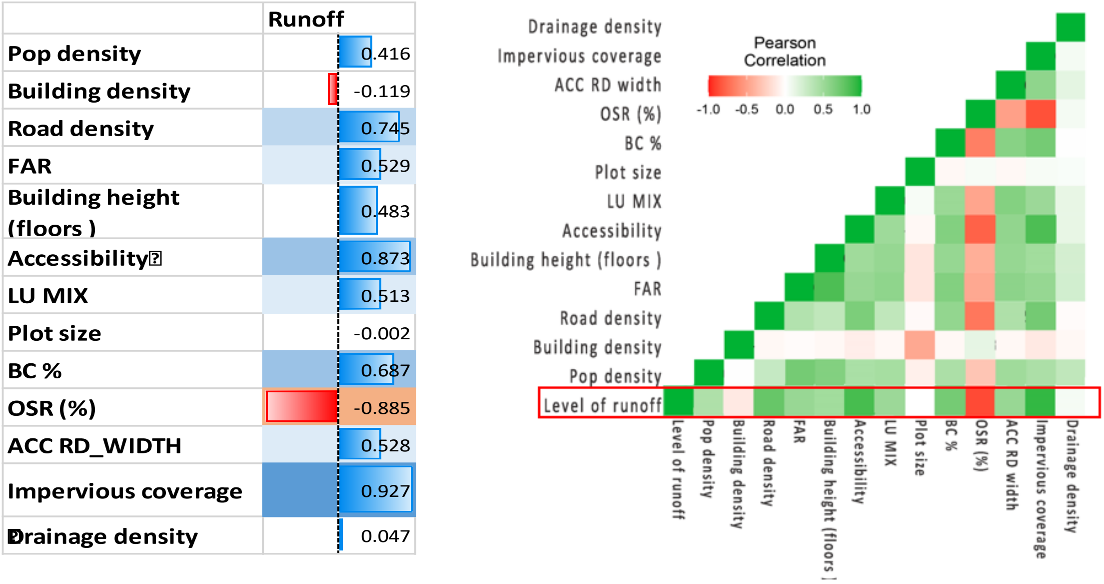
Stage	**Analysis carried out**	**Analysis's objective**
1	Pearson correlation analysis	To identify the correlation between 13 independent indicators of UD, Pearson correlation analysis is conducted.
2	AI-based decision tree analysis	The decision tree analysis (DTA) utilizing artificial intelligence is carried out to develop a model that can identify the most influencing UD parameter on SR. This helps in identifying the most significant factors that affect surface runoff and their relative importance. Here the DTA was to evaluate the level of accuracy and prediction probability of the framework that was developed beforehand.
3	Regression and spatial analysis	Regression analysis can be used to validate the developed framework with real flood data, specifically flood height and flood inundation time. This helps to assess the accuracy and reliability of the framework in predicting flood risk based on urban density indicators. Spatial analysis is used to analyse the relationship between different spatial features and to understand the spatial patterns in the data. It helps to identify areas that are more vulnerable to flooding and to develop flood-resilience urban planning strategies.

4.2 Correlation Analysis

This study conducted correlation analysis to determine the associations between the chosen individual UD indicators. This helped in understanding the interdependency and influence of each variable on the SR. The results of correlation analysis can help to identify which variables have a stronger or weaker relationship with SR, which can aid in selecting the most important variables for further analysis and modelling. Overall, correlation analysis is a useful statistical technique for exploring the relationships between variables and can help to inform subsequent modelling and analysis.

According to the analysis, impervious coverage and SR have a significant positive corelation with as R2 value of 0.92. The OSR has robust negative corelation as R2 value of -0.84. The degree of SR also shown substantial associations with accessibility and road density, with R2 values of 0.87 and 0.74, respectively. In urban settings, these variables—OSR, impervious covering, accessibility, road density, and FAR—are interconnected that have the most effects on rising urban flooding. OSR are being transformed into built-up areas, which reduces infiltration rates owing to impermeable covering and causes urban areas to flood during heavy rainfall events. Additionally, a relatively substantial link between SR and variables such FAR type, land use mix, built-up coverage, and access road width was observed, with a correlation value of +/- 6.00 > R +/-7.99 (p <0:01). The conceptual framework of 3Ds (density, diversity, and design) is used to display the Pearson correlation between each UD indicators in Figure 18.

A correlation heatmap is an important tool in data analysis as it helps to visually represent the correlation between different variables. In the context of urban flooding, the correlation heatmap provides valuable insights into how different UD indicators are related to SR. Furthermore, the moderate correlation between land_use_mix, built-up coverage, and access road width with SR, indicates that a mix of land use types and proper planning of built-up areas and access roads can also contribute to reducing flood risk in urban areas. Therefore, urban planners should consider the interdependence of these factors and take a holistic approach to urban design to address the challenges of flooding in cities. Overall, the correlation heatmap is a valuable tool in understanding the relationship between different variables and can provide insights that can inform urban planning and policy decisions to reduce the risk of urban flooding.



	Runoff
Pop density	0.416
Building density	-0.119
Road density	0.745
FAR	0.529
Building height (floors)	0.483
Accessibility	0.873
LU MIX	0.513
Plot size	-0.002
BC %	0.687
OSR (%)	-0.885
ACC RD_WIDTH	0.528
Impervious coverage	0.927
Drainage density	0.047

(a) (b)

Figure 18: Correlation values (a) | Correlation heat map (b)

4.3 Decision Tree Analysis (DTA)

In this study, AI based DTA was used to evaluate the accuracy and prediction probability of the developed theoretical framework. DTA with machine learning (ML) methods that establish relationships among predictor variable and target variable. They classify a dataset into different groups according to the occurrence rates of predictor variables. To perform the DTA, the researchers used the "Waikato Environment for Knowledge Analysis" (WEKA) tool and the J48 Classifier.

The J48 Classifier, also known as the C4.5 algorithm, is a decision tree algorithm used for classification tasks. It is based on the ID3 algorithm and uses a tree-based model to predict the target variable based on the input features. The J48 algorithm uses a set of training data to build the decision tree and then uses the tree to classify new instances. It is a popular and widely used algorithm due to its simplicity, accuracy, and interpretability. In the context of the study mentioned earlier, WEKA and the J48 Classifier were used to perform a DTA to measure the prediction probability and accuracy of the pre-developed theoretical framework. The DTA produced by the J48 algorithm was employed to determine the possible patterns of variable fluctuations across various SR levels.

The DTA can also be visualized as a tree diagram to understand the decision-making process and the hierarchy of predictor variables. The model results provide an example of how the level of SR can be decreased by considering various urban scenarios. Using DTA, three possible optional models were developed to categorize the level of SR into 05 categories, ranging from very low to very high, by taking independent density factors into account. The model discovered impervious covering, OSR, and density of roads as the three main factors that might lower the amount of runoff in urban watershed regions out of the 13 independent UD indicators. Additionally, the model revealed that the accessibility level, population density, width of access road, mix of land use, building coverage (BC), and size of the plot trigger or limit the amount of SR in macro-urban watersheds in a considerable way (refer Figure 19-21).

The analysis aimed to achieve a target output of low or very low SR levels to reduce urban flood risk (demarcate in green colours). If the urban area already has high or very high levels of SR, then the models can be used to reduce it to a moderate level (demarcate in yellow colour). The study found that the blue colour-demarcated areas along the branches of trees in an urban watershed can increase the risk of flooding. Therefore, planners can use this information to reduce the level of SR in critical points by analysing the UD indicators along the suitable branches and developing models accordingly. This approach can help to mitigate the risk of urban flooding in areas with such characteristics. The results and potential options for reducing SR levels are presented in Figures 19-21.

In this study, the DTA was used to identify the alternative flows of variables that could occur at various SR levels. This is similar to Root Cause Analysis. The link between root cause analysis and DTA is that both tools aim to identify the underlying causes of a problem or situation. Root cause analysis uses a structured approach to identify the root cause of a problem, while DTA uses a machine learning approach to identify the key factors that contribute to a particular outcome. Hence, examining the decision tree result, one can trace the path from the root node to the terminal node to identify the critical factors that lead to high levels of SR.

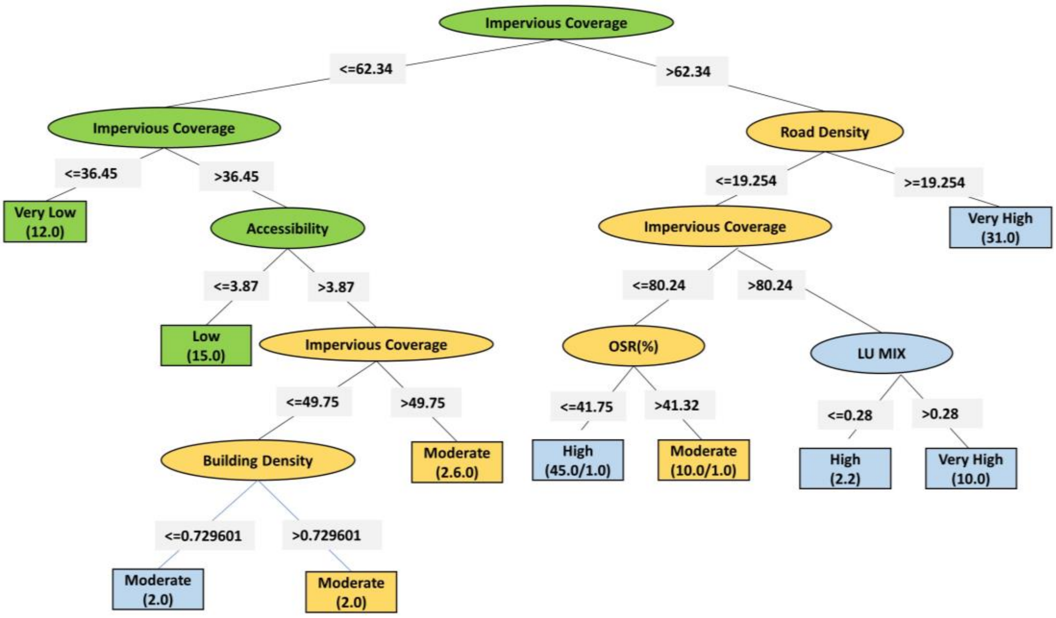


Figure 19: Optional Model 1 generated through DTA

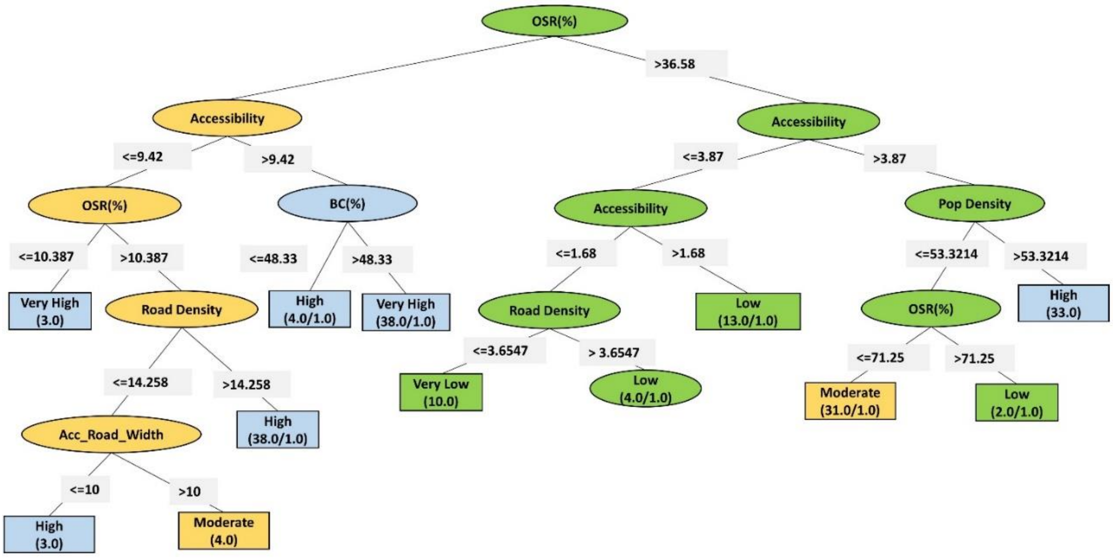


Figure 20: Optional Model 2 generated through DTA

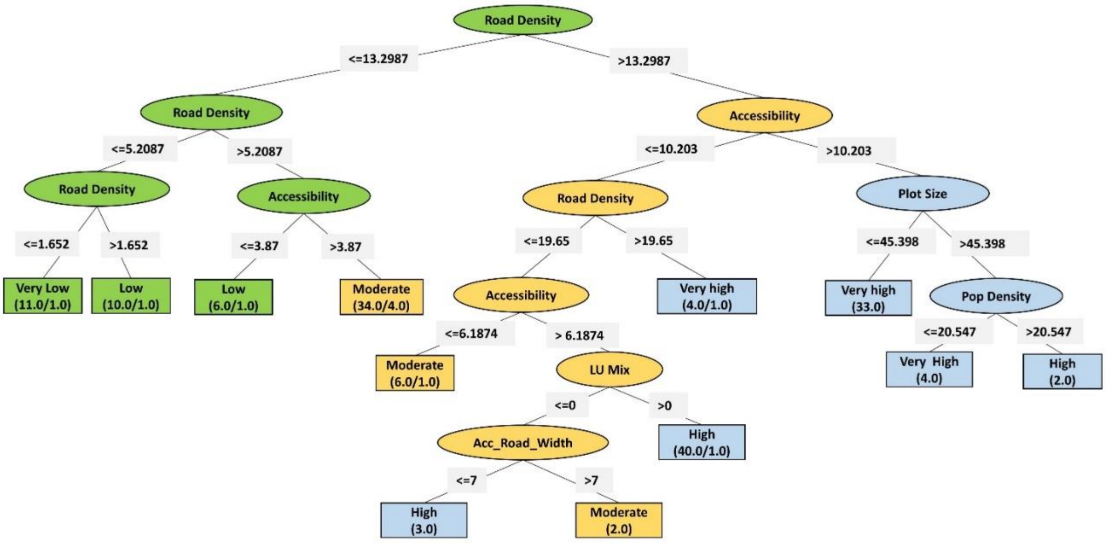


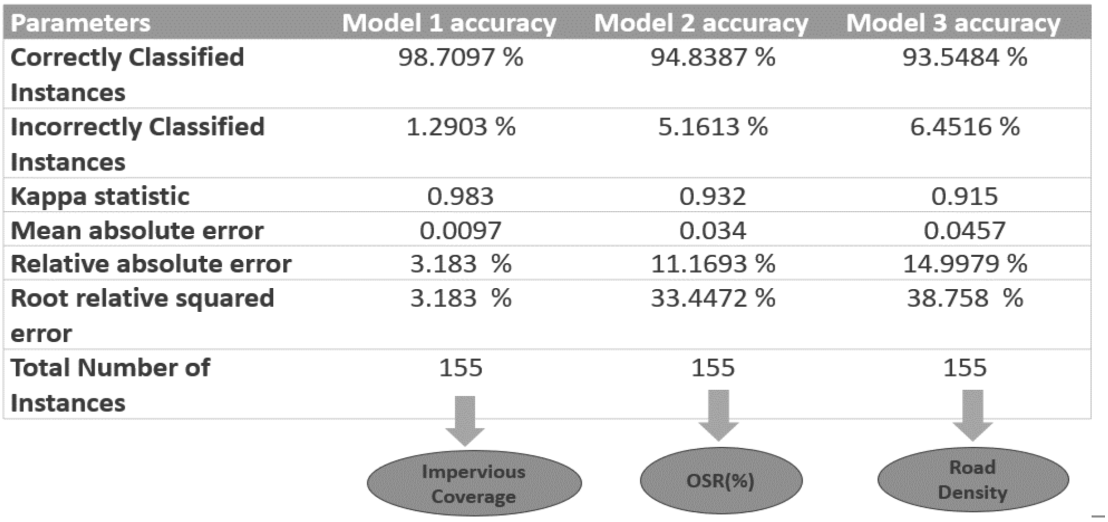
Figure 21: Optional Model 3 generated through DTA

4.3.1 Model Accuracy

under WEKA, the J48 decision tree algorithm produces a DTA that can be viewed using the classification table. The classification table displays the predicted class for each instance in the dataset based on the decision tree. It also shows the actual class and the associated probability of each predicted class. The classification table helps in evaluating the performance of the decision tree algorithm by providing measures such as accuracy, precision, recall, and F-measure.

As per the result of classification table it can be able to be deleted unnecessary attributes, and tree trimming can be performed by regenerating the classification process from the pre process tab of the decision tree. The accuracy of the model prediction is determined using parameters indicates in table 9. To decrease the level of SR, three optional models are generated, aiming to achieve a low or very low level of SR. If some catchment watersheds generates high or very high SR, that can be decreased to a modest level by flowing results of branch value. The accuracy of each generated model is summarized in Table 9.

Table 9: Accuracy of the each model of DTA

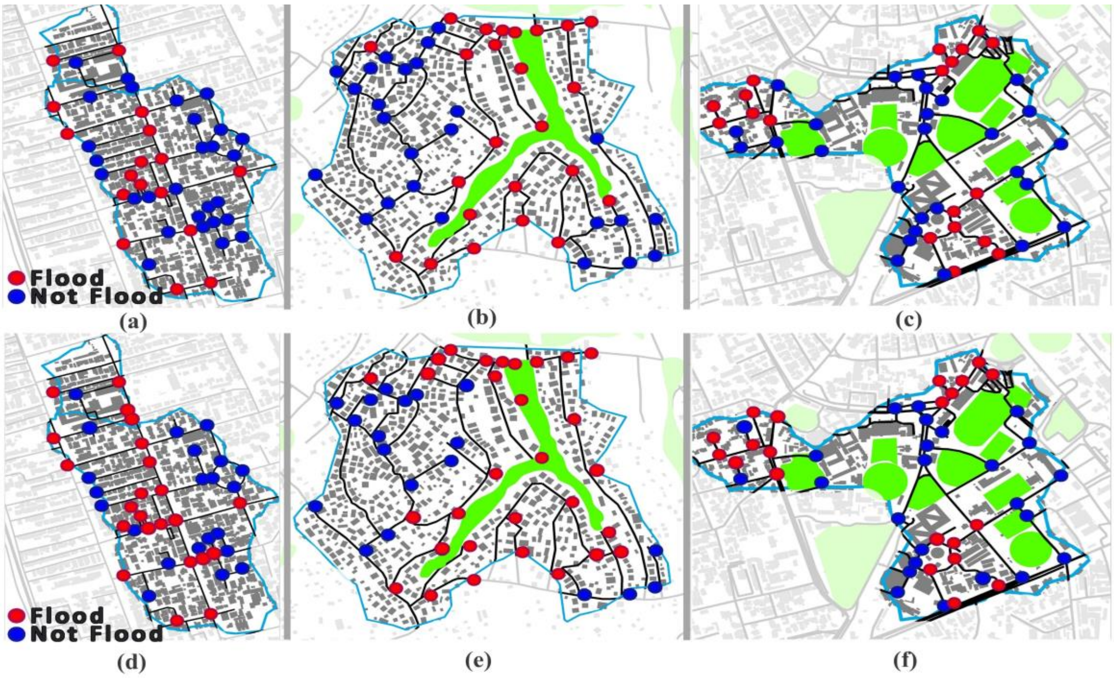


Parameters	Model 1 accuracy	Model 2 accuracy	Model 3 accuracy
Correctly Classified Instances	98.7097 %	94.8387 %	93.5484 %
Incorrectly Classified Instances	1.2903 %	5.1613 %	6.4516 %
Kappa statistic	0.983	0.932	0.915
Mean absolute error	0.0097	0.034	0.0457
Relative absolute error	3.183 %	11.1693 %	14.9979 %
Root relative squared error	3.183 %	33.4472 %	38.758 %
Total Number of Instances	155	155	155

4.4 Real ground verification with actual flood data

By contrasting the model projections with actual flood data, such as flood depth and inundation duration, the study confirmed the model's forecasts' accuracy. The study chose 3 case study watersheds in Sri Lanka's Colombo Metropolitan Region and conducted a comparison of historical flood data with simulated data produced by the model using GIS and SWMM tools. 140 locations (nodes) were used to evaluate the model's accuracy, and the findings revealed that more than 88% of the places where floods were predicted really recognized ground flooding. Figure 24 shows that the model's performance was adequate for both flood-prone and non-flood regions. This study conducted a comparative analysis between the results of the proposed model and the actual ground flooding data in three different case study areas (refer Figures 22 and 23). This proposed method can help disaster management, urban planners, architects, engineers, public agencies, non-governmental organizations institutions to make flood resilience cities.

In below figure 22 top three map series (i.e., a,b,c) indicates the actual flood locations. The red colour nods indicate the flooding, and the blue colour indicates not flooding. The latter three map series (i.e., d,e,f) indicates the simulation model result under each density category.



(a/d) High dense – Bambalapitiya area | (b/e) Moderate dense – Kalutara Hospital Junction | (c/f) Low dense – Colombo 07

Figure 22: Difference between real ground flood and simulated flood

The figure 23 refers to the comparison between the actual surface runoff observed on the ground and the surface runoff predicted by the model. It shows any differences or changes between the two results.

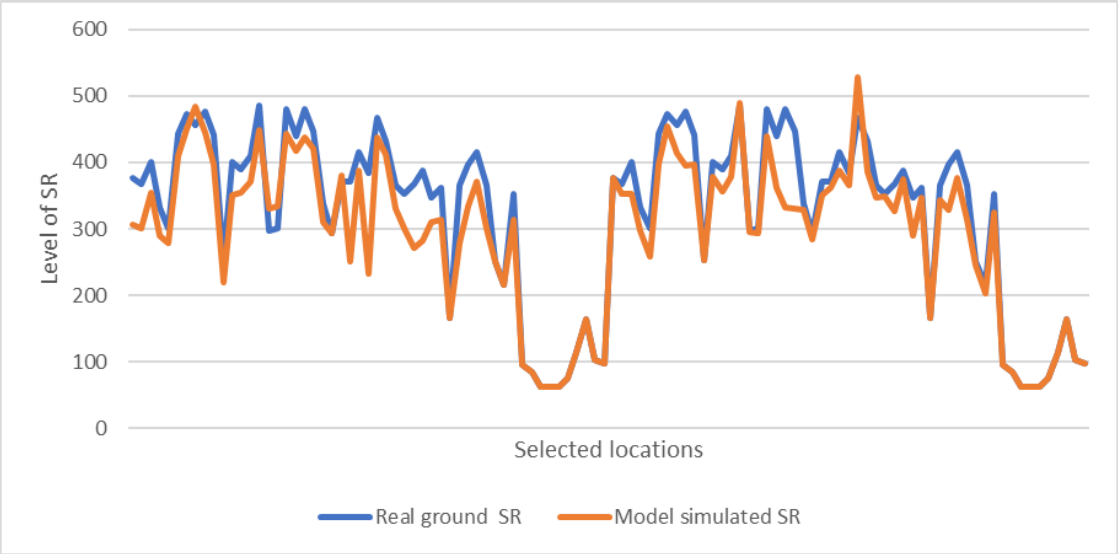


Figure 23: Differences between model results and real-world data on surface runoff – sub catchment level

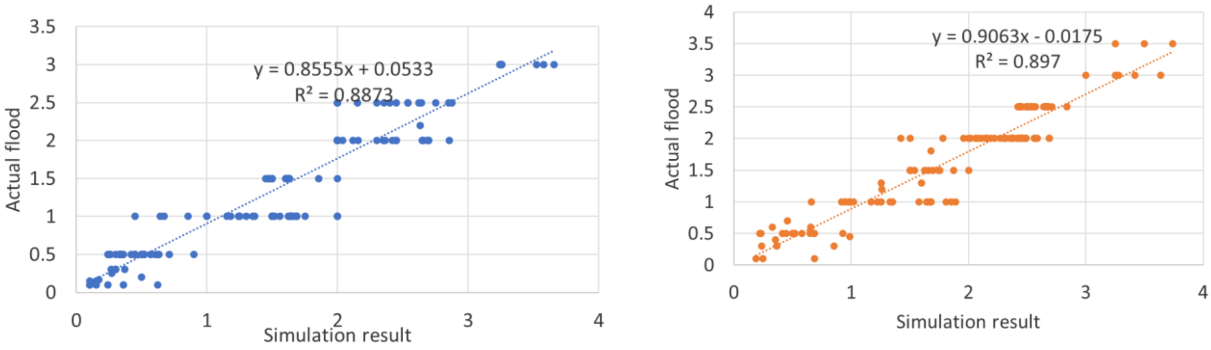


Figure 24: Validation of accuracy level – left indicates the flood depth in meters and right indicates the inundation duration in hours

4.5 Overall Results Discussion

According to the study's findings, urban density offers a great potential for controlling runoff from the surface in urban watershed on its own. Decision tree frameworks were created by analysing historical data that had been impacted by a variety of factors, and how various kinds of trees produce diverse results. Regression models, for instance, can forecast the real significance of upcoming forecasts. The density classification produced a model accuracy of above 90.00% for estimating runoff with density levels for each of the 13 individual density characteristics. The model findings agreed with the simulated values that were verified in the real-world flood data. Therefore, deliberate urban density improvements have the potential to increase the flood resistance of metropolitan areas.

By analysing the correlation heatmap, urban planners and policymakers can prioritize the implementation of strategies that target the key drivers of urban flooding. Here the impervious coverage is identified as the main driver of surface runoff, measures such as green roofs, permeable pavements, and rain gardens can be implemented to increase infiltration and reduce SR. Similarly, the open space ratio is found to be negatively correlated with SR. The preservation of green spaces and the creation of more parks and green areas can be prioritized to mitigate the risk of flooding.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The first section of this chapter discusses the key findings of the stakeholder perspective with the expert opinions which was carried out as a focus group discussion with planning and implementation bodies in Sri Lanka. Here includes variety of recommendations. Next, details describe the key contribution of this study, and the final section consists of the overall conclusion for this study.

5.2 Applicability of the proposed framework to make flood resilience cities.

The third objective of this study is to evaluate the effectiveness of created framework as a planning aid and decision-making tool with real ground validation. Here conducted a focus group discussion with local-level stakeholders involved in the planning sector. The content of the focused group discussion is attached under Appendix B and C. Here discuss the results obtained through a discussion regarding the effectiveness of the developed framework as a planning practice tool to make flood resilience cities.

Here collect the ideas among local stakeholders to identify the most critical factors/ indicators, clarify the model results, the possibility of applying the developed framework in planning practices, Suitable suggestions to improve the efficiency of developed framework and Limitations.

5.2.1 Identifying the most critical factors/ indicators with a stakeholder perspective.

Identifying the most critical density-based indicator, it may be depending on the type of development in a particular area. If an urban area is already developed with impervious cover, it is better to introduce more urban design solutions with environmental/ green approaches such as more green space, introducing LID options (i.e., rain barrels, artificial water retention areas, green roofs, rain gardens, and permeable pavements) to enhance infiltration over the imperviousness. Further, those solutions again change based on the type of development or land use type (i.e., individual housing, housing schemes, industrial zones, commercial areas etc).

If the proposed area is supposed to develop or natural land will be used for development; all 13 density indicators should be of vital importance. This proposed framework is directly applicable to simulate future flood events by changing each density indicator. There are several interventions that can be considered to reduce SR at the urban micro-watershed scale by changing/controlling the UD. Here are some possible interventions:

- **Increase the Open Space Ratio (OSR):** The OSR was one of the important factors the study discovered since it has a big influence on lowering surface runoff. The creation of more open spaces, such as parks, rooftop gardens, and other permeability surfaces, can be encouraged by planners. As a result, there will be less SR since the quantity of water the soil can absorb will be greater.
- **Limit Impervious Protection**: Significant SR contributions are made by impervious surfaces like concrete and asphalt. As such, it can control the amount of impermeable covering in metropolitan areas by limiting the amount of land that can be covered by such surfaces as a proportion of the total land area.
- **Improve Road Permeability**: Roads have a role in SR, particularly in places with heavy traffic. The adoption of permeability pavements, which enable water to seep into the soil rather than flow off the surface, can be encouraged by planners.
- **To Promote the Use of Green Infrastructure:** Planners may encourage the installation of green infrastructure, including as rain gardens, green roofs, and bioswales, which serve to collect and store rainfall and lessen surface runoff.

Furthermore, the topography of urban catchment areas can also play a role in runoff. Areas with steep slopes or hills can contribute to increased runoff. The rapid land use changes: such as the conversion of natural or agricultural land to urban land can result in increased impervious surfaces, which in turn can increase the amount of runoff. The rapid population growth and urbanization can lead to an increase in the number of paved surfaces, buildings, and other impervious structures, which can increase the amount of runoff.

5.2.2 Clarify the model results with a stakeholder perspective.

The most suitable option among the three density control options would depend on the specific characteristics and type of development. Each option (impervious_coverage, OSR, and road_density) may varying levels of effectiveness in reducing SR volumes depending on factors such as the current state of development, land use patterns, and hydrological conditions of the catchment area. It would be best to assess each option's feasibility and effectiveness on a case-by-case basis and tailor the planning interventions accordingly. Here they agreed with all three models.

In Sri Lanka, urban areas have been rapidly developing with high-density settlements and increased impervious surface coverage due to urbanization. This has resulted in an increase in surface runoff, leading to urban flooding during heavy rainfall events. To address this issue, the model results suggest that the regulation of impervious coverage and open space ratio (model 1 and 2) can be effective options to reduce surface runoff volumes. These options can be implemented through the revision of building codes and zoning regulations by local authorities or central government. For example, building codes could limit the percentage of impervious coverage on a property, and zoning regulations could require a minimum percentage of open space for each development.

However, the third option, road density, may require more investment and planning to implement. This may involve the construction of new drainage systems, upgrading existing infrastructure, or the construction of new roads to reduce traffic congestion and improve the road network.

In the Sri Lankan context, the implementation of proper drainage systems is also crucial for the success of any flood reduction strategy. The regulation of impervious coverage and open space ratio can be more easily implemented in Sri Lankan urban areas, while the third option, road density, may require more investment and planning to be effective. In addition, the proper planning and implementation of drainage systems are essential for any flood reduction strategy to succeed.

5.2.3 The possibility of applying the developed framework in planning practices as stakeholder perspective

The involvement of stakeholders is essential to ensure that the proposed solutions are relevant to the local context and that the planning process is transparent and inclusive. Stakeholders can include government agencies, local communities, NGOs, private sector actors, and academic institutions. By involving a diverse range of stakeholders, the planning process can take into account the different perspectives and priorities of different groups, and ensure that the proposed solutions are socially, environmentally, and economically sustainable.

For example, in the context of Sri Lanka, the involvement of local communities can be critical in identifying the most vulnerable areas to flooding and ensuring that proposed solutions take into account the local knowledge and experience of the communities. The involvement of government agencies can help ensure that the proposed solutions align with national policies and regulations. Overall, the involvement of stakeholders is critical to ensure that the proposed solutions are relevant, feasible, and sustainable and that the planning process is inclusive and transparent.

5.2.4 Suitable suggestions to improve the efficiency of developed framework in a stakeholder perspective.

Incorporating more detailed and accurate data: The accuracy of the framework depends heavily on the quality and detail of the input data. Therefore, more detailed and accurate data could improve the efficiency of the framework. This could include using more precise and high-resolution satellite imagery to map impervious surfaces and vegetation cover, collecting more detailed information on soil types and infiltration rates, and gathering more accurate data on precipitation patterns and intensity. Additionally, more accurate data on precipitation patterns and intensity could be obtained through the use of weather stations or other monitoring systems. By incorporating more detailed and accurate data, the framework could be improved to provide more accurate predictions and recommendations for reducing urban flooding.

Including additional factors: The framework could be improved by including additional factors that influence flood resilience, such as soil characteristics, topography, and climate patterns.

Testing in more diverse contexts: The framework could be tested in more diverse contexts to evaluate its effectiveness across different urban areas with varying characteristics (i.e., topology, special scale, and climate conditions. For example, the framework could be applied in a coastal city in Sri Lanka, where flooding is caused by a combination of heavy rainfall and tidal surges. This would require the incorporation of additional factors in the framework, such as sea level rise projections and storm surge modelling, to accurately predict flood risk in the area.

Addressing financial constraints: The framework could be made more efficient by addressing the financial constraints that hinder its implementation. This could involve exploring innovative financing mechanisms, such as public-private partnerships, to ensure the necessary funds are available.

Engaging with stakeholders: This is an essential step towards improving the efficiency of the developed framework. Urban planning is a complex process that involves multiple stakeholders, including government agencies, private developers, non-governmental organizations, and local communities. Each stakeholder has different perspectives, priorities, and interests in urban development. Therefore, engaging with stakeholders throughout the planning process could help to identify their needs and expectations, and incorporate them into the planning process.

For instance, government agencies could provide valuable input on regulatory requirements and provide necessary permits for development. Private developers could provide insights into the feasibility of implementing certain measures and their potential costs. NGOs and local communities could provide valuable feedback on the social and environmental impacts of the proposed developments.

5.2.5 Limitations/ opportunities in applying the proposed framework in planning practices in Sri Lanka in a stakeholder perspective.

Table 10: Limitations/ opportunities in applying the proposed framework

Type	Constraints/ Limitations	Opportunity
Planning and design	• The model results may not take into account the social, cultural, and economic factors that influence planning and design decisions. • Also, the availability of accurate data on urban catchment areas may be limited, which can affect the accuracy of the model results in Sri Lankan context.	• The model results can serve as a valuable tool for planners and designers to make informed decisions about managing urban catchment areas. • The model can help identify areas that are at risk of flooding and guide the development of appropriate land use and building codes to mitigate the risk.
Policy/ Political	• The implementation of policies to mitigate flood risks may be hindered by political situations. • The lack of a clear and consistent policy framework can also affect the effectiveness of the model results.	• The model results can help policymakers make data-driven decisions and develop evidence-based policies to mitigate flood risks. • The model provides a basis for developing a comprehensive flood management plan that involves multiple stakeholders and aligns with national and regional policies.

Technical know-how	• Technical expertise may be lacking in some areas in Sri Lankan practical situation, which can affect the implementation and effectiveness of the model results. • Model results may not account for changes in the physical environment, such as climate change, that can affect the level of runoff.	• The model results can help build technical capacity in urban flood management and serve as a tool for training and capacity-building initiatives. • The model can be updated to reflect changes in the physical environment and incorporate new technical knowledge and tools.
Financial capability	• Financing flood management projects may be challenging, particularly in areas with limited financial resources. • The cost of implementing the model results may vary depending on the size and complexity of the urban catchment area.	• The model results can help identify cost-effective solutions to mitigate flood risks, which can be particularly important in areas with limited financial resources. • The model can guide investment decisions and help attract funding from various sources, including international aid agencies and private investors.
Institutional Framework (Implementation body i.e. CG/ LA/ Private)	• The success of the framework is also contingent upon the allocation of sufficient resources and funding to support its implementation. • Constrains of institutional capacity and willingness to implement flood reduction strategies.	• The proposed framework presents an opportunity for different institutions (e.g. central government, local authorities, private sector) to work together to address urban flooding. Collaboration among these actors could lead to more coordinated and effective flood reduction strategies
Regulatory/ Legislature	• The implementation of the model results may be affected by the lack of clear regulatory and legislative frameworks in Sri Lankan Planning practices. • The existing laws and regulations may not adequately address the complex issues of urban flood management.	• The model results can help guide the development of comprehensive regulatory and legislative frameworks that promote integrated flood management. • The model can identify gaps and weaknesses in the existing regulatory and legislative frameworks and provide a basis for developing new regulations and standards.
External assistance	• The availability and effectiveness of external assistance may vary depending on the political and economic situation in the country.	• External assistance can provide resources, technical expertise, and knowledge-sharing opportunities to support the implementation of the model results. • External assistance can also help build partnerships and networks among different stakeholders and

		promote knowledge exchange and capacity building.
Research and Development	• The proposed model may have limitations due to the lack of data availability, particularly in developing countries like Sri Lanka. • The model may require continuous refinement and updating as new data becomes available and as urban environments change over time.	• Continued research and development can improve the accuracy and applicability of the proposed model. • The model can be used to identify knowledge gaps and research priorities related to urban flood resilience.

5.3 Key contributions of the study

The study created an evaluation approach that may be used both nationally and internationally to assess the amount of SR at various UD. The study demonstrates that regulating SR requires the use of all 3D s of UD indicators (Indicators of density, Indicators of diversity, Indicators of design). Percentage of imperviousness, OSR availability and road density has a notable impact in changing SR in urban environments while the level of accessibility, population density also influencing triggers the SR in urban areas of catchment. The study incorporates with previous research on the significance of urban design-based density indicators in reducing SR via LID , BMPs, and urban water management strategies.

This study proposes a novel framework that aims to quantify the impact of UD on flood levels, taking into account anthropogenic activities. The framework A case study was employed to investigate level of flood resilience and considers stakeholder perspectives, which makes it particularly relevant to urban flood management and planning practices. One of the key contributions of this study is its provides holistic approach to quantifying UD, which incorporates different perspectives (3D s) such as density, diversity, and design. By categorizing these three density areas, the framework can be applied to any urban context worldwide, providing a standardized approach to measuring urban density.

This new framework offers a significant novelty to the field of urban flood management by providing a comprehensive approach to measuring urban density. Previous studies have highlighted the influence of different UD morphological elements on SR, but this study takes it a step further by developing a quantitative evaluation mechanism that technique can be adapted to meet the specific demands of a given case study. The results of the study indicate that UD indicators, which includes natural factors, has the significant impact on changing flood levels in urban watershed areas.

To improve the efficiency of the developed framework, it is important to ensure that the proposed density control options are integrated into the urban planning and design process. One way to achieve this is by integrating the key indicators identified in this study, such as impervious_cover, OSR, and road_density, into current planning policies and guidelines. For instance, planning authorities can update the existing zoning regulations to include minimum open space requirements and maximum impervious coverage ratios. This would enable planners to better control the development density and reduce the potential for flooding in urban areas.

Furthermore, the framework can be improved by incorporating the principles of sustainable urban design. This includes promoting the use of green infrastructure, such as green roofs, permeable pavements, and rain gardens, which can help reduce the volume of runoff and improve water quality. For example, in the design of a new residential development, planners can incorporate green roofs to reduce the impervious coverage and increase the amount of open space. This not only helps to mitigate the impact of urban flooding but also provides additional benefits, such as reducing the urban heat island effect and improving air quality.

The proposed framework is to ensure that it is properly communicated to stakeholders. This includes raising awareness among developers, local authorities, and the public about the importance of sustainable urban design and the role that they can play in reducing the risk of urban flooding. For example, training sessions and workshops can be organized to educate developers on the benefits of green infrastructure and density control options.

5.4 Recommendations

The developed framework in this study has shown promising results and provides accurate outcomes for local-level applications. As a result, it is highly recommended to promote the adoption of this framework in urban planning and regulatory processes, particularly at the governance level. By incorporating urban design-based approaches derived from the framework, such as the identification of suitable density indicators, decision-makers can make more cost-effective and informed planning and regulatory decisions. This integration will help improve the overall management of stormwater runoff and enhance urban resilience.

Furthermore, future research should focus on exploring additional environmental approaches to reduce stormwater runoff. Strategies such as Low Impact Development (LID) techniques and water-sensitive urban design have shown effectiveness in mitigating stormwater runoff and improving water management. Investigating the applicability and effectiveness of these strategies in diverse urban settings will contribute to a better understanding of their potential and broaden their implementation in urban planning and design.

To enhance the robustness and generalizability of the findings, it is recommended to conduct further case study applications. The current study focused on flat terrain areas within the selected case study, but it is crucial to explore diverse density scenarios and different terrain conditions. This will provide a more comprehensive understanding of how the framework performs across various urban contexts and enable the formulation of context-specific strategies for stormwater management.

Finally, city governance should consider incorporating the research outcomes into their decision-making processes. The framework and its associated recommendations can serve as valuable tools for assessing and managing stormwater runoff in urban areas. By integrating the framework into their governance practices, cities can enhance their flood resilience, improve water management strategies, and foster sustainable urban development. This will lead to more effective urban planning, regulatory decisions, and overall sustainable growth.

5.5 Conclusion

A user-friendly interface has been designed for the developed framework to calculate and simulate various parameters with a range of SR intensity levels. The results can be displayed visually in a geospatial format, making it easier to understand and interpret. To enhance the usability of this framework, future studies could integrate existing policy regulations and expert opinions. The present study's approach has limitations in terms of its validation only at the micro-watershed scale. As a result, there is a possibility of enhancing the approach by adapting UD parameters for larger catchment areas at the macro-watershed level in future research. Furthermore, to enhance the applicability and accuracy of the proposed approach, more case studies are required to account for various land uses, topographical features, and UD management strategies. As a result, this research can be useful to stakeholders involved in land use planning, policy-making, and decision-making, as well as those working with implementing agencies. In summary, the findings of this study can serve as a valuable resource for stakeholders engaged in managing and mitigating flood-related disasters.

The use of density-based indicators can provide valuable insights into building resilience in an urbanizing world where flood damages are a growing concern. Geospatial indicators effectively capture the impact of increased risk due to the rapid expansion of built-up areas and the disruption of natural flood defence mechanisms. Therefore, this proposed framework recommended strengthening the urban form resilience as a pre-assessment tool. Further research on validating and refining these indicators can enhance the scientific rigour and comprehensiveness of the assessment process, leading to more effective initiatives for enhancing urban resilience.

Overall, the integration of well-defined, statistically verified geospatial indicators in a developed framework can guide future policy and planning decisions towards sustainable outcomes that empower communities to better cope with floods and safeguard the quality of the earth's life support systems.

Publications

1. Wijayawardana, Naduni, Chethika Abenayake, Amila Jayasinghe, and Nuwan Dias. "An Urban Density-Based Runoff Simulation Framework to Envisage Flood Resilience of Cities." Urban Science 7, no. 1 (2023): 17. https://doi.org/10.3390/urbansci7010017

2. Wijayawardana, P.N.P., Abenayake C.C., Dias N. "Density Based Urban Flood Simulation Framework to Envisage Future Flood Resilient Cities" in 1st Annual Symposium 2021/2022 organized by ITPSL, Sri Lanka – Abstract Publication

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Appendices

6.1 Appendix A: Identified Density-Based Indicators through systematic review

Identified Density-Based indicators	(Khalaj et al., 2021)	(Waqas et al., 2021)	(Lin et al., 2021)	(Liu et al., 2021)	(H. D. Nguyen et al., 2021)	(Piyumi et al., 2021)	(Abdrabo et al., 2020)	(Thoban & Hizbaron, 2020)	(Ress et al., 2020)	(Mwangi et al., 2020)	(Papilloud et al., 2020)	(Khadiyanto et al., 2020)	(Ogato et al., 2020)	(J. Chen et al., 2019)	(Albano, 2019)	(Fahy et al., 2019)	(Ahmed et al., 2019)	(Caparros-Midwood et al., 2019)	(Park & Lee, 2019)	(Afifi et al., 2019)	(Cai et al., 2019)	(Peng et al., 2018)	(Stetsenko & Yastrebova, 2018)	(Abo-El-Wafa et al., 2018)	(B. Kumar & Bhaduri, 2018)	(Sitzenfrei et al., 2017)	(Majid et al., 2013)	(I-soon et al., n.d.)	(Chrysochou et al., 2012)	(Schubert & Sanders, 2012)
Drainage Density	*	*				*			*			*	*	*		*										*				
Population Density			*	*	*		*	*								*				*				*	*				*	
Building Density			*	*				*		*						*						*	*		*	*	*			*
Building Height			*	*			*			*							*						*		*					
Green/Open Space Ratio			*					*								*	*	*							*					
Road/Street Density									*		*						*											*		
Accessibility/Access Road Width						*			*								*													
FAR										*		*			*		*		*											
Built Up/Ground Coverage Ratio (GCR)																*														
Impervious Surface Coverage/%						*										*					*	*					*			
Area of Building Footprints																	*													*
GSI																	*													
Plot Size			*							*							*													
Land Use			*			*					*										*				*					

6.2 Appendix B: Semi-structured interview guide for the focus group discussion

Dear Sir/Madam,

I am a Master by Research (Part-time) student of the Department of Town & Country Planning, University of Moratuwa supervised by Dr. (Mrs) Chethika Abenayake.

My Research title is "An Urban Density-Based Runoff Simulation Framework to Envisage the Flood Resilience of Cities". I am at the final stage of the study and am interested in externally validating the study findings with the DRR and Urban Planning in the Sri Lankan context.

Here I attach the research brief for your kind information as a guide-study summary that represents the study objective and existing results obtained so far. This focus group discussion aims to identify the expert opinion on the followings: (a) the relative importance of density-based indicators that have been identified through the existing literature on surface runoff simulation methods; (b) the applicability of the three alternative Urban Density-Based Runoff Simulation models in Sri Lankan context; and (c) any suggestions to improve the proposed framework.

Your support in this regard is highly appreciated.

Naduni Wijayawardana

A semi-structured interview guide for the focus group discussion

An Urban Density-Based Runoff Simulation Framework to Envisage the Flood Resilience of Cities

(* Please refer to the attached leaf lets regarding the aims and the existing results of the research carried out)

1. Level of importance on density-based indicators on surface runoff SR in Sri Lankan planning practices

		Allocate marks 0-100	
		Level of importance on SR (urban flood)	Current practice
	Population density (PD)		
	Building density		
	Road density		
	FSI (Floor Area Ratio)		
	Building height		
	Level of accessibility		
	Land use mix (Mixed Use Index)		
	Plot size		
	Built-up coverage (BC)		
	Open space ratio (OSR)		
	Access Road width		
	impervious surface coverage		
	Drainage density		

2. What are the most critical indicates on changing the level of runoff in urban catchment areas in Sri Lanka ?

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3. In the leaflet attached the three-alternative urban density-based simulation models are illustrated. Please refer to the leaflet and share your opinions on them.

3.1.Are you generally agreed with the outcome results of the models 1 / 2/ 3?

Model 1 (Agreed/ Not Agreed)
Model 2 (Agreed/ Not Agreed)
Model 3 (Agreed/ Not Agreed)

3.1.1. If not why? Please specify the reasons ……………………………

3.2. Which model is the best fit with Sri Lankan Urban context?...

3.2.what are the required improvements/ suggestions regarding model 1 /2/3 ?

4. How would you like to intervene in the surface runoff reduction at Urban micro-watershed scale by changing/controlling the density of build form?

4.1.Is there any intervention to manage those identified density-based indicators in urban watershed scale by aiming to reduce the impact of flood? (Yes/No)

4.1.1. If yes; which factor/s and how to manage? (e.g. initial plan preparation / regulatory level/ implementation level/ evaluation or site inspection/ other specify)
………………………………………………………………………………
……………………………………………………

4.1.2. If no; what else makes you intervene in density-based urban flood management
………………………………………………………………………………
…………………………………………………….

5. What are the limitations/ opportunities in applying the proposed framework in planning practices in Sri Lanka?

Type	Constraints/ Limitations	Opportunity
Planning and design		
Policy/ Political		
Technical know-how		
Financial capability		

Institutional Framework (Implementation body i.e. CG/ LA/ Private)		
Regulatory/ Legislature		
External assistance		
Research and Development		
Other		

6. What are the possible suggestions to improve the level of accuracy of the proposed framework?

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6.3 Appendix C: Leaf lets - aims and the existing results of the research

An Urban Density-Based Runoff Simulation Framework to Envisage Flood Resilience of Cities

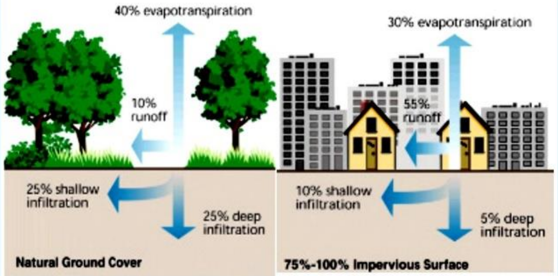
This indicates the summary of the results that reveal the influence of all three types of density-measuring parameters that are important to managing surface runoff.
The results show the density-based parameters such as ***Impervious coverage, OSR and road density are the critical factors*** *incorporated with the level of accessibility, population density and built-up coverage to determine surface runoff in the urban catchment.*

1. INTRODUCTION

- The **urbanization increases** the size and **frequency of floods in urban areas** to a greater level.
- Urban areas have **become more vulnerable hotspots of extreme flood events** due to high-intensity developments.
- The urban watersheds have **greater peak discharge rates** than rural watersheds which reduces the water storage capacity.
- The **high-density urban form** indicates **a high level of impervious surfaces** which reduces the natural penetration capacity while decreasing the infiltration rate. That leads to peak runoff in the urban environment, and which generally **reduces hydrologic response time and increases flood risk**.

The expected outcomes of the expert opinion survey

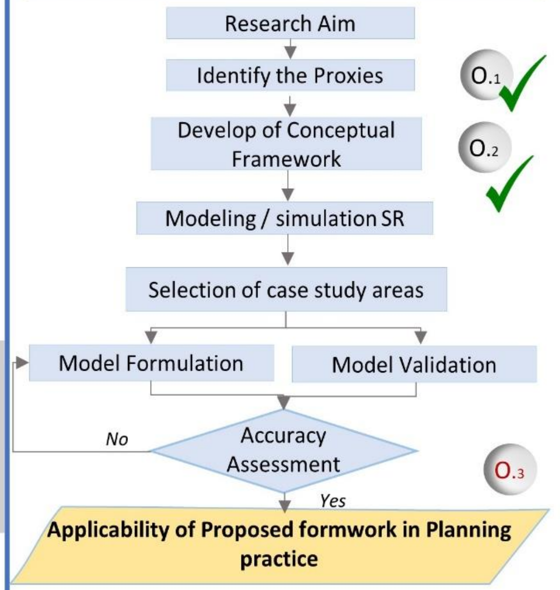
✓ To identify the most critical factors/ Proxies
✓ Clarify the model results
✓ Possibility of applying in planning practices
✓ Suitable suggestions
✓ Limitations



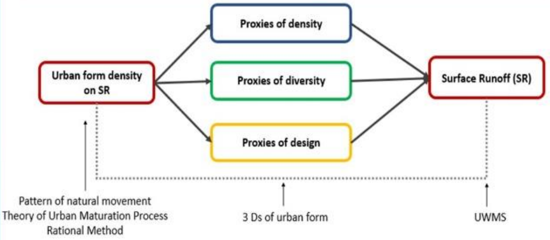
2. Aims and Objectives

Aim : To develop a spatial simulation framework to assess the impact of urban density on surface runoff in urban watersheds scale, under different urban form scenarios

3. Methodology



3.1. Proposed Framework



3.2. Categorization of Indicators

Indicators of Density	Indicators of diversity	Indicators of Urban design
Population density (PD)	Building height	Open space ratio (OSR)
Building density	Level of accessibility	Access Road width
Road density	Land use mix (Mixed Use Index)	impervious surface coverage
FSI (FAR)	Plot size	Drainage density
	Built-up coverage (BC)	

4. Analysis and Results

Step 1 ✓ Generation of **procedural urban form layouts** to each density aspect.

Step 2 ✓ **Calculation of surface runoff** with SWMM simulation approach for pre-derived case study areas under step 1.

Step 3 ✓ Identify the **statistical relationship** between variables utilizing correlation analysis.

Step 4 ✓ Find out the **prediction possibility, and model accuracy** of the pre-defined model as a decision-making tool by utilizing Decision Tree analysis.

Determining key costive proxies or group of proxies

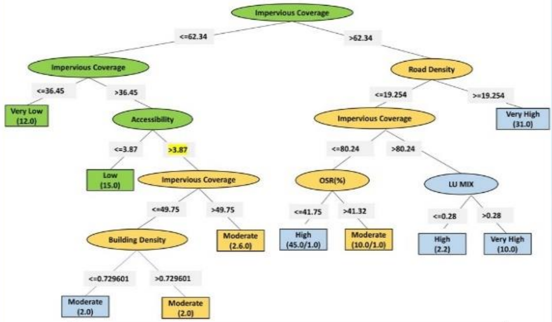
Step 5 ✓ **Grand verification** of the developed framework with **actual rainfall data** (**flood height, inundation duration and flooding locations**) with regression analysis.

Step 6 Demonstrate the applicability of Proposed formwork in planning practice as discussion making tool.

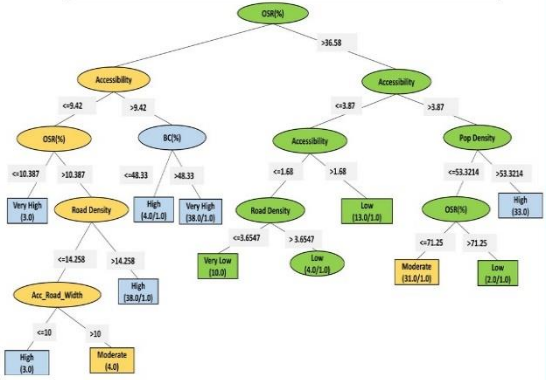
1. What are the **most critical indicates** on **changing the level of runoff**?
2. Which model is the **best fit with Sri Lankan** Urban context
3. are the **required improvements/ suggestions regarding** model 1 /2/3?
4. How would you like to **intervene in the surface runoff reduction** at Urban micro-watershed scale by changing/controlling the density of build form….
5. What are the **limitations/ opportunities** in applying the proposed framework in planning practices in Sri Lanka?

4.1. Decision Tree

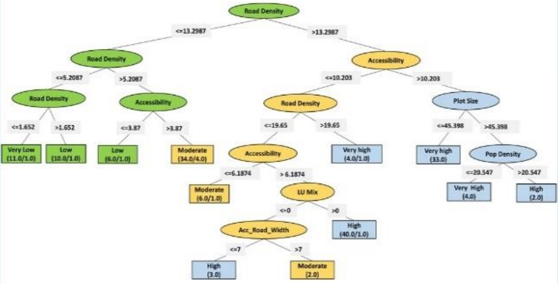
Model 1 (Level of Accuracy 98.7097 %)



Model 2 (Level of Accuracy 94.83 %)



Model 3 (Level of Accuracy 93.54 %)

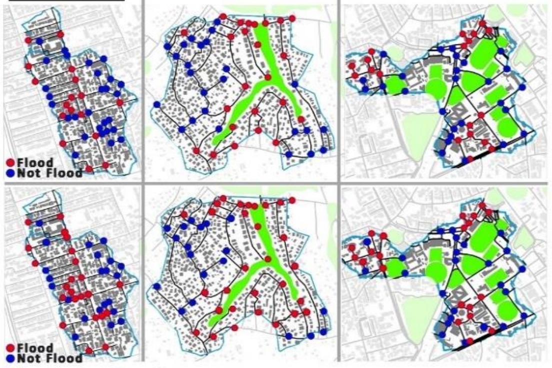


4.2. Correlation analysis

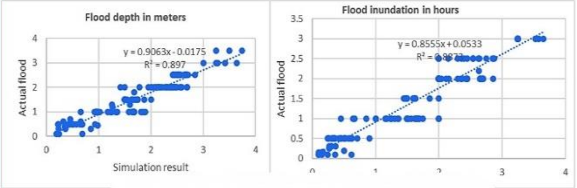
	Runoff		Runoff
Pop density	0.416	LU MIX	0.513
Building density	-0.119	Plot size	-0.002
Road density	0.745	BC %	0.687
FAR	0.529	OSR (%)	-0.885
Building height (floors)	0.483	ACC RD_WIDTH	0.528
Accessibility	0.873	Impervious coverage	0.927
		Drainage density	0.047

4.3. Real Ground Verification

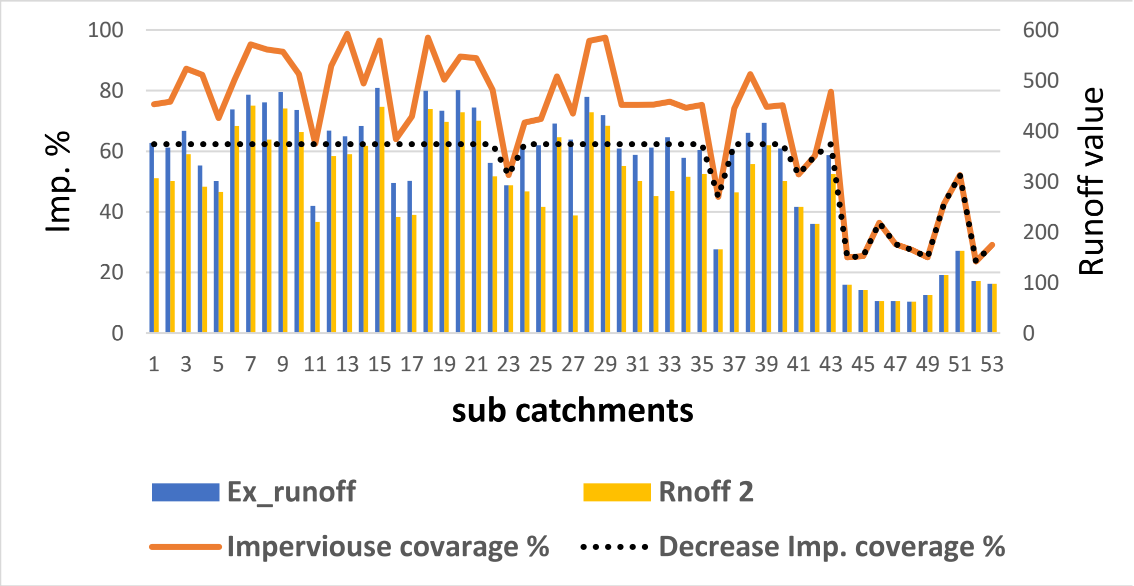
Actual Flood

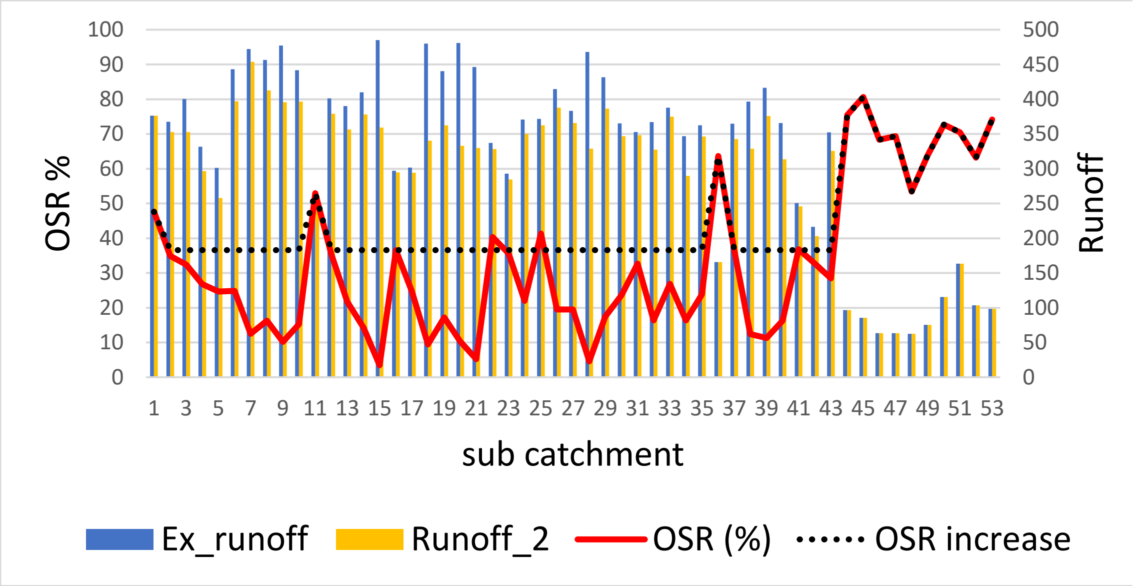


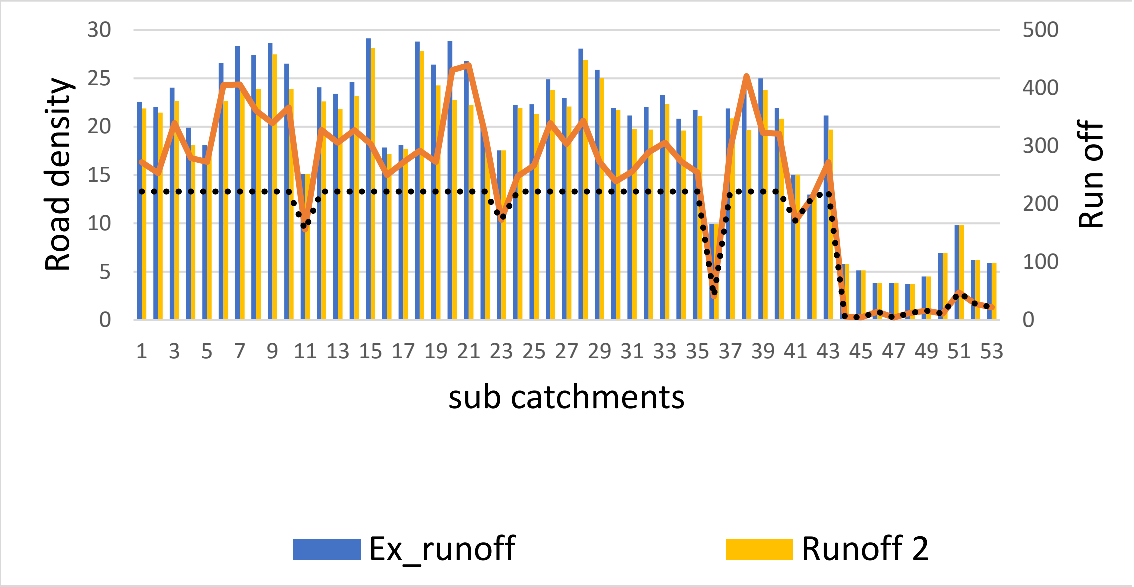
Simulation Result



6.4 Appendix D: Existing flood and future flood reduction under three models







6.5 Appendix E

Overview of the purpose of the study applied in different urban scales with simulation approaches and considered UD factors against urban flood.

Purpose of the study	Considered density-based factor	Scale	Simulation approach	References
To assess the flood risk (i.e. including hazard, vulnerability, exposure) impact assessment, reduction and management.	Drainage density population density building density Road density Plot coverage open or green space ratio FAR Built-up coverage ratio	N, R, L, S	SWMM, HEC-RAS, GIS, MIKE, DEM base, Remote sensing, 2D RRI[4], ML, Generic algorithms, with evaluations models such as MCDM (i.e., AHP, Fuzzy etc.)	(Costa , et al., 2021) (H. D. Nguyen et al., 2021) (Abdrabo et al., 2020) (Ress et al., 2020) (Caparros-Midwood et al., 2019)
Flood susceptibility quantifying using DEM based modelling or topographic features of remote sensing.	Building density Drainage density population density building height Plot coverage open or green space ratio	N, R, L	HEC- RAS, ML, GIS, Remote sensing, 3Di Model with evaluations models such as MCDM (i.e., AHP, Fuzzy etc.)	(Waqas et al., 2021) (Walczykiewicz & Skonieczna, 2020)

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[4] Rainfall runoff inundation city model

	FAR, Built-up coverage ratio			(Afifi et al., 2019)
To assess three-dimensional building density impact flooding.	Population Density Building Density Building Height Road density Mean building height (MBH) Mean building volume (MBV) Standard deviation of building height (SDBH) Standard deviation of building volume (SDBV) Green/open space ratio POI data	L, S	ML, Aerial imagery	(Lin et al., 2021; Mwangi et al., 2020)
To assess the performance, stranders, application of UWMS (i.e., WSUD, BGI, LID, GI, SUDS, BMPs etc.).	Building density Green/open space ratio Road/ street Density building footprints FSI GSI Built-up coverage ratio	L, S	GIS, the Digital Water Simulation hydrodynamic model (DS Model), SWMM, PC-SWMM, MIKE with evaluations models such as MCDM (i.e., AHP, Fuzzy etc.)	(Peng et al., 2018) (Kumar & Bhaduri, 2018) (Keyvanfar et al., 2021)
Flood resilience assessment	Building density Drainage density population density Green/open space ratio	R, L, S	ML, GIS, Remote sensing, SWMM, MIKE with evaluations models such as MCDM (i.e., AHP, Fuzzy etc.)	(Thoban & Hizbaron, 2020)
High-resolution Areal imaginary or LIDAR image-based approaches to evaluate urban flood with urban building configuration.	Population density Road density Built-up coverage ratio built-up volume densities (BVD)	L, S	ML, GIS, Remote sensing	(Albano, 2019)
To assess the factors that cause violation of built form	Built-up coverage ratio	S	N/A	(Khadiyanto et al., 2020)

regulations and calculate the impact on runoff.				
To develop and evaluate flood indexes or conceptual framework related to urban form factors	Drainage density	R, L	GIS, ML with MCDM (i.e., AHP, Fuzzy etc.)	(J. Chen et al., 2019)
To assess the urban flood modelling applications with urban density related factors.	Drainage density Population density Built-up coverage ratio	L	GIS, SWMM with MCDM (i.e., AHP, Fuzzy etc.)	(Abenayake, et al., 2021) (Abenayake, et al., 2020)
To evaluate the accuracy and performance of Urban flood Simulation models.	Drainage density Population density Built-up coverage ratio Building density	R, L, S	HEC- RAS, SWMM, PC-SWMM, MIKE, GIS, ML with MCDM (i.e., AHP, Fuzzy etc.)	(Park & Lee, 2019) (Peng et al., 2018) (Darabi et al., 2020)

Note: N- National scale | R- Regional Scale | L – Local Scale | S – Site or neighborhood level

6.5.1 Limitations of existing model and local level applicability in Sri Lankan Context

Model/ Tools	**N**	**R**	**L**	**S**	**Limitations**
HEC-RAS		√	√	√	Mainly **used for river-based** floods not for urban-flood. **Cannot simulate flood inundation from the subsurface drainage systems** in a study area.
SWMM			√	√	This is **2D simulation** application but **high accuracy in local and site levels**
PC- SWMM			√	√	This is a **commercial model** used for flood simulation and which is **unable to capture the spatial dynamics** of the urban environment.
Urban BEATS			√		**long-term system dynamics** (e.g., in rainfall and water demands) are **not considered**.
MIKE flood		√	√	√	**commercial** model which most suitable for hydraulic simulations.
City Drain3			√		This is free and open-source C++/Python environment application which used to evaluate performance evaluation of UWMS. But **needs some modifications on catchment characteristics**.
3Di Model		√			This is most **suitable for residential buildings** smaller in size or dispersed distribution.
2D RRI[1]			√		This method developed for **flood risk evaluation and** need to improve this model with more case studies on a local scale to take more accurate result.
DS[2] Model			√		This model **simulates the risk and uncertainty of rainfall** scenarios in urban areas. But not considered the urban form dynamics.

DEM based		√	√	√	Most studies use to risk evaluation of urban character using topological features. All reviewed case studies **analysis the urban flood related to riverine.**
Remote sensing		√	√		**Quantification of the impact is somewhat challenging** with distinct urban contexts.
LIDAR image + GIS		√	√		It requires **high-performance computers, and cost for data acquisition**. The simulation takes more time to give an accurate result.
ML	√	√	√	√	Urban flood is a complex system depend on various selected factors.

Note: N- National scale | R- Regional Scale | L – Local Scale | S – Site or neighborhood level

According to the objectives of this study more concerned on applicability in Urban watershed scale (i.e., accuracy in local or site context).

6.5.2 Need of combined Urban density and Flood Modelling to make Decision Making Tool

As per the purpose of the study, only a few studies are carried out on focusing on the building density component. Not only that, of the total number of reviewed studies, less than 2% of the studies focus on both flood modeling and density as a factor to assess urban flooding (refer Figure 25). Those studies are not concerned with urban planning issues. But in current practice, spatial planning is expected to help with flood mitigation since it may impact the regularity of floods and the damage they cause by manipulating built form activity locations, land use categories, development sizes, and physical building designs (Ran & Nedovic-Budic, 2016). As a result, the existing studies are fragmented among different subject areas (i.e., risk management and mitigation, assessing the performance/ stranders/ application of UWMS, and flood resilient building), which need to be made into a single platform to apply urban planning practices to make future flood resilient cities. Then the decision makers realize the benefits of land use planning as a flood management tool.

Propose/ objective of the study	Percentage
Flood risk impact assessment, reduction, and management.	31
Flood susceptibility with topographic features	19
Evaluate accuracy and performance Urban flood Simulation	16
To assess UWMS	14
To assess three-dimensional building density impact flooding.	5

Urban flood modelling with urban density factors.	4
Flood resilience assessment	2
High-resolution imaginary approaches with urban building configuration.	1
Violation of built form vs impact on runoff.	1
Flood indexes or conceptual framework to urban form factors	1

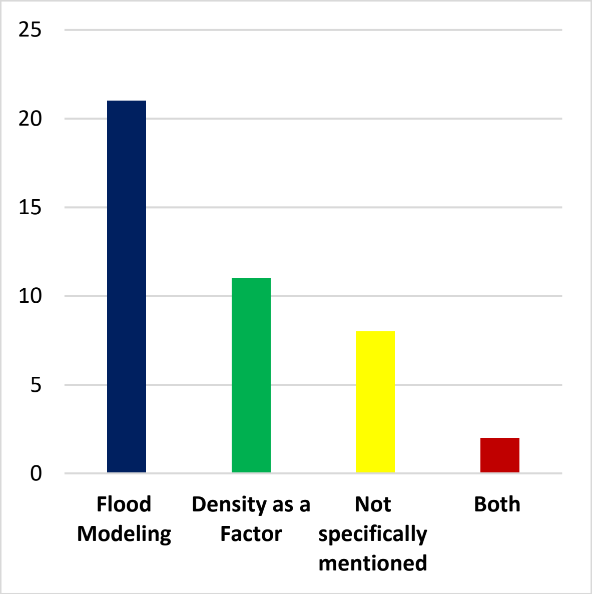

Figure 25: Focus area by the study