

Exploring Opportunity Sites for Implementing Nature-Based Solutions against Flooding in Urban Vacant and Derelict Land

Case Study Area: Glasgow City

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Abstract <p>Rapid urban expansion and changing climate are continuously modifying the natural hydrological cycle. Thus, extreme precipitation-related urban surface water flooding is occurring frequently, with disastrous consequences for both human life and infrastructure. On the other hand, the accumulation of urban vacant and derelict land (VDL) has resulted in many flood-affected metropolitan areas being more environmentally and socially fragmented. Though redevelopment is the primary objective, a balance between developing land uses and nature-based solutions (NbS) for VDL regeneration might assist flood mitigation, where implementing NbS is difficult due to space constraints. The umbrella concept of NbS can help to tackle flood risks, water security, and water quality issues by emulating natural processes, which also can provide multi-dimensional ecosystem services through interconnecting fragmented ecosystems. However, the success and effectiveness of these solutions heavily depend on the specific characteristics of the site. This paper aims to explore the suitable site for NbS implementation by considering the interrelationship or dependency of NbS on different environmental criteria in the context of managing surface runoff in the Glasgow City region. The case study area was taken based on both excessive VDL and surface flood issues and the NbS were divided into three categories based on key functions; 1) Retention based, 2) Storage based, and 3) Conveyance based NbS. Seven environmental criteria were considered for this analysis and the relative importance of those criteria was carried out through the multi-criteria AHP analysis based on experts' opinion. To map the identified possible opportunity sites, Geographic Information System (GIS) software was used. Among the selected environmental criteria, surface slope and proximity to flood-prone areas had the most significant impact on the final suitability maps for NbS. Glasgow city showed maximum optimal suitability for retention-based NbS (27% of VDL; 1% of total city territory) rather than conveyance-based NbS and storage-based NbS (5% of VDL; 0.1% of total city territory). For all the NbS, the maximum portion of the 9.38 km² VDL was found as moderately suitable, which were 68% (1% of Glasgow city territory), 90% (2% of Glasgow city territory), and 89% (2% of Glasgow city territory) for retention-based, storage-based, and conveyance-based NbS respectively. Lastly, this study can contribute to planners, leaders, and decision-makers with a better understanding of surface flooding, NbS in surface run-off management, and site suitability analysis to pick the right places for these solutions while making the city more flood-resistant.</p>		
Keywords Urban Surface Flooding, Nature-based Solution, Urban Rainwater Management, Site suitability		
Originality statement. I hereby declare that this Master's dissertation is my own original work, does not contain other people's work without this being stated, cited, and referenced, has not been submitted elsewhere in fulfillment of the requirements of this or any other award.	Signature	

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ABBREVIATION

NbS	-Nature-based Solutions
VDL	-Vacant and Derelict Land
MCA	-Multi-Criteria Analysis
AHP	-Analytical Hierarchy Process
SAW	-Simple Additive Weighting
CI	-Consistency Index
CR	-Consistency Ratio
GIS	-Geographic Information System
SuDS	-Sustainable Drainage Systems
PIMP	-Percentage of impermeable area
NBWMS	-Nature Based Water Management Solution
DEM	-Digital Elevation Model
SRSP	-Scottish Remote Sensing Portal
GCC	-Glasgow City Council
UKCCRA	-United Kingdom Climate Change Risk Assessment
SEPA	-Scottish Environmental Protection Agency
MGSDP	-Metropolitan Glasgow Strategic Drainage Partnership
GCPH	-Glasgow Centre for Population Health
IPCC	-Intergovernmental Panel on Climate Change
SWOT	-Strength, Weaknesses, Opportunities and, Threats

Chapter 01

1 INTRODUCTION

1.1 The Rationale

The number of total urban areas exposed to flooding is growing rapidly (Mensah and Ahadzie, 2020), creating a tremendous problem in coping with flood disasters. According to several research, Europe may anticipate an increase in the frequency and intensity of extreme weather phenomena including heavy precipitation. As a result, floods are becoming more frequent and severe, which may have catastrophic effects on infrastructure and human life. On the other hand, the situation is getting worse due to the continued urban growth with the replacement of permeable surfaces with impermeable ones (Warner, 2023). Moreover, the present urban drainage systems in many cities are not adequate to reduce surface flooding due to the growth of impermeable surfaces, which indicates that the difficulties brought on by flood hazards will become much more severe (Ferreira and colleagues, 2012). To effectively manage urban floods, it is important to promote urban design that "works with" nature by addressing issues including water absorption and storage, habitat connectivity, and emergency response needs.

In this context, nature-based solutions (NbSs) can be promising solutions as they are actions aimed at sustainably managing, protecting, or restoring natural or modified ecosystems to effectively address challenges such as climate change, natural disasters, and benefits biodiversity (Cohen-Shacham *et al.*, 2018). By simulating natural processes like infiltration, evapotranspiration, and phytoremediation, NbS may be used to address concerns with flooding, water security, and water quality, which can decrease the danger of urban flooding by up to 30% (Liu *et al.*, 2019). Furthermore, NbSs can boost biodiversity and give other co-benefits like improved air quality and urban cooling, all of which can help to overall urban resilience.

However, the success and efficiency of these solutions are strongly dependent on the unique characteristics of the place where they are applied. NbSs, according to Cheng *et al.*, (2017), are place-based solutions, which means, to maximize their positive effects and reduce any possible

negative effects, they must be adapted to the specific environmental context of the area. Therefore, for their success and efficacy in offering multi-functional advantages, it is essential to conduct a site-specific evaluation and choose the proper NbSs type depending on the site's features and demands.

But as cities are becoming more crowded, the need for urban space is growing, and the implementation of NbSs is often hindered by the lack of available space (Cousins, 2017; Zhang *et al.*, 2017). This problem can be solved sustainably by using urban vacant and derelict lands (VDL) for creating nature-based solutions to mitigate and build resilience to flood events while also reducing the pressure on other urban green spaces. In sealed urban areas with high runoff, these underutilized VDLs can provide potential opportunity sites for NbS implementation, which can hold and attenuate stormwater flow, increase infiltration, and recharge aquifers, hence lowering runoff and the danger of floods (Sanches *et al.*, 2016).

Following the hypothesis that NbSs implementation in the right place can manage the flood risk, this work was focused on exploring potential areas for implementing nature-based solutions against flooding in urban VDLs, using Glasgow City as a case study. A comprehensive site selection approach was conducted to determine suitable locations that can implement efficient and long-lasting NbSs to support urban resilience and flood risk reduction.

1.2 Aim and Objective

Aim

To identify and evaluate potential sites in urban vacant and derelict land for the implementation of Nature-based Solutions (NbS) against flooding.

Objectives

Conceptual Understanding

- To develop a comprehensive understanding on surface water flooding and aspects of NbS associated with floodwater management.
- To identify relevant environmental criteria for NbS implementation.

Contextualization and Localization

- To score the relative importance of individual environmental criteria with a multi-criteria decision analysis (MCA-AHP) approach.
- To evaluate the suitability of the sites for nature-based solutions implementation based on identified environmental criteria.
- Mapping the opportunity sites for NbS implementation in urban vacant and derelict areas using ArcGIS pro software.

1.3 Structure of the Document

The structure of this dissertation was divided into six main chapters as following:

Chapter One provided a rationale for the study by scoping literature available on urban flooding problem and NbS, describes the aim and objectives and the paper's overall strategy.

This is followed by **Chapter Two** with a 'Critical Literature Review' of the findings on general concepts and common approaches on these issues offered by a collection and review of different papers, literature, articles, and reports on the relative topic. There are **four sections** to this chapter: **part one** highlights surface water flood hazards and effect of urbanization on surface flooding and traditional management strategies; **part two** highlights the concept and functions of Nature-based solution (NbS) in a context of urban flood management. **Part three** continues the discussion on effectiveness and importance of site selection for NbS implementation in urban settings including urban vacant and derelict land. **Part four** discussed the research gap related to this area of study.

Chapter Three outlines the materials and methodological approach applied throughout this research. The major phases are-1) Understanding and conceptualization and 2) Contextualization and Localization. As the first step of phase one, NbSs were reclassified into three categories based on function in managing floodwater (i.e., retention, storage, or conveyance of stormwater) with detailed understanding. Phase two presented the case study area and provided details on the data collection, processing, and analysis towards the compilation of indicators for:

- Narrowing down and scoring of relevant environmental criteria
- Suitability analysis based on environmental criteria
- Relative Weight of Environmental Criteria and
- Opportunity site mapping

Results and analysis from this chapter are shown in **Chapter Four** followed by discussion of the findings in **Chapter five**. Conclusions of this study along with Limitations and Scope for further Research were provided in the last chapter (**Chapter six**).

Chapter 02

2 LITERATURE REVIEW

Floods pose a significant threat to communities worldwide and have become the most common natural disaster. Urban areas particularly are experiencing the detrimental effects of flooding, impacting society, the economy, and the environment. Climate change plays a significant role in exacerbating these floods, endangering populations globally. In Europe, floods already account for a considerable portion (33%) of recorded natural events spanning the period between 1900 and 2019 (Ferreira *et al.*, 2021). Moreover, in the UK, over the last 20 years, nearly 14% of the population has increased and more people are shifting to live in urban areas (Flood risk management Act, 2018). The existing drainage systems in the UK are also inadequate to cope with the increasing population and urbanization trends. Consequently, since 2011, several major UK cities have faced severe flooding from surface water runoff (Lashford *et al.*, 2019).

2.1 Part One: Surface Water Flooding

2.1.1 Surface water flooding

In natural catchments, when it rains, a portion of rainwater evaporates directly into the atmosphere, where some enter the ground through infiltration. Portions of the water that infiltrates are absorbed by plants and evaporate through transpiration. Any remaining surface water flows through a system of smaller drainage channels, streams, rivers, and lakes to reach the ocean, called surface water runoff and this cycle of water flow is a hydro-logical cycle (Flood risk management Act, 2018). Rainfall-runoff hydrograph, a graph showing surface runoff flow against a specific time, can explain how hydro-logical cycle in the catchment drainage system or river is affected by rainfall and leads to flooding (figure 2.1). From Figure 2.1, the highest point of rainfall is called peak rainfall, while the peak discharge is the time when the drainage or river system reaches its highest flow. The lag time is the delay between the peak rainfall and peak discharge as it takes some time for the water to flow to the drainage or river system. The base flow of the river increases gradually when run-off, ground, and soil water reach the drainage or

river system, and this is depicted as the rising limb on the hydrograph. On the other hand, the falling limb shows that water is still flowing into the drainage or river system, but in diminishing amounts. During heavy rainfall, streams become full and overflow onto floodplains. Then the graph shows steep rising limb and short lag time, this indicates, the rapid increase of discharge over a short time period, stormwater reaches the system very quickly and leads to surface flooding (also called pluvial flood).

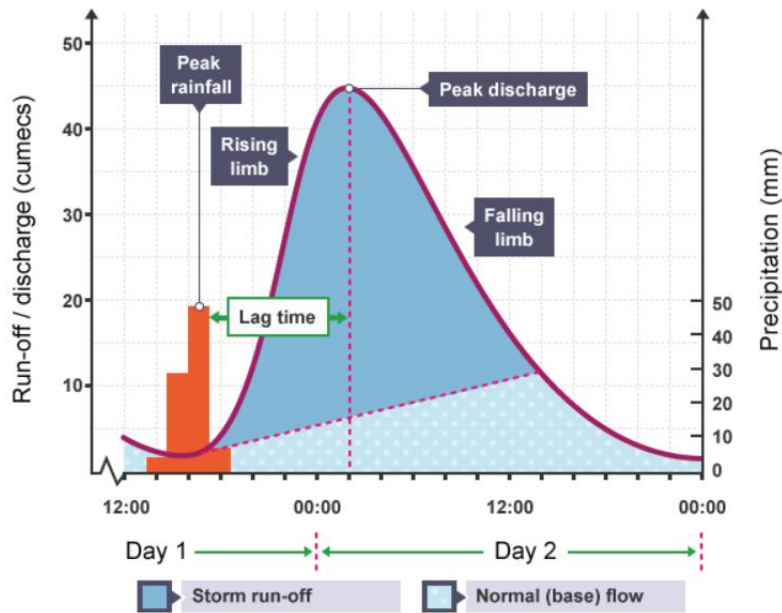


Figure 2.1: Rainfall-runoff hydrograph

In reality, the term surface water flooding is often a combination of various sources, including both natural (like small watercourses) and artificial (like sewers) drainage systems, as well as direct inundation from surface water run-off (Flood risk management Act, 2018). According to Qin (2020) and Flood risk management Act (2018), this term includes-

- Flooding from pluvial sources, where the rainfall run-off flows or accumulates on the surface before it enters a natural (e.g., watercourse) or artificial (e.g., sewer) drainage system.
- Flooding from exceeded capacity of sewers and other drainage systems, and when it cannot enter a drainage system (when capacity is exceeded).
- Flooding because of the capacity of sewers or other drainage system being exceeded by rainfall run-off.

2.1.2 Effects of Urbanization on Surface Flooding

In the last several decades, the combination of climate change effects and urbanization are disturbing the hydrological cycle (Guswa, Hamel, & Denedy-Frank, 2017). For example, climate change is leading to increasing rainfall intensity and urbanization is converting the natural landscapes to residential, commercial, and industrial area with increased impervious surface and decreased vegetation. Thus, it typically affects natural water systems such as increasing rainfall runoff, decreasing infiltration, evapotranspiration, and groundwater recharge, which is intensifying surface runoff rate and volume (Figure 2.2); significantly increases urban flood events (Zölch *et al.*, 2017).

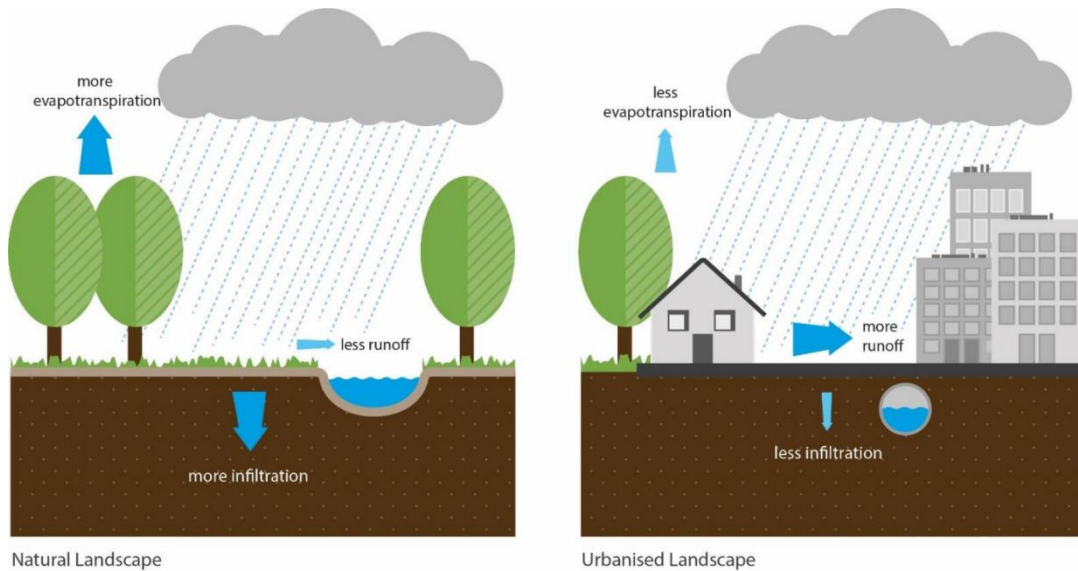


Figure 2.2: Surface water run-off in natural and urbanized landscapes
(Flood risk management (Scotland) Act, 2018)

Figure 2.3 shows a comparison between the discharge hydrograph before and after urbanization in a watershed. It can be observed that urbanization has greatly reduced the time to peak in the post-development scenario. Additionally, the peak discharge has considerably increased after urbanization. This indicates that the development of impervious surfaces and urbanization are altering the shape of the discharge hydrograph in watersheds and leading to an increased probability of surface flooding (Ferreira *et al.*, 2021).

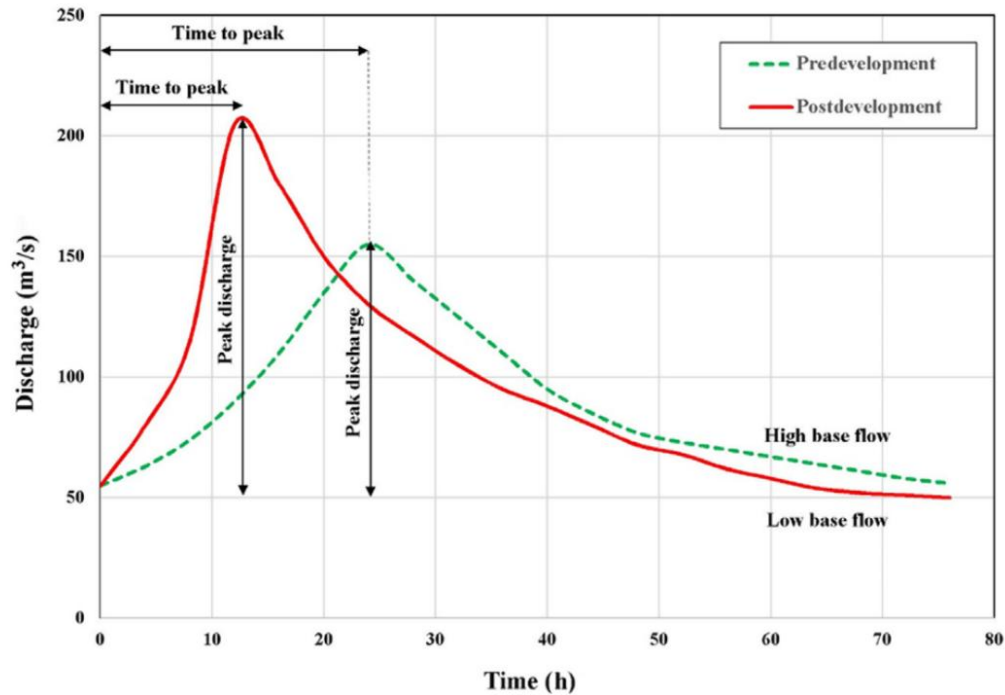


Figure 2.3: Discharge hydrograph before and after urbanization (Ferreira *et al.*, 2021)

Rapid urbanization can change catchment hydrology as natural areas are converted into impermeable surfaces, some watercourses and natural drainage features are replaced or removed by drains and culverts with limited capacity (Zhang *et al.*, 2017), thus leading surface flood risk.

2.1.3 Necessity of Surface Flood Management

In the past 150 years, there has been a staggering 1000% increase in the number of total urban areas vulnerable to flooding (Mensah and Ahadzie, 2020). This rise presents a significant challenge in dealing with flood events. The reports from the IPCC consistently emphasize the severity of the impacts and the projected increase in both frequency and intensity of flooding caused by climate change (Ferreira *et al.*, 2021). Various studies indicate that Europe can expect more frequent and intense extreme weather events such as heavy precipitation, storms, and floods, although the specific patterns may vary across regions, seasons, and time periods. Moreover, research shows, shortages of housing for population are leading urban areas to continue expansion. This ongoing expansion along with consequent replacement of natural

surfaces into impermeable surface increases the likelihood of urban flooding (Warner, 2023), which is making the situation worse. The average damage resulting from this flooding is predicted to rise annually from €3 billion to €38 billion by the year 2100 (Ferreira *et. al*, 2021). Therefore, the challenges associated with flood risks are expected to increase substantially in the future (Ferreira *et. al*, 2021). Figure 2.4 shows the projections for new homes and surface water flood risk in Scotland based on data from SEPA flood risk data (2013). Thus, it is crucial to tackle the flood risk to reduce societal and ecological damage.

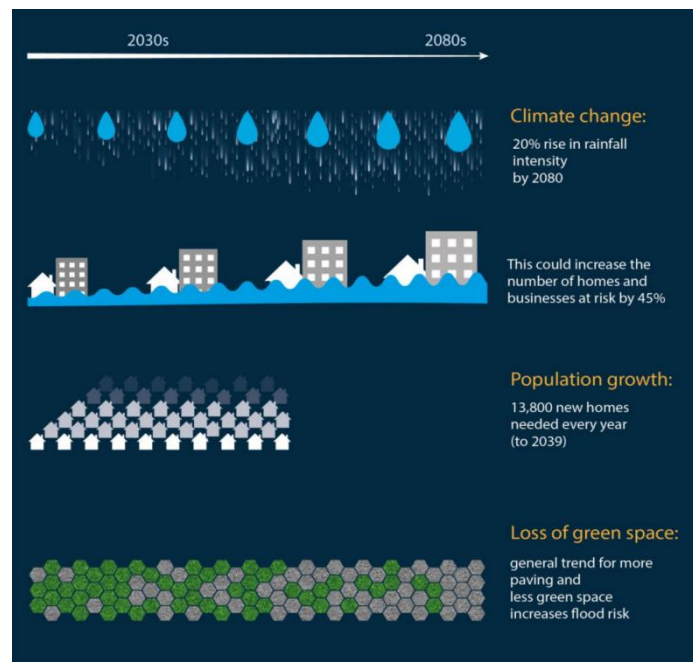


Figure 2.4: Projections for new homes and surface water flood risk in Scotland (SEPA, 2013)

2.1.4 Traditional Flood Management and Driving Source for Flood Risk:

In the past, the management of floods primarily relied on engineering infrastructure solutions, commonly known as "grey solutions," such as dikes and dams. However, there has been growing skepticism about the effectiveness of these solutions in recent decades as they are designed to withstand floods with specific return periods; limiting their adaptability to cope with increasing flood hazards driven by climate and urbanization uncertainties (Kapetas and Fenner, 2020). Moreover, the potential failure of these solutions can have severe social, economic, and environmental consequences, while also creating a false sense of security, known as the "dike

paradox" (Ferreira *et. al*, 2021). Although the focus remains largely on grey infrastructure, there has been a paradigm shift in Europe since the 1990s towards sustainable flood risk management that considers vulnerabilities (Ferreira *et. al*, 2021). In sustainable flood risk management, to assess and understand the potential flood risks, and the vulnerabilities of environment and populations, we need to consider the presence of sources, a pathway that transports the floodwater to a receptor, and the vulnerability of the receptor to flooding (O'Donnell & Thorne, (2020). This framework is known as the source-pathway-receptor model. Çoban (2021) described weather events or sequences of events (such as a river, heavy rainfall) as sources of flooding, mechanisms that convey floodwaters (such as residential area, floodplain) as pathways, and people, industries, buildings, or nature itself as receptors that can be damaged by flooding (Figure 2.5).

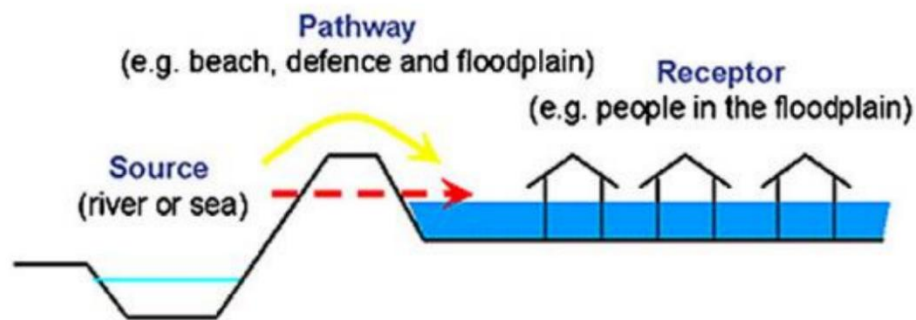


Figure 2.5: Source-pathway-receptor-consequence conceptual model for flooding (Çoban, 2021)

The study by O'Donnell & Thorne (2020) also showed that Climate change-induced rainfall is the primary source driver for urban flood risk. Urbanization and deterioration of urban assets are the leading pathway drivers, resulting in various consequential flood risks. Social impacts and continued capital investment in buildings and contents have strengthened as receptor drivers of urban flood risk. The following table 2.1 shows a list of drivers for urban flood risk, classified according to the source (S)–pathways (P)–receptor (R) model of the flooding system.

Table 2.1: List of drivers for urban flood risk, classified according to the source (S)–pathways (P)–receptor (R) model of the flooding system (O’Donnell & Thorne, 2020)

Driver group	Drivers	Explanation
Climate change(S)	Precipitation	Changes in short-duration precipitation—amount, intensity, location, seasonality, and clustering.
	Temperature	Influence of temperature on soil moisture and hence runoff.
Catchment runoff (P)	Urbanization	Change in land management with green field and previous surfaces covered by less pervious materials (buildings and infrastructure) and associated new conveyance systems.
Urban systems and processes (P)	Sewer conveyance, blockage, and sedimentation	Processes associated with above ground, overland surface flow and human-caused, below-ground drainage systems, including performance, maintenance, and operation.
	Urban asset deterioration	Changes in performance, condition, and serviceability of urban drainage assets (ageing, performance, wear and tear, and rehabilitation management).
	Loss of floodable urban spaces	Loss of urban spaces that previously helped reduce flood risk through infiltration, attenuation, or storage. Includes the loss of urban green space and brownfield land (to buildings and infrastructure) and changes in the types of urban green space that affect its rainfall-runoff reduction potential.
Socioeconomics (R)	Buildings and contents	The damage to domestic and commercial buildings and their contents.
	Urban impacts	Changes in the way in which urban areas are managed and urbanization is affected, and how planning and management may change climate- and social-change effects.
	Infrastructure impacts	The relationship between flood risks and the array of networks and nodes that deliver physical services including gas, water,electricity,transport, telecoms, etc.
	Social impacts	The risks to life and health, and the intangible impacts of flooding on people and their communities, recognizing that some sections of society are more vulnerable than others.
	Indirect economic impacts	The indirect impacts of flood events including losses from capital and labour productivity disruptions, e.g., flooded roads interrupting transportation and consequentially disrupting economic activities.

Drivers often interact with each other, and these interactions change in flood risk. For instance, socio-economic drivers affect the type and rate of urbanization, leading to changes in pluvial flood risk. The differentiation between drivers and responses may not always be clear. For example, responses that are poorly planned or executed can become drivers themselves, and drivers that are influenced by flood risk management can also function as responses if they are managed effectively. Because of this complexity of drivers and responses, urban flooding needs multi-functional sustainable management approaches (Lennon *et al.*, 2014), rather being dependent on traditional grey solution. The idea of multi-functional sustainable management is to meet ongoing environmental, social, and economic challenges through sustainable use of nature which is referred to as ‘Nature-based Solution (NbS)’ (Chiu *et al.*, 2021). Multi-functional management approach will also ensure that surface water management provides countless benefits, such as managing rainfall run-off and surface water flooding, reducing sewer overflow, improving the quality of water environment, promoting biodiversity, creating attractive and welcoming places for people, and making the urban environment more adaptable to future changes.

2.2 Part Two: Nature-based Solution (NbS)

2.2.1 NbS definition and terms in a context of urban flooding

According to Cohen-Shacham *et al.*, (2018) NbSs are actions, aim to sustainably manage, protect, or restore natural or modified ecosystems to effectively address societal challenges such as climate change, natural disasters, while providing human well-being and biodiversity benefits. NbS can be utilized to tackle flood risks, water security, and water quality issues by emulating natural processes such as infiltration, evapotranspiration, and phytoremediation. According to Ruangpan *et al.*, (2020), as an ‘umbrella concept’ the terminology of Nature-based solution covers a range of ecosystem-related approaches (giving importance to the relationships between different components of the ecosystem). This concept has evolved nine different terms in scientific literature in the context of flood water management: low-impact developments (LIDs), best management practices (BMPs), water-sensitive urban design (WSUD), sustainable urban

drainage systems (SuDs), green infrastructure (GI), blue–green infrastructure (BGI), ecosystem-based adaptation (EbA) and ecosystem-based disaster risk reduction (EcoDRR) (Table 2.2).

Table 2.2: Glossary of terms and their geographical usage. (Ruangpan et. al., 2020)

Terminology	Definition, objectives and purpose	Places where commonly used
Low-impact development (LIDs)	“LID is used as a retro- fit designed to reduce the stress on urban stormwater infrastructure and/or create the resiliency to adapt to climate changes, LID relies heavily on infiltration and evapotranspiration and attempts to incorporate natural features into design.”	– US – New Zealand
Best management practices (BMPs)	“A device, practice or method for removing, reducing, retarding or preventing targeted stormwater run-off constituents, pollutants and contaminants from reaching receiving waters.”	– US – Canada
Water-sensitive urban design (WSUD)	“Manage the water balance, maintain and where possible enhance water quality, encourage water conservation and maintain water-related environmental and recreational opportunities.”	– Australia
Sustainable urban drainage systems (SuDs)	“Replicate the natural drainage processes of an area – typically through the use of vegetation-based interventions such as swales, water gardens and green roofs, which increase localised infiltration, attenuation and/or detention of stormwater.”	– UK
Green infrastructure (GI)	“The network of natural and semi-natural areas, features and green spaces in rural and urban, and terrestrial, freshwater, coastal and marine areas, which together enhance ecosystem health and resilience, contribute to biodiversity conservation and benefit human populations through the maintenance and enhancement of ecosystem services.”	– US – UK
Ecosystem-based adaptation (EbA)	“The use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change.”	– Canada – Europe
Ecosystem-based disaster risk reduction (Eco-DRR)	“The sustainable management, conservation, and restoration of ecosystems to reduce disaster risk, with the aim of achieving sustainable and resilient development.”	– Europe – US
Blue–green infrastructure (BGI)	“BGI provides a range of services that include; water supply, climate regulation, pollution control and hazard regulation (blue services/goods), crops, food and timber, wild species diversity, detoxification, cultural services (physical health, aesthetics, spiritual), plus abilities to adapt to and mitigate climate change.”	– UK
Nature-based solution	“NBS aim to help societies address a variety of environmental, social and economic challenges in sustainable ways. They are actions inspired by, supported by or copied from nature, both using and enhancing existing solutions to challenges as well as exploring more novel solutions.”	– Europe

Warner (2023) addressed the ‘nature-based solutions’ in context of floodwater management as ‘Nature Based Water Management Solution (NBWMS)’ and noted some options of (NBWMS) is being implementing in the UK for flood management showing in table 2.3.

Table 2.3: NBWMS for stormwater management in the UK (Warner, 2023)

Nature-based water management solution (NBWMS)	Description
Retention pond/water basin	Water body to captures, store and retains water for long time.
Detention/infiltration basin (periodic/ temporary inundation)	Attenuation of water flow, usually dry but stored water during periods of high flow.
Riparian grassland for amenity areas	Grassland adjacent to watercourses for recreational purposes, frequent mowing, controlled periodic flooding during high water flow.
Bumpout	Raised planted bed with detention area, adjacent to roads
Bioswale/drainage corridor	Linear channel/depression, gently sloping side, porous pipe running below ground to remove water, mulched or vegetated surface
Infiltration or storage trench	Below ground temporary water storage or soak away
Permeable pavement	Porous material or gaps between blocks to permit drainage used instead of a hard surface.
Tree—individual in trench	Drainage trench with a single tree
Trees—in line	Drainage trench forming linear feature with multiple trees
Green roof	Vegetated roof to slow and reduce surface run-off
Rain garden	Vegetated depression captures and retains water temporarily.
Garden ponds	Water body, captures and retains water for long time
Bio-retention system	Consisting of shallow excavations planted with native wetland species, retains water, allows to infiltrate.

Sahani *et al.*, (2019) investigated a range of methods involving urban flood risk management via potential nature-based solutions (NbS). This study stated, NbS can be classified into two major groups: soil Solutions (which will improve soil resilience and soil function to maintain and

restore the local ecosystem) and landscape solutions (which will focus on connectivity). NbS can be blue approach (e.g., retention and detention pond etc.) which increases the capacity of water storage or green approach (e.g., pocket park, urban green space etc.) which is vegetation-based strategies, allows water to infiltrate the soil and be stored in vegetation. The NbS including both blue and green like rain garden, bioswales, porous pavement, green roofs, urban drainage system, constructed wetlands etc. are called hybrid approaches. Sahani *et al.*, (2019) analyzed functions of NbS (Table 2.4) across Europe and highlighted that NbS has multi-functionality for flood risk management in an environment-friendly and cost-effective way.

Table 2.4: List of NbS and principles used against floods risk (based on Sahani et. al., 2019).

Types of NbS	Principles
<ul style="list-style-type: none"> ● Use of grass strips ● River revitalization 	<ul style="list-style-type: none"> ● Re-nature water bodies, and pathway ● Revitalization of flood plains, Reduce canalization of the urban water bodies
<ul style="list-style-type: none"> ● Rain gardens ● Pocket Park, urban parks, nature-based playgrounds, linear urban waterfront park 	<ul style="list-style-type: none"> ● Use of balancing ponds to release water slowly ● Re-vegetation in urban areas to protection of flora and fauna
<ul style="list-style-type: none"> ● Bioswells, ● Wetlands including ponds, lakes, swamps 	<ul style="list-style-type: none"> ● Rerouting floodwater to wetlands, ● Create water bodies for short term water storage
<ul style="list-style-type: none"> ● Concave green land ● Vegetated foreshores 	<ul style="list-style-type: none"> ● Preventing soil compaction, ● Preventing bank erosion with short and forest vegetation

2.2.2 Functions of NbS to manage urban flooding

According to Lennon *et al.*, (2014), Nature-based solution (NbS) has a potential to deliver a comprehensive multi-functional service by managing all rainfall event (Figure 2.6) and providing other socio-ecological benefits (e.g., using foot paths and cycle paths as routes for infiltrating and conveying water, contributing to ‘green and blue networks’) (Figure 2.7). Table 2.5 showing multi-functional services of NbS may include-

Table 2.5: Multi-functional services of NbS

NbS Services	Descriptions
In managing rainfall events	
Small rain	Manage rain at the source, increase rate of infiltration and evapotranspiration by utilizing permeable surfaces and vegetation. Water may be stored for later use. There should be minimal to no surface water run-off in these frequent occurrences.
Moderate rain	Collect, delay, and convey rainwater securely above ground to watercourses in accordance with the natural land. Increased surface water in the combined sewers can be avoided since it might lead to flooding in other areas.
Extreme rain	Delay, store, and convey above-ground run-off to watercourses following the natural topography. Water can be stored for later use.
Other Multifunctional benefits	
People	Create attractive and welcoming spaces for people to live, work, and visit while integrating with, protecting, and improving the urban landscape.
Management of drainage and floods	Control all precipitation events, prevent flooding of people and infrastructures, and prevent increasing flows into receiving watercourses or combined sewers.
Water quality	Protect and improve the physical habitat and water quality of receiving watercourses. Water collection for usage can lessen the need to extract water from other sources.
Biodiversity	Protect and promote biodiversity, maximizing permeable surfaces and vegetation to attract wildlife.
Adaptability to future change	Mitigate the loss of green space while assisting the urban environment in adapting to future challenges of climate change (e.g., increasing rainfall and rising temperature).

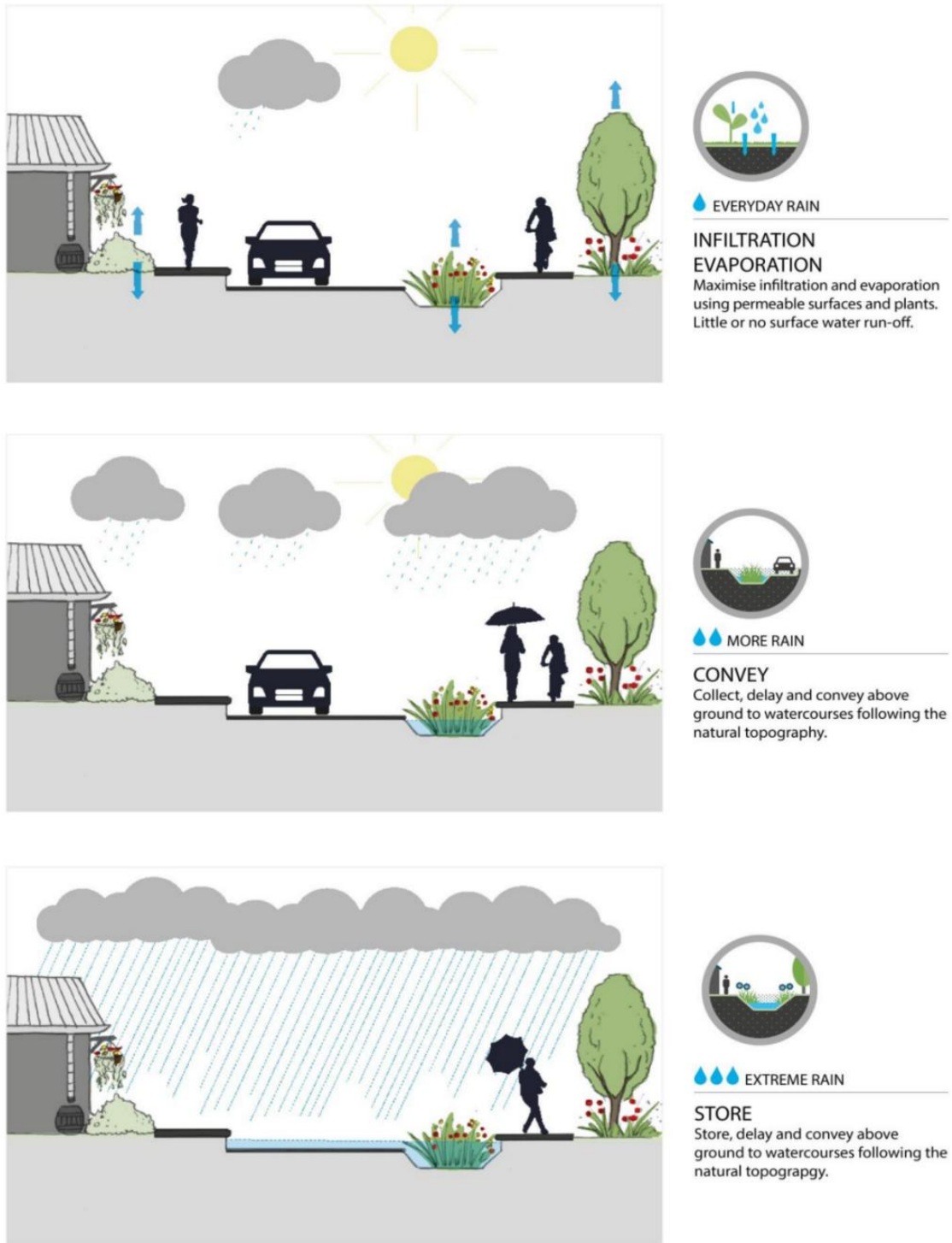


Figure 2.6: NbS design for all rainfall events (Flood risk management (Scotland) Act, 2018).

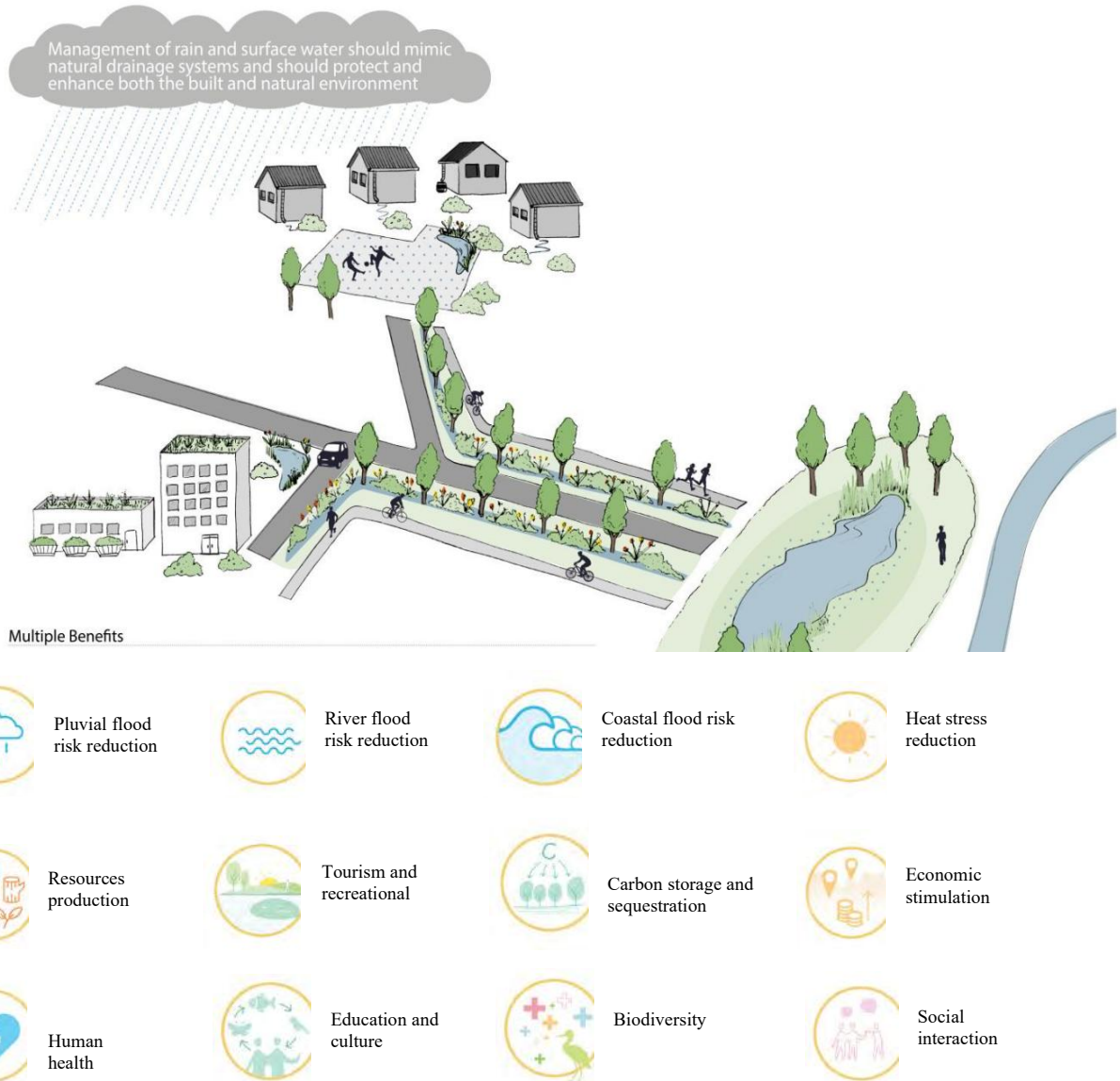


Figure 2.7: NbS for other multi-dimensional benefits (modified from Flood risk management Act, 2018 and World Bank, 2021)

Warner (2023) stated that, the primary function of NbS align with the sustainable drainage system (SuDS) principle, which is to reduce the water volume entering drainage or river network through rainfall intercepting, capturing, slowing down and/or providing storage of overland runoff.

The main processes associated in providing multifunctional benefits are-

- Do not let the water go from urban impervious ground and roof surfaces by capturing, harvesting, and storing rainwater for further use.
- Let the water seep through restoring permeable ground and let it infiltrate underground, feed the aquifers, and allow humidity exchange within air and soil.
- Promotes managing the rainfall as closely as possible within the natural environmental system by increased infiltration (vegetation, porous paving), evapotranspiration and mimic natural recharge to allow water to soak into ground. Thus, in Rainfall-runoff hydrograph, the peak surface runoff discharge decreases and lag time between extreme rainfall event and water discharge into drainage system increases (UK Govt 2021; Woods Ballard *et al.*, 2015).
- Can modify the source of flood risk by altering the hydrological cycle through increased evapotranspiration, infiltration, and interception of precipitation (Diao *et al.*, 2021). Nature-based solutions provide responses focused on the receptor of flooding and mimic the pathways taken under natural conditions by which stormwater reaches those receptors (Lennon *et. al.*, 2014). In terms of pathways, nature-based solutions influence floodwater movement and distribution by increasing water storage and reducing runoff. As for receptors, nature-based solutions can mitigate the impacts of flooding on communities and the environment by providing flood protection, improving water quality, and enhancing biodiversity.
- From a biodiversity standpoint, nature-based solutions improve the connectivity of habitats within fragmented urban environment by developing green feature or "wildlife corridor" and linking fragmented urban habitats (Warner, 2023).

2.3 Part Three: Effectiveness and Importance of Site Selection

The success and effectiveness of these solutions heavily depend on the specific characteristics of the site where they are implemented. According to Cheng *et al.*, (2017), NbS are place-based solutions, meaning they need to be tailored to the specific environmental and social context of the location to maximize their benefits and minimize negative impacts. For example, if a green infrastructure project is implemented in a location with inappropriate soil conditions, it may not be able to function properly or may even cause negative environmental impacts such as soil erosion. Similarly, if a blue infrastructure project is implemented in a location where the hydrological characteristics are not suitable, it may not be able to effectively manage stormwater and flooding. Therefore, conducting a site-specific assessment and selecting appropriate NbS based on the site's characteristics and needs is crucial for their success and effectiveness in providing multi-functional benefits.

However, in urban areas, the implementation of NbS is often hindered by the lack of available space, which has been highlighted in several studies (Cousins, 2017; Zhang *et al.*, 2017). Use of **vacant and derelict land (VDL)** for NbS implementation can be a promising solution with the co-benefit of utilizing unused land while addressing the issue of limited space for NbS (Qiao *et al.*, 2018.). If VDLs are in sealed area with high runoff and converted into green spaces, they can be able to retain, store (Palermo *et al.*, 2018) and attenuate the stormwater flow, maximize infiltration and aquifer recharge, thus reducing the volume of runoff and risk of flooding (Sanchez *et al.*, 2016). A study by Nassauer *et al.*, (2019) concluded that, without any NbSs, VDLs on their own are much less efficient for rainfall runoff capturing in compared to the vacant area with the NbS or LID interventions which make them highly effective in runoff capturing. Therefore, VDLs needs to be assessed for finding potential and appropriate location for different NbSs to effectively manage stormwater. Successful implementation of natural flood mitigation strategies in urban VDLs can improve water quality, habitat protection and enhance community value (Brody & Highfield, 2013), also can create room for public interaction and build ecosystem communication.

2.4 Part Four: Research Gap

Though several low-impact development and water sensitive design projects are promoting retain, detain, infiltration, harvest, evaporate, transpire or re-use stormwater, still the urban flooding problem is severe and unresolved problem (Qin, 2020) and urban stormwater management is still heavily dominated by traditional gray infrastructure (Yao *et al.*, 2021). Research shows following barriers for the NbS implementation in an urban setting-

1. Urban areas are complex with systems density, interdependent social, ecological, and technical components (Frantzeskaki *et al.*, 2021). Due to the system density and their interconnections, conflicts often arise over land use, particularly between urban development projects (commercial, residential or transport) and the preservation or creation of urban green and blue spaces for mitigating and adapting climate change (Artmann *et al.*, 2019). Therefore, while planning for urban development, planners must consider the interdependency of urban systems on multidimensional nature-based solutions (NbS) to effectively address problems such as surface flooding along with maintaining a high quality of life in urban areas (Kabisch *et al.*, 2022). The challenges are due to lack of research on identifying the link of NbS with environmental criteria (Dhakal and Chevalier, 2017). Choosing the appropriate site for NbSs considering inter-connection with significant environmental criteria may ensure that the intervention can function properly while proving the multidimensional facilities.
2. Research found, NbS principles are hard to replicate in urban landscape scale, due to lack of connectivity and complexity in environmental conditions and human activities as urban areas are often fragmented with isolated green spaces that are not well-connected. Therefore, a spatial translation is needed to identify appropriate locations for NbSs implementation in the urban scale (Kabisch *et al.*, 2022) in order to enhance urban connectivity. Spatial translation involves process of adapting or transforming something to fit a new context, considering urban environmental criteria such as available space, land use, topography, existing infrastructure etc. A Multi-Criteria Analysis (MCA) process is a commonly applied decision-making approach (Kirk, 2021) that involves considering and weighing multiple

criteria or factors when evaluating and selecting among different options or alternatives. The Analytical Hierarchy Process (AHP) developed by Saaty in 1980, is a popular MCA approach that assigns relative importance to different attributes and combines them using simple additive weighting (SAW) (e.g., Gonzalez-Ollauri, Thomson, and Mickovski, 2020). In the context of NbS implementation, this selection process could analyse priority of numerous factors such as soil type, topography, land use feasibility, and flood proneness when determining the most suitable location and type of NbS to implement.

3. The implementation of NbS is often hindered by the lack of available space, which has been highlighted in several studies (Cousins, 2017; Zhang *et al.*, 2017). To overcome this challenge, using vacant land for NbS implementation can be a promising solution. If derelict and vacant lands are in sealed area with high runoff and converted into green spaces, they can be able to retain and attenuate the stormwater flow, maximize infiltration and aquifer recharge, thus reducing the volume of runoff and risk of flooding (Sanches *et al.*, 2016).

To Identify the opportunity sites for NbS in urban environment for stormwater management, it is crucial to conduct a suitability analysis that considers both site-specific conditions and the surrounding context to ensure long-term effectiveness of the interventions (Kirk, 2021). Details on the function of individual NbSs in the context of stormwater management, relevant environmental criteria, and relationship with NbS are needed to clarify how exactly nature-based solutions (NbSs) can be involved in stormwater management. A multi-criteria selection process that considers multiple significant environmental factors is necessary for a comprehensive site suitability analysis for NbS implementation (Kirk, 2021) in urban vacant and derelict areas for stormwater management.

3 MATERIALS AND METHODS

3.1 Research Approach

The research approach for this study was a mixed-methods approach, combining qualitative and quantitative data collection methods. **Qualitative methods** were used to gather detailed information on the potential site's characteristics for NbSs, including processes involved in NbSs, general classification of NbS for storm-water management, environmental criteria related to NbS implementation in an urban setting. **Quantitative methods** were used to identify trends including data collection, processing, and analysis. The research was planned to design under two major contexts as following (Figure 3.1)-

- Understanding and conceptualization
- Contextualization and Localization

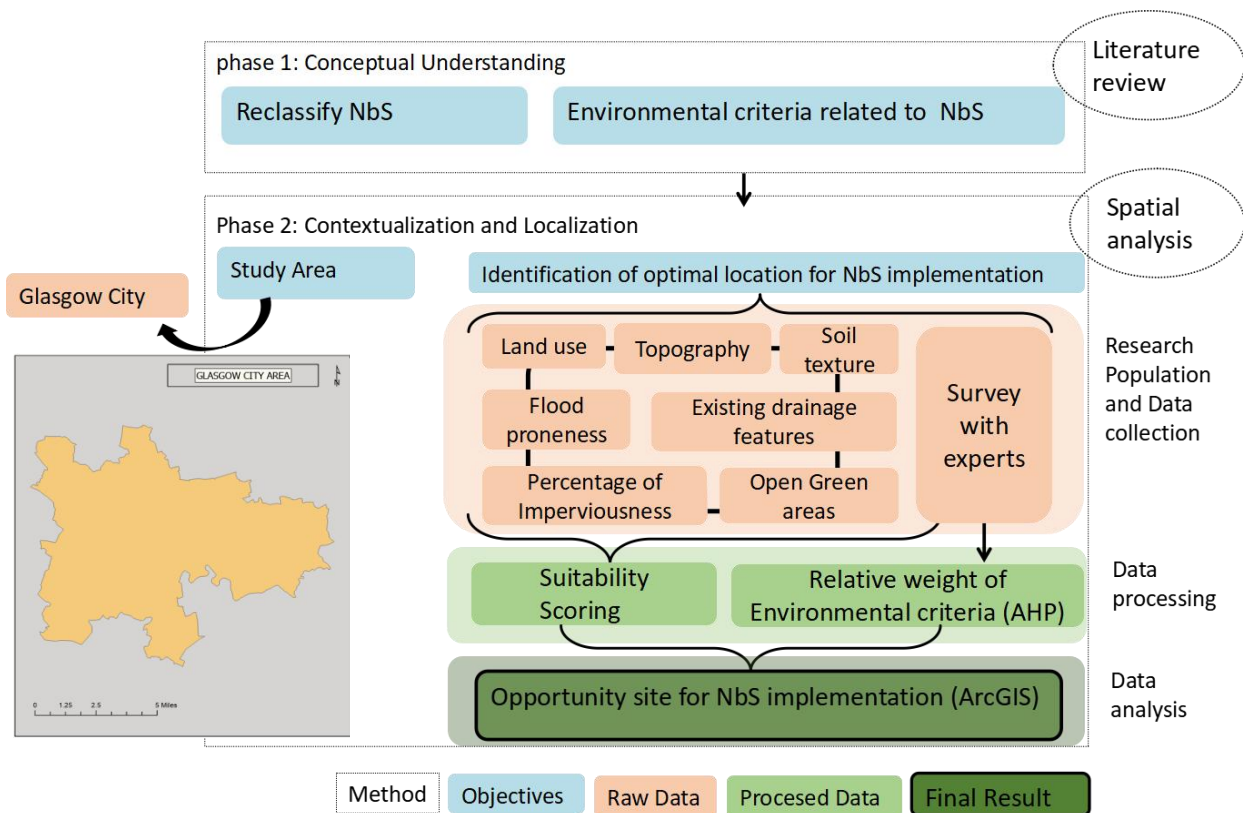


Figure 3.1: Methodology Framework

3.2. Phases, Methods, and Material

3.2.1 Understanding and conceptualization:

The objective of this phase was to understand functions of NbS in regards of flood management, environmental factors related to the effectiveness on NbS implementation which was gathered in chapter 2. General concepts and common approaches on these issues offered by a collection and review of different papers, literature, articles, and reports on the relative topic.

3.2.2 Contextualization and Localization:

Following the general understanding of the concept, this Contextualization and Localization phase focused on (1) case study and (2) sampling and data analysis to visualize the result and effectiveness of the main objective of this study.

3.2.2.1 Case study:

This study focused on Glasgow city as the case study area. The location of Glasgow city within Scotland and its administrative border, which was considered for the study's data collection, processing, and analysis, are shown in figure 3.2.

The selection of Glasgow city was based on several factors, including the

- Presence of significant flooding issues,
- The availability of vacant and derelict areas,
- Data accessibility, and
- Its urban setting.

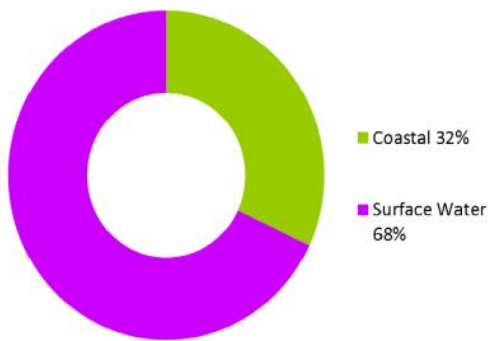
Glasgow is the largest and most populous city in Scotland, with approximately 635,640 residents living within an area of 177.3 km² (GCPH, 2022b). Geographically, it is situated in the temperate humid climatic zone (oceanic climate) at 55.85° North longitude and 4.44° West latitude (Köppen, 1884). The city has an average annual temperature of 9.83° C and 1,262.83mm of precipitation (Met Office, 2022).



Figure 3.2: Location of the Glasgow city and its administrative boundary

Due to its long history of being affected by severe weather, Glasgow City is prone to a variety of flooding, including coastal and surface water flooding. According to a report by GCC (2021), about 68% of Glasgow city is at risk of surface water flooding; which is responsible for the majority of damage caused by flooding in the region. Currently, there are approximately 420 residential properties and 460 non-residential properties at risk of surface water flooding, resulting in an estimated around £550,000 annual average damages (Figure 3.3). The challenge of mitigating the impacts of flooding becomes even more complex when considering the effects of climate change, such as more intense storms and rising sea levels, as stated by UKCCRA (2017). Taking these factors into account, it is projected that within this vulnerable area, the number of residential properties at flood risk will increase from around 420 to 680, and the number of non-residential properties at risk will increase from 460 to 830. Research conducted by Majekodunmi, Emmanuel, and Jafry (2020) revealed that the adverse effects of flooding are likely to disproportionately affect Glasgow's deprived population, which accounts for 44% of the city's population according to the Scottish Government (2020).

Summary of flooding impacts



At risk of flooding

- 420 residential properties
- 460 non-residential properties
- £550,000 Annual Average Damages

(damages by flood source shown left)

Figure 3.3 Annual Average Damages by flood source (GCC' 2021)

Glasgow City is actively collaborating with stakeholders to create a resilient and sustainable city in the face of flood risks. One major focus is surface water flooding, and the Metropolitan Glasgow Strategic Drainage Partnership (MGSDP) has been promoting the use of Sustainable Drainage Systems (SuDS) in addressing flood risk. Glasgow wants to improve biodiversity, make open spaces, and construct green networks through the incorporation of SuDS and a placemaking strategy into urban planning (MGSDP, 2022; UNA, 2022). The Scottish Government's "Designing Streets" guidance' 2021, recommends SuDS measures that promote water infiltration, evapotranspiration, and stormwater reuse to manage surface water runoff.

Glasgow has the largest area of vacant and derelict land (VDL) in Scotland, totaling 880 hectares (9% of the national total). In Glasgow, there is 9.38 km² of VDL, accounting for 5.29% of the city's territory (Ordnance Survey, 2021a). Significantly, 55.5% of Glasgow's population resides within 500 meters of derelict land, with almost half (49%) of all such land located within 15% of the most deprived data zone areas. Glasgow has made progress in re-purposing VDL focused on using for residential purposes (66.4%) with other uses including transport and recreational (GCC, 2018). This exemplifies the city's commitment to transforming unused land into functional spaces. Therefore, for sustainable urban extension, VDL needs to be assessed for effective stormwater management.

3.2.2.2 Sampling and data analysis

For the data analysis, data collection and selection were the first step after generalization of case study to find suitable location for NbSs. Input for this analysis required a range of data, where based on conceptual understanding, this study considered seven environmental criteria: Land Cover, Percentage of impermeable area (PIMP), Proximity to existing drainage features, Proximity to flood prone area, Soil Texture, Topography and Proximity to urban green areas data. These factors has significant impact on/off NbS implementation and play a critical role on the interventions overall performance and effectiveness. The method was subdivided into three phases 1) collecting the primary data. 2) data processing and 3) data analysis. The data analysis techniques for this research included content analysis, and spatial analysis. The results were explained as maps, table, and diagram.

Collecting data: For content Analysis, the research population were experts in nature-based solutions and urban flood management, including local government officials, planners, and environmental experts. The data collection methods were through original questionnaire surveys (Appendix I), which was sent to anonymous experts in NbS by email. Out of a total of 32 experts invited, 5 responded to the survey, where through a pairwise comparison matrix, experts offered their comparison assessments on the relative importance of one attribute in comparison to another in their view of suitable sites selection for implementing NbSs. For spatial analysis, data collection involved gathering data from various online sources, including EDINA Environment Digimap Service, SEPA's Flood Risk Management Scotland, Copernicus Land Monitoring Service, Glasgow Open Data Portal, Glasgow City Corporation etc.

Data Processing and Analysis Techniques: This assessment involved evaluating the environmental attributes to explore opportunity sites for NbS implementation.

The content analysis was used to analyze the survey data. Based on Chapter 2, identified relative environmental criteria were scored according to suitability. Based on the response, criteria comparison matrices were built with values ranging from 1 to 5, and their inverse counterparts (e.g., 1/n) (Table 3.1). Following the Analytic Hierarchy Process (AHP) method, a spatial multi-criteria analysis (MCA) was then carried out to

determine the relative importance of each environmental criterion, based on expert opinions. The key steps are shown in Figure 3.4. Criteria comparison matrices were constructed, with values ranging from 1 to 5 and their inverse equivalents (for example, 1/n) (Table 3.1).

Table 3.1: Scale of Relative Importance

Scale	Numerical Rating (More Important)	Reciprocal (Less Important)
Strongly	5	1/5
Moderately	3	1/3
Equally	1	1

An eigenvector was obtained after the AHP had been applied to assign weights (i.e., relative priority to each environmental parameter). The total sum of the eigenvector components was one. The Consistency Index (CI) and Consistency Ratio (CR) were used to assess the consistency of the pairwise comparison matrix. CR was calculated using the formula ‘ $CR = CI/Random\ Consistency\ Index$ ’ and CI was calculated using the formula ‘ $CI = (\lambda_{max} - n) / (n - 1)$ ’, where λ_{max} is the maximum eigenvalue of the matrix and n is the number of criteria. The AHP results should be considered consistent and acceptable if the CI and CR values are both less than 0.14 and 0.10, respectively (Saaty, 1980). To calculate the spatial suitability scores, these evaluations were then integrated using a simple additive weighting (SAW) methodology (e.g., Gonzalez-Ollauri, Thomson, and Mickovski, 2020).

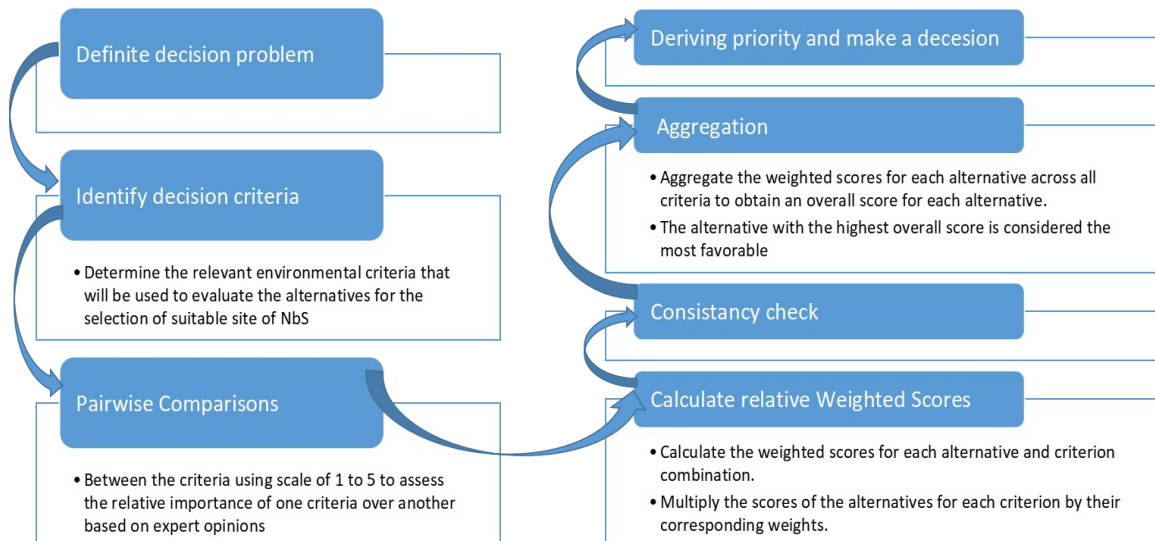


Figure 3.4: Key Methods 1 (Steps in MCA-AHP Procedures for suitability analysis)

for **Spatial Analysis**, Geographic Information System (GIS) software ESRI ArcGIS Pro 2.8.0 was used to process and analyse the data to map the identified potential sites and assess their suitability for nature-based solutions (Figure 3.5).

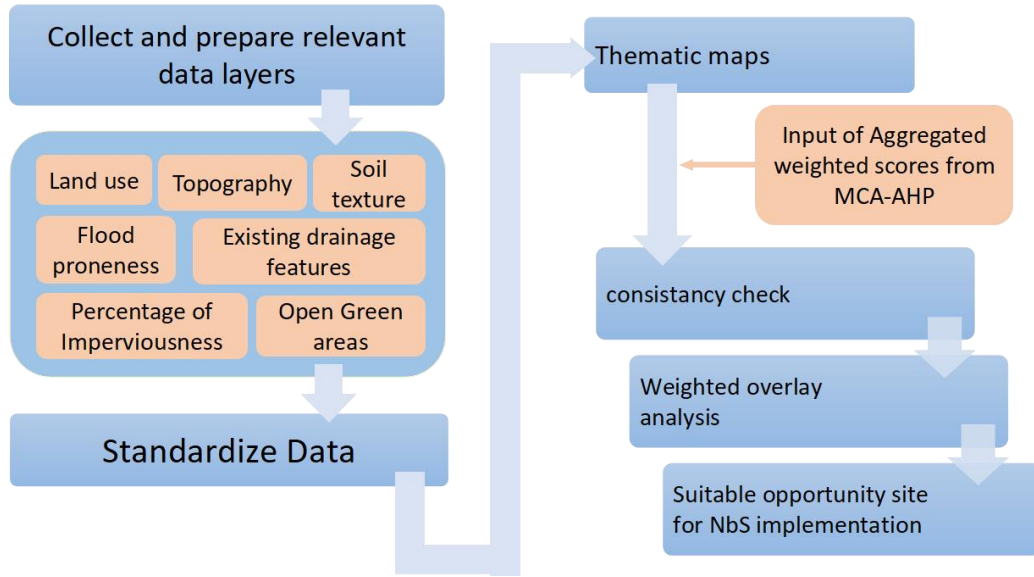


Figure 3.5: Key methods 2 (Geospatial analysis for NbS opportunity site selection)

This included spatial layers of selected seven environmental attributes data. By summing the GIS layers that integrate selected attributes and their weights (from the MCA-AHP), Weighted Overlay Analysis generated a composite suitability map for implementing NbSs within the Glasgow City area. The suitable site was categorized as following table (Table 3.2):

Table 3.2: Framework for suitability classification

Suitability Class	Suitability Score	Description
Optimal suitability	5	Land having no significant or only minor limitations.
Moderate suitability	3	Land having the limitations which will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciably inferior.
Low suitability	1	Land having limitations which in aggregate are severe for sustained application of a given use and will so reduce productivity or benefits, or increase required inputs, that this expenditure will be only marginally justified.
Restricted	R	Land that cannot be used for interventions.

Chapter 04

4 RESULT AND ANALYSIS

4.1: Understanding and Conceptualization

This study conducted a thorough assessment on nature-based solutions (NbSs) based on the literature and case studies for managing stormwater and identified a number of NbSs (Appendix III). The multi-dimensional advantages of NbSs deployment in improving the health and resilience of ecosystems were also underlined by the literature review. Based on the understanding and to facilitate the analysis, this study categorized the NbSs into three classes according to their basis functions (i.e., retention, storage, or conveyance of water) of lowering storm-water runoff (detail in Appendix II) as following-

- **Retention-based NbS:** Water retention NbSs should be designed to foster infiltration and prevent the discharge of a specified volume of stormwater into sewer networks or surface waters and does not therefore become runoff (Aquafor *et al.*, 2016). These solutions aim to slow down and retain stormwater at the point of rainfall, reducing runoff and allowing water to seep into the soil. Examples of water retention NbS include- green roofs, Rain Garden, Subsurface wetlands etc.
- **Storage-based NbS:** Water storage NbS is focused on temporarily holding and storing stormwater, which is then either reused or released in a controlled manner to sewers or receiving channels after water levels recede following a storm event (Aquaforet *al.*, 2016). These solutions maximize water storage capacity and minimize the risk of overflow. Examples of water storage NbS include Created Wetlands, Underground storm-water detention area, Floodplains with storage ponds.
- **Conveyance-based NbS:** Water conveying NbS should be designed to redirect excess stormwater away from vulnerable areas and minimize the risk of overflow. In areas where infiltration would be encouraged but would require an under-drain due to extraneous

circumstances, a conveyance system is suggested. Examples of water conveying NbS may include- Permeable pavements, Live pole drain, Bioswales.

Environmental factors identified in the literature review and based on data availability for a suitability analysis for NbS included: Land Cover, Percentage of impermeable area (PIMP), Proximity to existing drainage features, Proximity to flood prone area, Soil Texture, Topography, Proximity to urban green areas. This study considered a number of variables, including ecological integrity and site-specific features, to determine these seven significant environmental conditions for NbS implementation that play a crucial role in effective NbSs implementation for storm-water management. Ecological integrity was concerned with how NbSs would affect the ecosystems and their capacity to sustain native plants. NbS's suitability for various geographical regions was assessed using site-specific features that took into consideration the soil, topography, and drainage conditions. Existing buildings and road data were analyzed as subdivisions of the land cover suitability analysis. Same as proximity to existing drainage system, where the proximity to existing culvert and a distance from natural watercourse (river) were considered with equal importance.

Herein the following table 4.1 shows the shortlisted Environmental criteria and the possible effect on/off the categorized three types of NbS. And table 4.2 shows the scoring of each environmental criteria for the context of different types of nature-based solution implementation according to the framework for suitability classification (table 3.2) discussed beforehand.

Table 4.1: The shortlisted Environmental criteria and the possible effect on/off the categorized three types of NbS.

Environmental Criteria	Definition	Impact on/off NbS		
		water retention NbS	water storage NbS	water conveyance NbS
Land Cover	Area covered by buildings, roads, forests, and water body etc.	It helps to identify soil availability; restricted sites and the way land is used in a region that is related to identifying areas where NbS may be particularly effective.	It helps to identify soil availability; restricted sites and the way land is used in a region that is related to identifying areas where NbS may be particularly effective.	It helps to identify soil availability; restricted sites and the way land is used in a region and helps to increase the connectivity of urban ecosystem.
Percentage of impermeable area (PIMP)	Proportion of land in an area that is covered by impervious surfaces	Intervention can hold back and slow down the overland storm-water flow. Possible replacement of impermeable area to permeable can improve water retention and reduce runoff.	Intervention can hold back and store the overland excess stormwater runoff from high percentage of impermeable area. This can provide a sustainable water source for non-potable uses such as irrigation and toilet flushing.	Intervention can redirect the overland storm-water flow from a high percentage of impermeable areas towards areas where it can be safely managed or absorbed.
Proximity to flood prone area	It indicates the susceptibility of the land to surface water flooding.	In the areas prone to frequent flooding, ground may already be saturated. Additional intervention can improve infiltration, evaporation, and aquifer recharge.	Areas prone to frequent flooding may require more extensive or larger Nature-Based Solutions or combined systems.	The implementation of water conveyance NbS can help redirect water away from areas prone to surface flooding and towards areas where it can be safely stored or released.
Proximity to existing Drainage features	Information about the drainage network in an area. This includes the location and extent of existing culverts, rivers, and other water bodies.	Water retention NbS near existing Drainage features can improve the effectiveness by providing additional support and connectivity with the features.	The design of NbS can manage runoff before reaching the existing drainage system and can reduce the pressure. Thus improve the effectiveness and connectivity of the existing drainage system.	Improve the effectiveness of existing system by creating connectivity with the features by providing additional conveyance capacity, reducing the risk of culvert blockage, and promoting the dispersion of water over a larger area.
Soil Texture	Relative distribution of solid particles (i.e., the percentage of gravel, sand, silt, clay particles and organic matter).	Can affect infiltration and percolation rates which is related to runoff speed and amount. For example, where soil has a higher infiltration rate and retention-based solutions may be more effective.	For example, areas with clayey loam soils, some water may infiltrate, and some run off quickly, where intervention can store the overland storm-water flow and allow reuse water.	Intervention can redirect the overland storm-water flow and allow water to be dispersed over a larger area to take time for infiltration where soil has low infiltration rate.
Topography	Description of Surface gradient (steepness of the land)	If a water retention NbS is on a flat surface, it may require less engineering work to retain water compared to a place with a steep slope.	If a water storing NbS is on a flat surface, it may require less engineering work to hold back water flow compared to a place with a steep slope.	Water conveyance NbS can help to convey water out of accumulation zones where, in the convex slope area, they can help disperse and slow down the water flow.
Proximity to urban green areas	Distance or closeness of an area or site to natural or designed vegetated areas.	Intervention supports ecosystem connectivity by connecting existing green areas/infrastructures. Closeness to vegetated area helps retrieval native stock to develop the NbS, which reduces costs, and improves performance.	Intervention supports ecosystem connectivity by connecting existing green areas. Closeness to vegetated area helps retrieval native stock to develop the NbS, which reduces costs, and improves performance.	Intervention supports ecosystem connectivity by connecting existing green areas/infrastructures. Closeness to vegetated area helps retrieval native stock to develop the NbS, which reduces costs, and improves performance.

Table 4.2: Scoring of each environmental criteria for the context of different type of nature-based solution implementation

Environmental Criteria		Unit	Class	Retention	Storage	Conveyance
Land Cover	Land cover Source: Ordnance Survey (2021) EDINA Environment Digimap Service Raw Data Type: Polygon	Level	Broadleaf woodland	5	5	1
			Built-up areas	1	3	5
			Coniferous woodland	5	3	1
			Arable	1	1	3
			Improved grassland	3	3	1
			Semi-natural	5	3	3
			Mountain, heath	1	1	1
			Open Water body	R	R	R
	Proximity to Buildings Source: Ordnance Survey (2021) EDINA Environment Digimap Service Raw Data Type: Polygon	m	0-70	1	1	5
			70-200	1	3	3
			200-350	3	5	1
			>350	5	3	1
Proximity to main Road Source: Ordnance Survey (2021) EDINA Environment Digimap Service Raw Data Type: Polygon	m	0-50	1	1	5	
		50-200	3	1	3	
		200-350	5	3	1	
		>350	3	5	1	
Percentage of impermeable area (PIMP) Source: Copernicus Land Monitoring Service Raw Data Type: Raster		%	0-35	5	1	1
35-70	3		5	3		
70-100	1		3	5		
Proximity to surface flood prone area Source: SEPA's Flood Risk Management Scotland Raw Data Type: Polygon		m	0-100	1	1	5
100-250	5		5	3		
250-400	5		3	3		
400-550	3		1	1		
>550	1		1	1		
Proximity to existing Drainage features	Proximity to main watercourses Source: Ordnance Survey (2021) EDINA Environment Digimap Service Raw Data Type: Polygon	m	0-100	5	5	1
			100-300	5	5	3
			300-700	3	3	5
			>700	1	1	3
	Proximity to existing culverts	m	0-100	1	1	5

	Source: Glasgow city council (2023) Raw Data Type: Polygon		100-250 250-700 >700	5 5 3	3 3 5	3 3 1
Soil Texture Source: Ordnance Survey (2021) EDINA Geology Digimap Service Raw Data Type: Polygon	Level	Clay to loam Clay to sandy loam Clayey loam to sandy loam Clayey loam to silty loam Loam Loam to Clayey loam Loam to sandy loam Loam to silty loam Peat Sand to loam Sand to sandy loam Sandy loam Sandy loam to loam Sandy loam to silty loam	3 5 3 3 5 3 5 5 5 3 3 5 5 5	1 3 3 3 5 3 3 5 5 3 3 3 3 3	1 1 3 3 1 1 3 1 3 3 3 1 1 3	
Topography (Slope) Source: Ordnance Survey (2021) EDINA Geology Digimap Service Raw Data Type: Raster	Degree	0-1° 1-5° 5-15° 15-35° >35°	5 5 3 1 1	5 5 3 1 1	1 5 3 3 1	
Proximity to open green areas Source: Ordnance Survey (2021) EDINA Environment Digimap Service Raw Data Type: Polygon	m	0-80m 80-200m 200-350m >350m	5 5 3 1	5 3 3 1	5 3 3 1	

4.2 Contextualization and Localization

4.2.1 Land suitability based on each Environmental Criteria

By analyzing the score of the relative importance of individual environmental criteria, this section is showing environmental criteria suitability maps and area percentage for each type of NbSs implementation within Glasgow City.

4.2.1.1 Retention based NbS:

In terms of land cover (Figure 4.2a) for water retention-based NbSs implementing, Glasgow city showed moderately suitable condition (60%) (Figure 4.1a). Only 1% of the land showed optimal suitability where 30% of the land may not be well-suited for retention-based NbS approaches. 9% of the Glasgow area in terms of land use was restricted.

94% of the city area in terms of percentage of impermeable area (Figure 4.2b) showed optimal suitability for retention based NbS implementation, where 3% of area considered as moderately suitable for retention-based NbS (Figure 4.1b). 3% found as low suitable.

In terms proximity to flood prone area (Figure 4.2c), suitability of 26% area was considered low for retention-based NbS while 24% area was found with moderate suitability (Figure 4.1c). 50% of areas have a higher suitability for retention-based NbS.

78% of the area showed low suitability for retention based NbS based on proximity to existing drainage feature (Figure 4.2d) (Figure 4.1d), where river channel and existing culvert considered as restricted. 11% of areas which are within 300m of river and 100-700 me from existing culverts were considered as optimally suitable site for this type of NbS where 10% of the area in of moderate suitability.

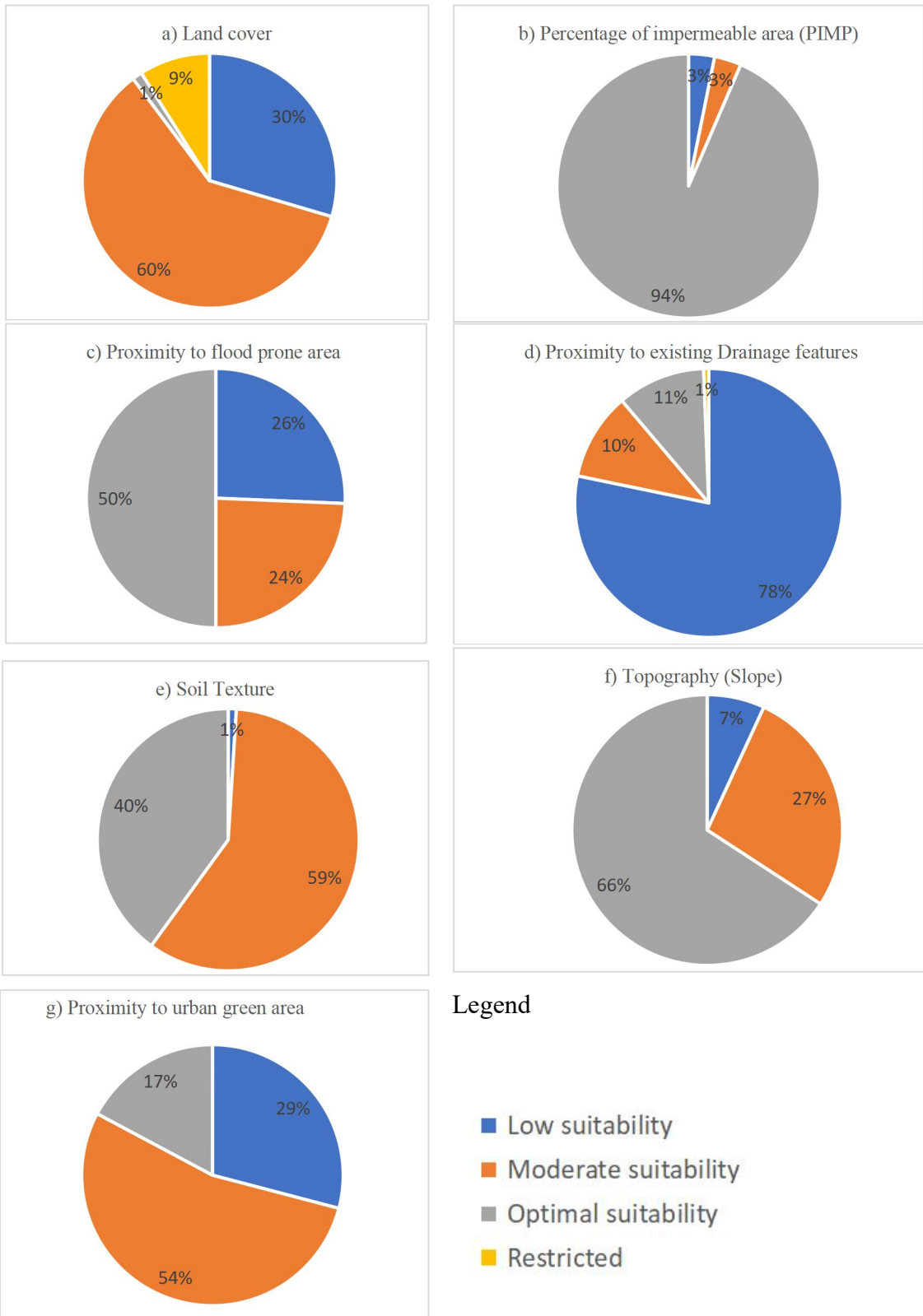


Figure 4.1: Suitable area percentage based on environmental criteria suitability for Retention based NbS creation within Glasgow City.

In terms of soil texture (Figure 4.2e), about 40% (Figure 4.1e) of land showed optimal suitability for retention based NbS. Only 1% of the soil with highly sandy texture showed as least suitable for this NbS , where 59% of land considered as moderately suitable.

In terms of slope (Figure 4.2f), 66% of the areas with comparatively flat or gentle slopes considered optimally suitable for implementing the NbS focused retention. 27% of the area has moderate suitability and 7% area has low suitability due to steep slope (Figure 4.1f).

While considering proximity to urban green space (Figure 4.2g) 17% of the area considered as optimally suitable for implementing this kind of NbS. 54% of the areas situated between 80 and 350 meters from open green areas showed moderate suitability and 29% considered the least suitable for retention-based NbS in terms of proximity (Figure 4.1g).

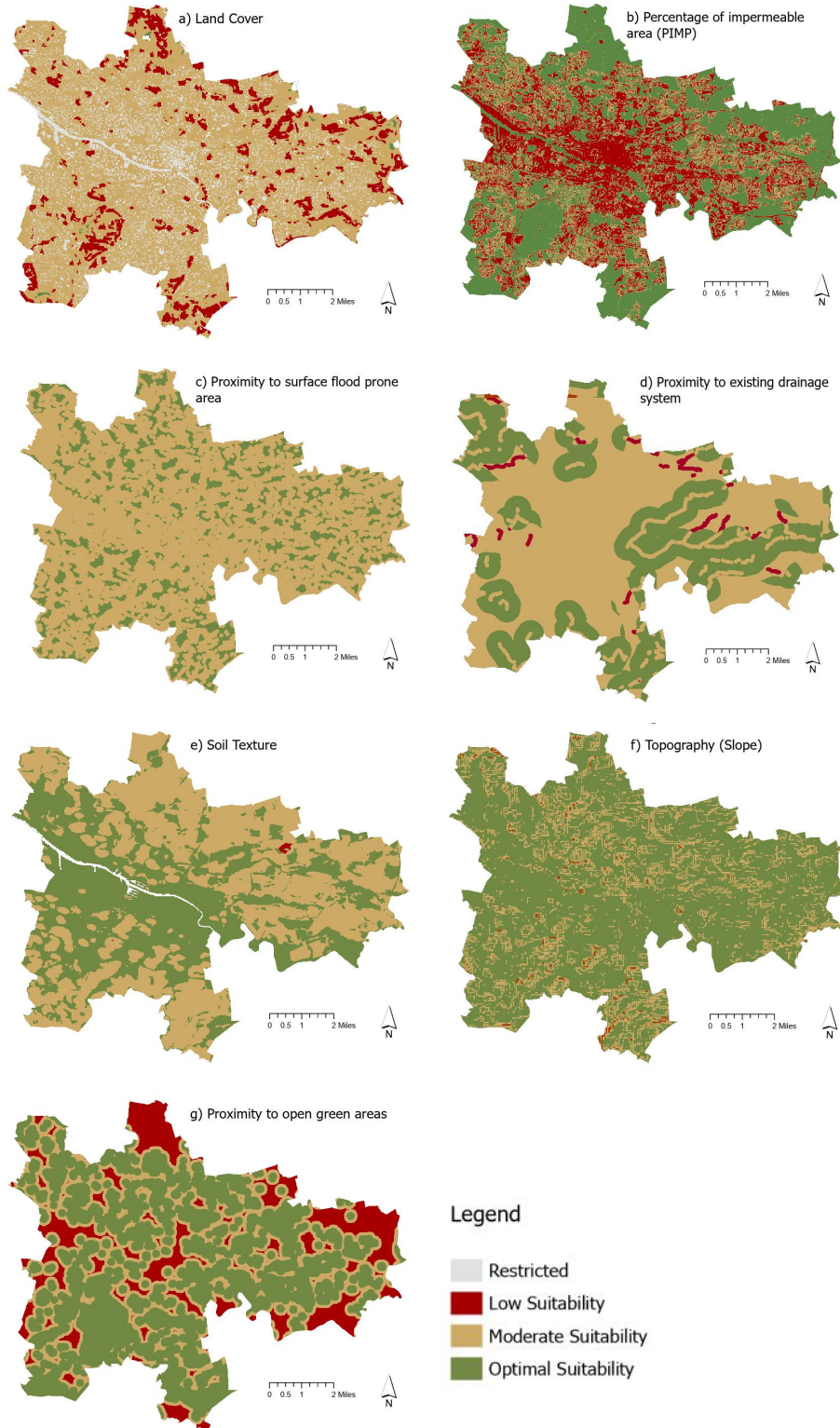


Figure 4.2: Environmental criteria suitability maps for Retention based NbS creation within Glasgow city

4.2.1.2 Storage based NbS

75% (Figure 4.3a) of the area showed moderate suitability in terms of land cover (figure 4.4a) where only 5% of the area was found optimally suitable for storage based NbS. Almost 11% of the areas were of low suitability with 9% of restricted areas.

For almost 96% area (Figure 4.3b) considered as having least suitability for storage based NbS based on percentage of impermeable area (Figure 4.4b). Only 3% of the areas with the highest impermeability were considered as optimally suitable for storage based NbS. On the other hand, 3% of the area can serve moderately in floodwater management.

Overall, 54% (Figure 4.3c) of areas showed optimal suitability for storage based NbS implementation in terms of proximity to flood prone area (Figure 4.4c). About 20% of the area had moderate suitability and a proportion of 26% was considered as a low suitable area for storage based NbS.

In terms of proximity to existing drainage features (Figure 4.4d), most of the area (78%) was found to be low suitable for storage-based NbS. 11% of areas which were within 300m of river and 100-700m from existing culverts were considered as optimally suitable sites for this type of NbS where 10% of the area was found as moderately suitable (Figure 4.3d).

In terms of soil texture (Figure 4.4e), only 11% soil areas of Glasgow city have optimal soil condition for storage based NbS creation, where almost 89% of the area has moderate suitability. A very small area (1%) with a high percentage of sand was of low suitability for this type of NbS implementation (Figure 4.3e).

In terms of slope (Figure 4.4f), 66% of the areas with comparatively flat or gentle slopes considered optimally suitable for implementing the NbS focused on stormwater retention. 27% of areas have moderate suitability, and 7% of areas have low suitability due to steep slopes (Figure 4.3f).

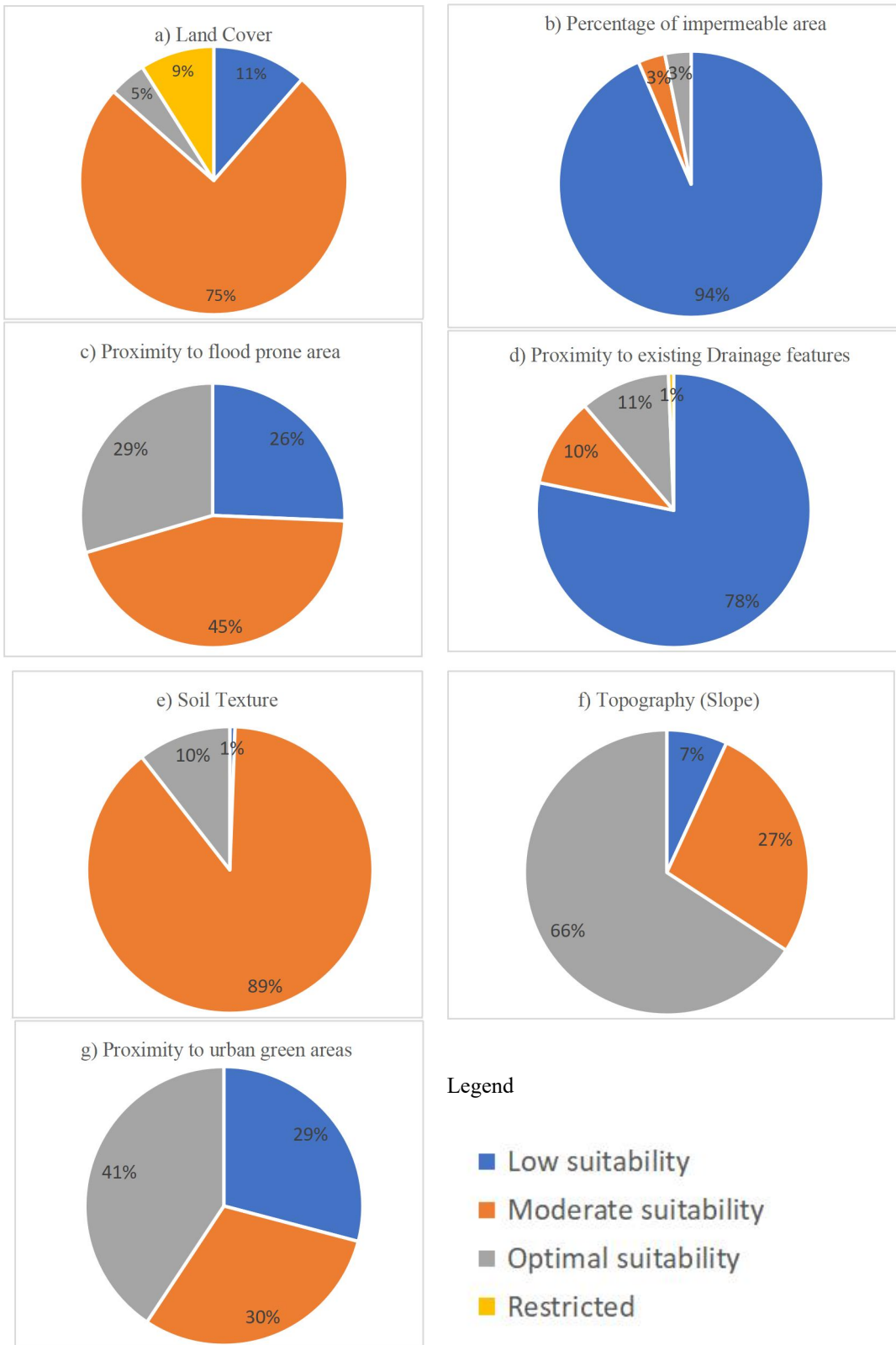


Figure 4.3: Suitable area percentage based on environmental criteria suitability for storage based NbS creation within Glasgow City

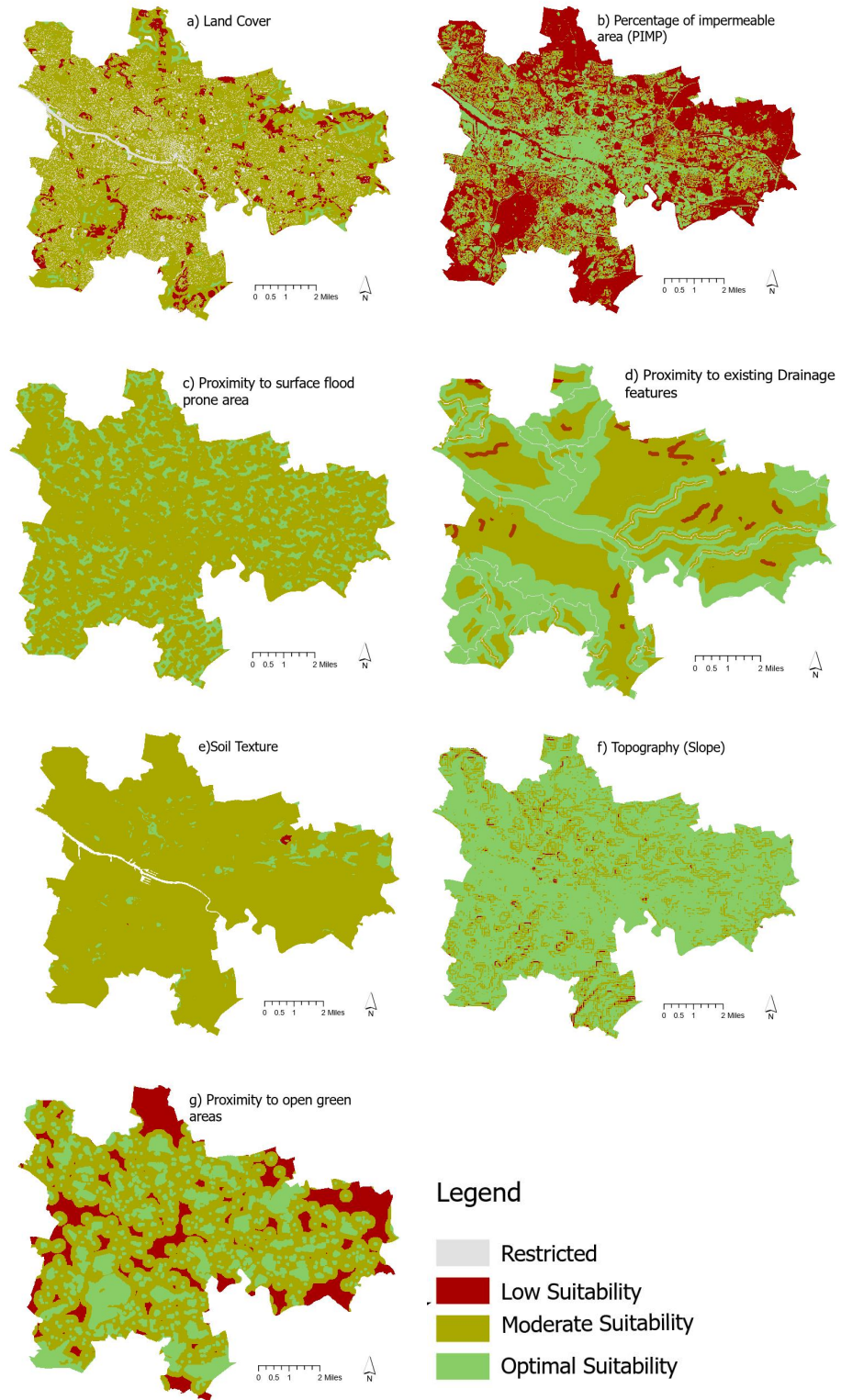


Figure 4.4: Environmental criteria suitability maps for Storage-based NbS creation within Glasgow city

While considering proximity to urban green space (Figure 4.4g), 41% of area within 200 meters of open green areas was ranked as optimally suitable for storage-based NbS. 30% of areas have a moderate suitability for storage-based NbS and 29% of the area considered as least suitable areas for storage-based NbS (Figure 4.3g).

4.2.1.3 Conveyance-based NbS

In the context of land cover suitability (Figure 4.6a), 60% of the area was scored as moderately suitable for the NbS focused on storm water conveyance to manage stormwater runoff efficiently and 2% was found to have optimal suitability. 29% of the area of Glasgow city considered as least suitable while 9% was found restricted (Figure 4.5a).

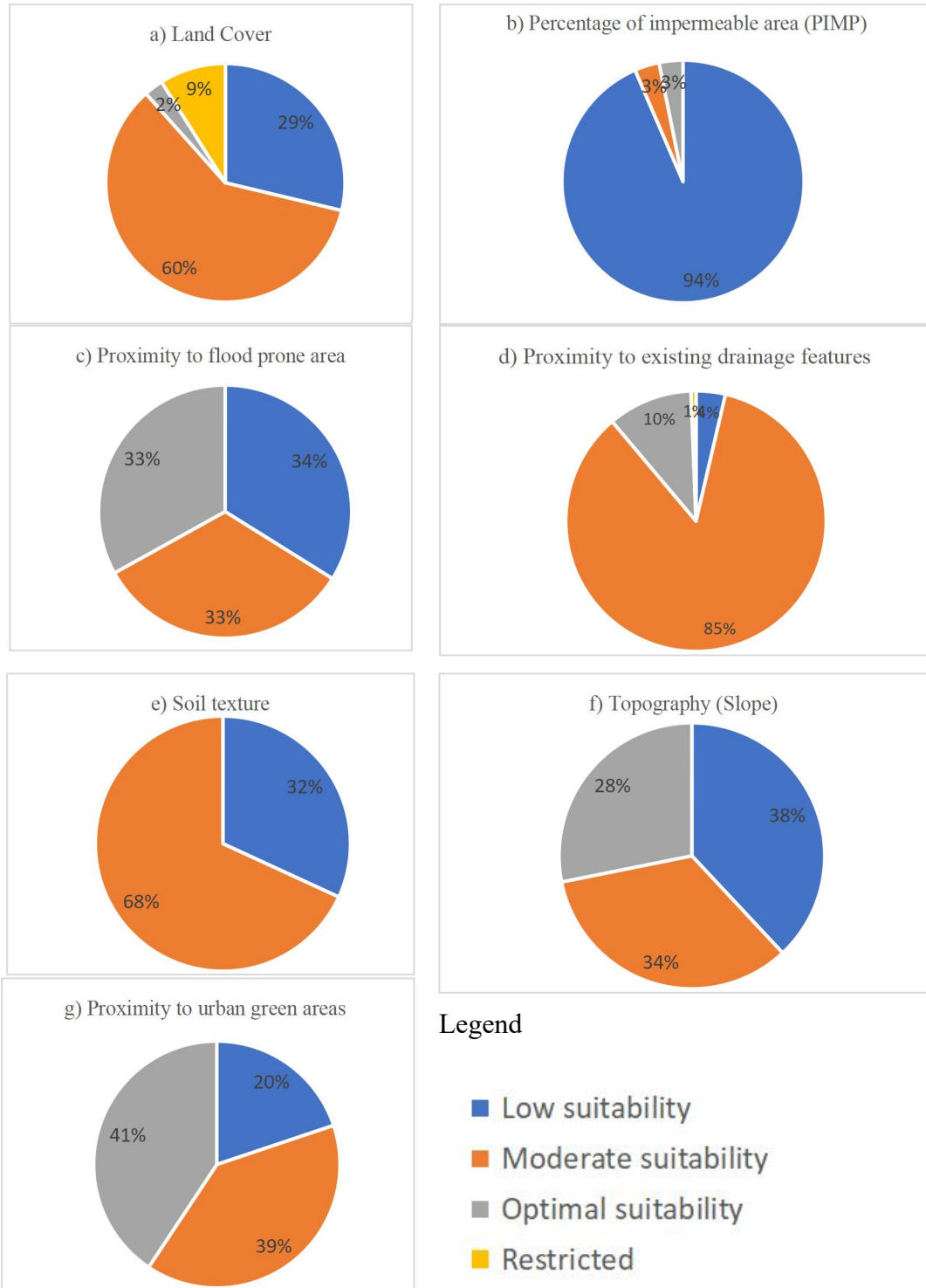
Based on percentage of impermeable area (Figure 4.6b), almost 96% areas were considered as low suitable for conveyance based NbS and 3% area with highest impermeability considered as optimally suitable. On the other hand, 3% of the area can serve moderately for this type of NbS (Figure 4.5b).

Overall, 33% (Figure 4.5c) of areas within 100 meters of a flood-prone area are near the flood zone, considered as highly suitable for conveyance-based NbS in terms of proximity to flood prone area. About 33% of the area had moderate suitability. A proportion of 34% was considered as low suitable area for conveyance-based NbS (Figure 4.6c).

In terms of proximity to existing drainage features (Figure 4.6d), most of the areas (85%) were found to be moderately suitable for sitting conveyance-based NbS. Only 4% of the area were found to be low suitable, and 10% areas were considered as optimally suitable site for this type of NbS (Figure 4.5d).

In terms of soil texture (Figure 4.6e), almost 68% of the area has moderate suitability, and 32% area was of low suitability (Figure 4.5e) for this type of NbS implementation. No area in the Glasgow territory was found to be optimally suitable in terms of soil texture.

Figure 4.5: Suitable area percentage based on environmental criteria suitability for conveyance based NbS creation within Glasgow City



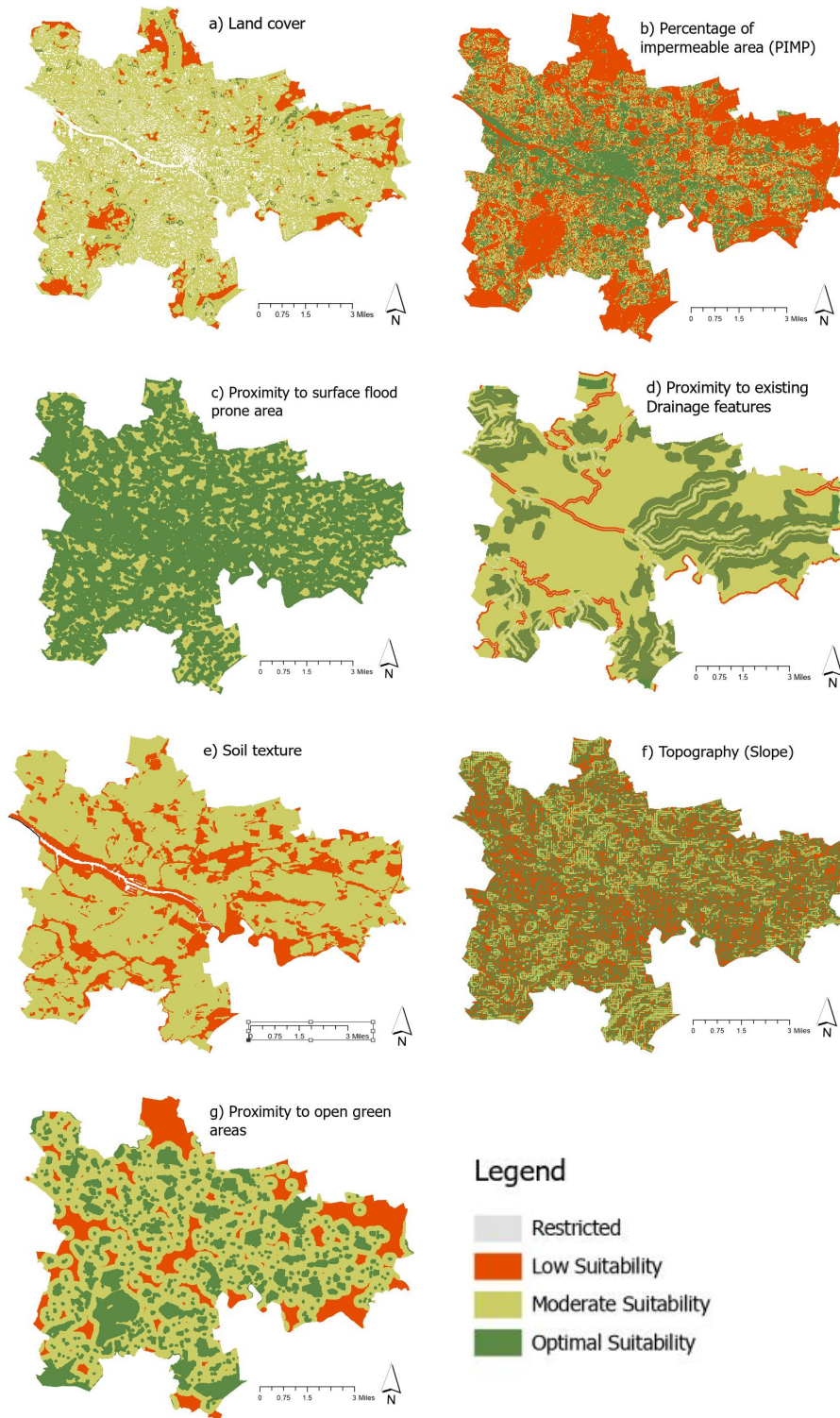


Figure 4.6: Environmental criteria suitability maps for conveyance based NbS creation within Glasgow city

In the context of slope (Figure 4.6f), 28% of the area with gentle slopes considered as optimally suitable for implementing the NbS focused on stormwater conveyance. 34% of areas with average steepness have moderate suitability. 38% of areas comprising either very flat surface or steep slopes have low suitability (Figure 4.5f).

While considering proximity to urban green area (Figure 4.6g), 41% area was ranked as optimally suitable for conveyance based NbS. 39% of areas had a moderate suitability while 20% of the area considered as least suitable areas for this type of NbS (Figure 4.5g).

4.2.2 Content Analysis: Relative Weight of Environmental Criteria

Following table 4.4 shows the results from AHP analysis. For the Retention-based NbS and Storage-based NbS, Topography (Slope) was considered as the most significant environmental criteria (RW = 0.18 and 0.29 respectively). For the Conveyance-based NbS, proximity to flood prone area (RW = 0.20) was defined as the most important environmental criteria before Topography (Slope) (RW = 0.18). For all the three categories of NbS, Proximity to urban green areas was counted as the least important environmental criterion, and the RW values were 0.07, 0.06, 0.06 for Retention based, Storage based, and Conveyance based NbS respectively. Since the values of consistency index (CI) and consistency ratio (CR) were below the standard values of 0.14 and 1.10 respectively, for each category of NbSs, the results of the AHP were consistent (Table 4.4). While calculating the consistency ratio (CR), Random index (RI)=**1.32** was considered as here seven elements were calculated (Table 4.3).

Table 4.3: Random index (RI)

Matrix Size	1	2	3	4	5	6	7
RI	0	0	0.58	0.9	1.12	1.24	1.32

Table 4.4: Relative Weight of Environmental Criteria

Environmental Criteria	Relative Weight (RW) in context of -		
	Retention based NbS	Storage based NbS	Conveyance based NbS
Land Cover	0.16	0.13	0.12
Percentage of impermeable area (PIMP)	0.17	0.15	0.16
Proximity to existing Drainage features	0.12	0.10	0.17
Proximity to flood prone area	0.13	0.11	0.20
Soil Texture	0.17	0.16	0.11
Topography (Slope)	0.18	0.29	0.18
Proximity to urban green areas	0.07	0.06	0.06
CI	0.03	0.09	0.02
CR	0.02	0.07	0.02

These relative weights from MCA-AHP were then used to compute the overall spatial suitability for each type of NbS implementation through equation of Simple Additive Weighting (SAW) (Table 4.5).

Table 4.5: Equations for Spatial suitability

Spatial suitability for Retention-based NbS = Land Cover \times 0.16 + Percentage of impermeable area (PIMP) \times 0.17 + Proximity to existing Drainage features \times 0.12 + Proximity to flood prone area \times 0.13 + Soil Texture \times 0.17 + Topography (Slope) \times 0.18 + Proximity to urban green areas \times 0.07

Spatial suitability for Storage-based NbS = Land Cover \times 0.13 + Percentage of impermeable area (PIMP) \times 0.15 + Proximity to existing Drainage features \times 0.10 + Proximity to flood prone area \times 0.11 + Soil Texture \times 0.16 + Topography (Slope) \times 0.29 + Proximity to urban green areas \times 0.06

Spatial suitability for Conveyance-based NbS = Land Cover \times 0.12 + Percentage of impermeable area (PIMP) \times 0.16 + Proximity to existing Drainage features \times 0.17 + Proximity to flood prone area \times 0.20 + Soil Texture \times 0.11 + Topography (Slope) \times 0.18 + Proximity to urban green areas \times 0.06

This result from AHP analysis based on expert's opinion is showing the classification of environmental criteria, where higher number will have higher impact and lower number will have lower influence on final output map.

4.2.3 Spatial Analysis: Opportunity site mapping for NbS implementation

4.2.3.1 Opportunity site mapping in Glasgow City

Using weighted overlay tools in ArcGIS software, the seven maps had been overlaid and weights of the environmental criteria achieved through SAW analysis were combined; thus suitable opportunity sites for three NbSs types in Glasgow were produced (Figure 4.7). Suitability scores were classified into three classes (low suitability, moderate suitability, and optimal suitability). 11% of the Glasgow city area was accounted as restricted area because of buildings, roads, and open water area. For implementing retention-based NbS (Figure 4.7a), moderate suitability was found for most of the area (71%) while 18% of the area considered optimally suitable. While considering storage-based NbS (Figure 4.7b), almost 85% of the area was of moderate suitability which is about 81% for conveyance-based NbS (Figure 4.7c). Optimal site proportion for storage-based and conveyance-based NbS were 4% and 5% respectively. Nearly 0% of Glasgow city was found to be least suitable for both Retention and storage-based NbS where that is only 2% for Conveyance-based NbS.

From table 4.4, topography (with gentle slope) was the most favourable criterion (18%) in analyzing opportunity sites for Retention-based NbS. Percentage of impermeable area (PIMP) and soil texture had equal impact (17%) on this final opportunity mapping. The percentage of impermeable area analysis showed highest opportunity site (94%), while proximity to existing drainage feature showed highest least suitable site (78%) for retention-based NbS.

For storage-based NbS creation, topography (slope) (with gentle slope) was also the most significant criterion (29%) while, percentage of impermeable area (PIMP) and soil texture had equal impact (15%) on final storage-based suitable site mapping. Topography (slope) analysis showed the highest opportunity site (66%), while percentage of impermeable area showed highest least suitable site (94%) for retention-based NbS.

On the other hand, while mapping opportunity sites for conveyance-based NbS creation, proximity to flood prone areas was also the most important criterion (20%), showed highest proportion of optimally suitable areas (33%). Topography (slope) (18%) was the second most

significant criterion followed by proximity to existing drainage feature (17%), while mapping final opportunity sites for conveyance-based NbS. The highest proportion of low suitable area was found based on percentage of impermeable area (PIMP) (94%) for this type of NbS.

4.2.3.2 Opportunity site mapping in urban vacant and derelict area of Glasgow City

After finding the opportunity sites in Glasgow, VDLs were prioritized for further analysis (Figure 4.8). 5% of vacant and derelict land of Glasgow city area was accounted for restricted area for retention-based and conveyance-based NbS, where 4% was for storage-based NbS. While considering VDLs, for all the NbSs, maximum portion of the area was found as moderately suitable, which were 68% (1% of Glasgow city territory), 90% (2% of Glasgow city territory) and 89% (2% of Glasgow city territory) for retention-based (Figure 4.8a), storage-based (Figure 4.8b), and conveyance-based NbS (Figure 4.8c) respectively.

Though the optimal suitability for NbS in compared to overall city territory was found nearly 0.1%, but of 9.38 km² VDL, 5% was considered as optimally suitable for both storage-based and conveyance-based NbS (Figure 4.8c). The highest proportion (27%) of vacant and derelict areas (1% of total city territory) showed optimal suitability in context of implementing retention-based NbS (Figure 4.8a) in VDLs, with no low suitability for NbS creation. It also found no unsuitable sites for retention and storage-based NbS in VDL of Glasgow, where only 1% land was of low suitability for conveyance-based NbSs implementation.

Figure 4.9 showed a delimited zone expanded (Figure 4.9 A) to explore the site suitability of VDL in detail for three types of NbS (Figure 4.9 (a-c)). This detailed satellite imagery assessment allowed us to better understand the scale and the shape of the opportunity site for NbS implementation within VDL.

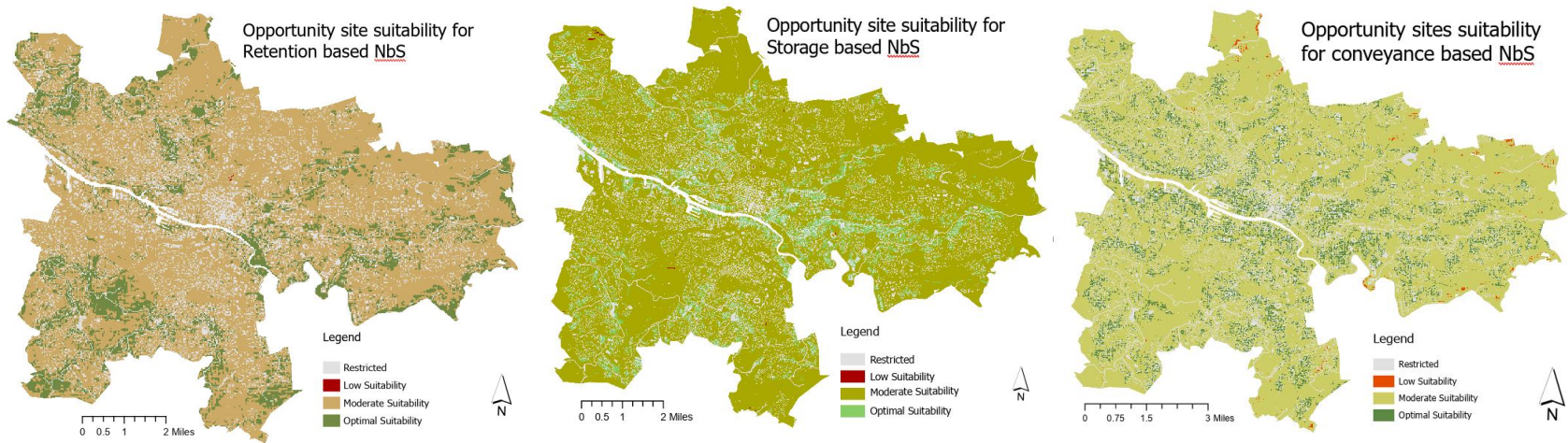


Figure 4.7: Opportunity site mapping in Glasgow City

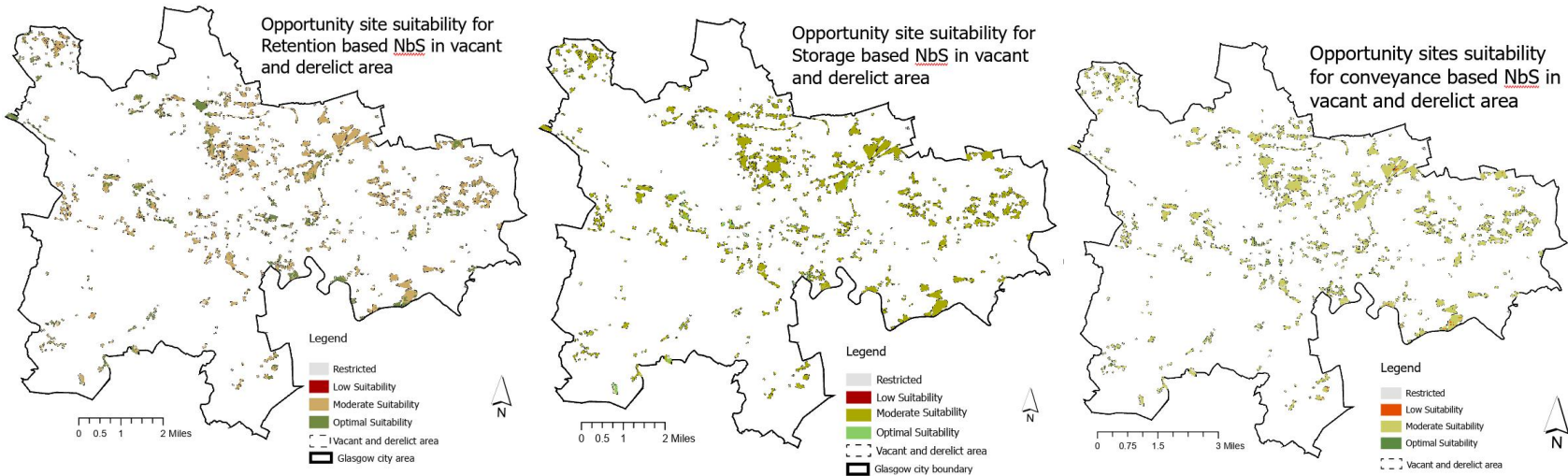


Figure 4.8: Opportunity site mapping in urban vacant and derelict area of Glasgow City

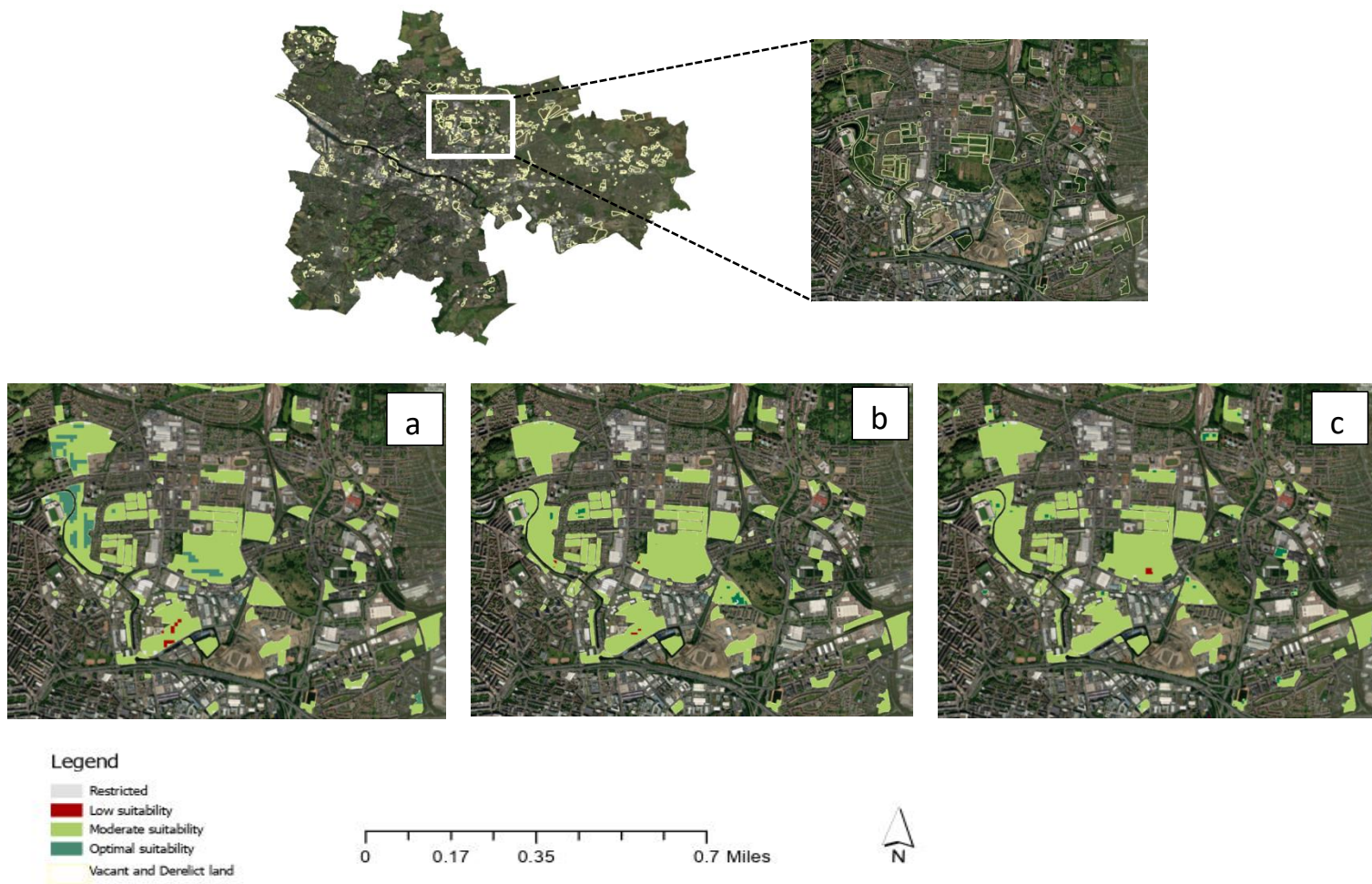


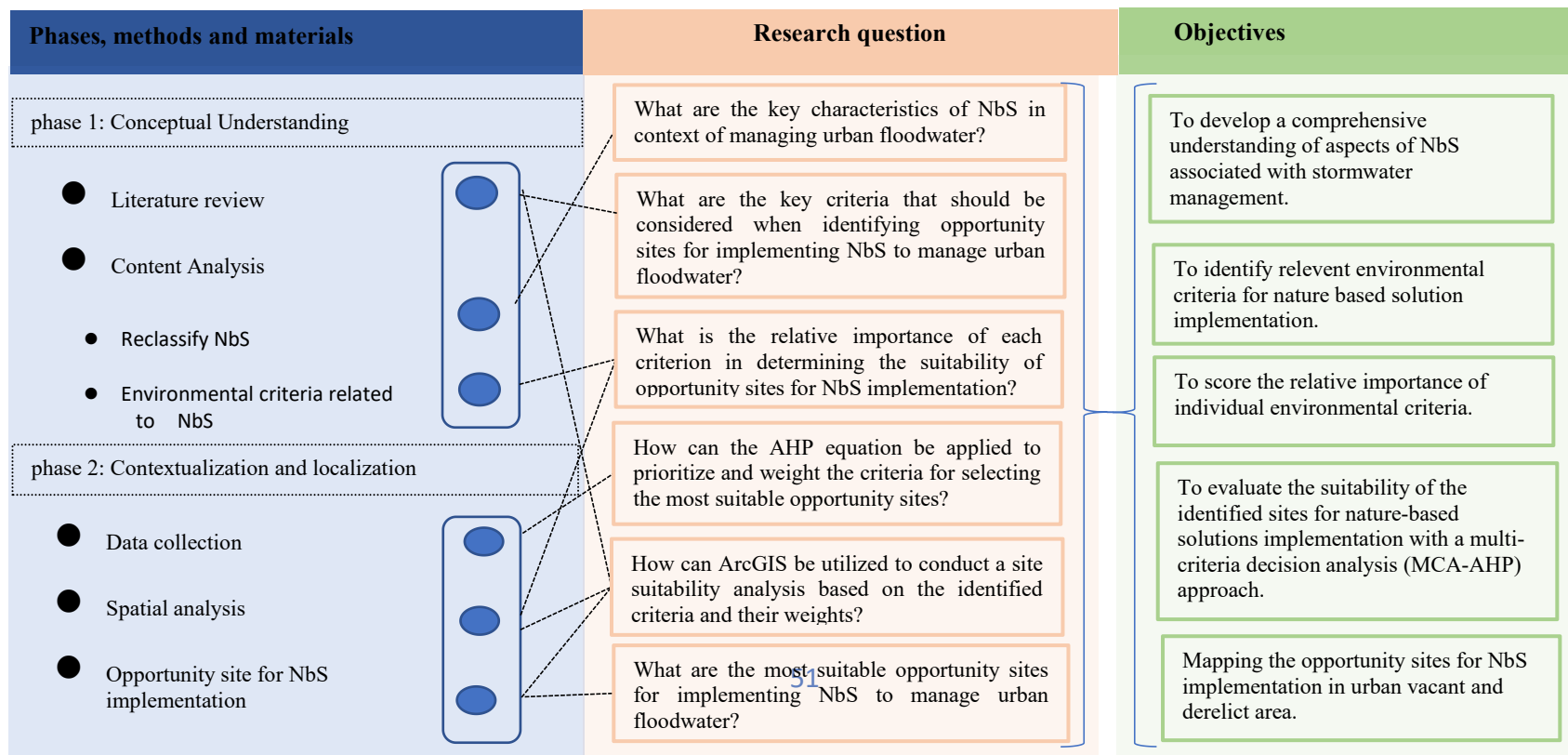
Figure 4.9: In-detail suitability outputs of VDL for NbS implementation based on Satellite imagery; A) shape of expanded VDL portions a) Retention-based NbS, b) Storage-based NbS, c) Conveyance-based NbS.

5 DISCUSSIONS

5.1: Understanding and Conceptualization

The overall understanding of the concept and methodological framework followed in this study while exploring available opportunity site to manage urban surface water flood shown well-structured connections between steps, research questions, and the objectives (drawn in the following diagram (Table 5.1)).

Table 5.1: Connections between research questions, objectives and phases of the methodology



5.2 Contextualization and Localization

Opportunity site mapping for NbS implementation

The methodology applied to this study allowed us to identify and quantify the available suitable opportunity sites for NbS at the city level, which can help to manage surface water flooding. The findings of this study demonstrate, to accommodate both storage and conveyance-based NbS, Glasgow City has shown only 5% optimal suitability, whereas in the case of retention-based NbS, the percentage is higher (27%), which is satisfactory. For instance, 7.1% of Florence city was found as completely suitable for retention-based NbS (like Bioretention area and Rain garden) creation, whereas 1.7% - 2.5% for different conveyance-based NbS (like Tree box filter, infiltration trenches, bioswals and permeable pavement) and 0.3-0.9% for storage-based NbS (like detention basin and ponds) in context of pluvial flood management (Pacetti *et al.*, 2022). On the other hand, Glasgow city has the highest portion (90%) of the area with moderate suitability to accommodate storage-based NbS, followed by conveyance (89%) and then retention-based NbS (68%). According to Senes *et al.*, (2021), about 14.01% area of the municipality of Caponago was presented as medium-low suitability in the context of storm-water management, where 42.93% as low suitability for green infrastructure construction. For all these types of NbS, a limited area (only 1-2%) of Glasgow city showed least suitability. So, it can be said that the highest proportion of Glasgow City has a satisfactory rate of moderate suitability for all three types of NbS, indicated in the opportunity sites map (Figure 4.7; a) Retention-based NbS, b) Storage-based NbS, c) Conveyance-based NbS).

However, Pacetti *et al.*, (2022) suggested that the site suitability range can be varied or limited for the cities depending on the dense of urbanization and environmental attributes. From the MCA-AHP analysis, for retention-based and storage-based NbS, Topography (Slope) was found to have the most influenced environmental criterion, where it was second most important criterion for conveyance-based NbS. Experts assigned proximity to flood prone areas as the most important criterion for conveyance-based NbS. 'Proximity to urban green area' found as the least important environmental criterion for all the types of NbS.

Land Cover defines an area covered by built-up areas, forests, wetlands, agriculture, and water types. It helps to identify areas where NbS may be particularly effective and increase the connectivity of urban ecosystem. 9% of restricted areas were defined based on Glasgow's land cover map, as it was assumed that the open water environments cannot be transformed into any form of NbS. Though many buildings can be used for green roofs or other forms of NbS, this study still considered the buildings as restricted because this study did not analyze the roof structure and size of buildings. A Euclidean distance was calculated to find suitable distance which will not harm the infrastructure. Within the land use data, the building data and the road data were analyzed with the same weight as the land cover from AHP result (Appendix IV). In terms of land cover for implementing the NbS, storage-based NbS has the highest optimal opportunity site in compared to other two types of NbS. Areas with dense vegetation and deep root systems of Broadleaf woodland and Coniferous woodland can allow infiltration and provide excellent natural retention capabilities. Christman et al., (2018) reported that, among highly suitable sites for green stormwater infrastructure implementation in Philadelphia (USA), between 5-22% area was non-urban (e.g., semi-natural, agricultural, and wooded area). This kind of area was considered as most suitable area for retention-based NbS, and for storage-based NbS, which can provide some conveyance benefits (least suitable) by intercepting and slowing down runoff, but their primary strength lies in retention rather than conveyance.

0-35% of imperviousness which can effectively allow storm water infiltration, so conveyance NbS measures are less necessary. These areas were considered optimally suitable for retention-based NbS (94%). Moderate imperviousness of an area can effectively captures and store stormwater runoff, while it can allow some infiltration, was considered as optimal for storage-based NbS (3%). The effectiveness of retention techniques may be significantly reduced due to the limited permeability of the site with high percentage of impermeable area (70-100%) and considered as optimally suitable for conveyance-based NbS which can effectively convey excess runoff, mitigating the risks of flooding.

Areas prone to flooding pose a challenge for cities as they put infrastructure, human life, and the environment at risk, making them more vulnerable to flooding. Implementation of NbS in proximity to surface flood prone area are basic toward surface run-off management and flood

mitigation for all types of NbSs. But areas with a distance below 100m prone to frequent flooding, ground may already be saturated. Implementing retention-based NbS in these areas may be challenging and negatively influenced by floodwater flow. These areas considered as low for retention and storage-based NbS while highly suitable for conveyance-based NbS (33%).

For proximity to existing drainage features, distance from the river channel and existing culverts were considered with the same weight as the proximity to existing drainage feature from AHP result (Appendix IV). The exact location of the river channel and the existing culvert were considered restricted. Implementing NbS near existing drainage features (e.g., existing culvert) can reduce runoff flow by improved retention, infiltration, evapotranspiration, and aquifer recharge, thus reducing the risk of culvert blockage and can improve the effectiveness by providing additional support and connectivity with the features. Implementing NbS based on conveyance far from the river channel can promote the dispersion of water over a larger area and reduce runoff volume to the river channel.

For all types of NbS, the highest proportion of Glasgow's territory was accounted as moderately suitable and the lowest proportion of the territory as least suitable areas for NbS creation which is related to soil textures. Soil texture defines overall infiltration, retention and percolation rates which are related to runoff speed and amount. Where the area has a high proportion of peaty and loamy soil, has higher infiltration rate and retention-based solutions may be more effective. 40% of land showed optimal suitability for retention-based NbS, where due to soil characterized with low infiltration potential, only 2.5% and 3.2% areas were reported as highly suitable for NbS in Conventry (UK) (Charlesworth et al., 2016) and Trondheim (Norway) (Muthanna et al., 2018) for SuDS creation. 11% of areas with, for example clayey loam, have slower infiltration rate than loamy soil, but higher than clayey soil, where storage-based intervention can be best option which will store the overland storm-water flow and allow infiltrate or reuse water. Areas with clay soils, water may run off more quickly, to manage flooding risk, conveyance -based intervention can redirect the overland storm-water flow and allow water to be dispersed over a larger area to take time for infiltration.

Where the land is flat/gentle (0-5°), NbSs can provide permeable surface with a slow water flow and can work delivering processes simulating subsurface flow wetlands (i.e., phytoremediation, e.g., Stefanakis (2019)). If a water retention NbS is on a flat surface, it may require less engineering work compared to a place with a steep slope and can be cost effective. From the AHP result, topography (slope) was found as the most important environmental criterion for storage-based NbS implementation. Areas with comparatively flat or gentle slopes (1-5°) considered as optimally suitable for implementing the NbS focused on stormwater retention (66%) and storage (66%). On the other hand, gentle slopes (5-15°) which will allow water flow was considered as most suitable for implementing conveyance-based NbS (28%).

NbS supports ecosystem connectivity by connecting existing green areas/infrastructures. Closeness to vegetated area helps retrieval native stock to develop the NbS, which reduces costs, and improves performance. Though Proximity to urban green areas was considered as the least important environmental criterion for all the types of NbS according to experts' opinion, the green network in Glasgow is strong which leads to good ecosystem connectivity. Intervention within 80 meters of open green areas can enhance the potential for capturing and retaining stormwater runoff, supporting infiltration and groundwater recharge and they were considered as highly suitable for retention-based NbS. Area within 200 meters of open green areas was ranked as optimally suitable for storage-based NbS and conveyance based NbS. In an urban setting like Glasgow, the development of NbSs would increase connectivity, provide habitat for animals, and even lessen socio-economic and environmental inequities, while managing the flood water.

While considering VDLs, about 2% land of total Glasgow city territory, (almost 90%, 89% of VDLs) was found moderately suitable for storage and conveyance-based NbS respectively and 1% of total Glasgow city territory (68% of vacant and derelict land) for retention-based NbS. 1% of total city territory (27% of VDLs) showed optimal suitability for implementing retention-based NbS and 0.1% (5% of vacant and derelict land) were found for both storage-based and conveyance-based NbS. When comparing with other study, this research demonstrate, utilizing VDLs in Glasgow city can present a significant chance to manage urban surface water flooding. For instant, Cheng *et al.*, identified that about 0.87 km² (50% of analyzed vacant land) suitable land surface can have a potential of reducing 29%, 25% runoff for a 2-year and 5-year design

storm respectively, where Glasgow found 5.05 km² (27% of VDLs) as optimal suitability of retention-based NbS.

It is important to note that, literature review was used to specify the environmental criteria as well as the ascribed appropriateness ratings. On the other hand, the experts' opinions were used to determine the relative importance of each environmental criterion in comparison to one another. Even though these methods have been used in earlier research (e.g., Gonzalez-Ollauri, Thomson, and Mickovski, 2020), the multi-criteria analysis process was based on only five responses from 32 invited experts, which indicates that, the relative importance on the criteria should be interpreted with cautious and further assessment is therefore advised, as the dependability and quality of input datasets, and the survey responses all had a direct influence on the final opportunity sites identification for NbS creation.

When it comes to the input datasets, the utilization of high-resolution data, specially for the DEM (Digital Elevation Model) creation has influenced considerably on the appropriate results. Despite few limitations, it should be noted that, while exploring the opportunity sites for three types of NbS, it found, Glasgow has free and ready access for the user like urban planners, sustainable decision-maker to all the data used here except the location of existing culverts, which made the method simple.

Chapter 06

6 CONCLUSIONS

While urban surface water flooding is happening frequently due to changing climate and ongoing urban development, overall, several case studies have shown that sustainable solutions like NbS can contribute a significant role in buffering communities from urban flood risk (Debele *et al.*, 2019). But NbS implementation is most of the time hindered due to lack of suitable site availability. The main goal of this study was to investigate potential opportunity sites in urban vacant and derelict land (VDL) for the implementation of Nature-based Solutions (NbS) against surface water runoff management, while Glasgow City was taken as the case study area. This study provides an overview of the general phenomenon of urban surface water flooding, sources and drivers of flooding intensified by climate change and rapid urbanizations. It also reviewed the trend and classification schemes of NbS, how NbS improves resilience and create a sustainable environment, environmental factors connected with their implementation, methodological framework for exploring suitable opportunity sites and gaps that limit the uptake of NbS for successful NbS creation.

On the light of conceptual understanding, this work, as explained before, divided the NbS into three separate categories according to their roles and investigated site suitability to deploy those NbS for effective storm-water management. The categories are **1)** Water retention based NbS (focused on slowing down and retain stormwater, allowing water to seep into the soil), **2)** Water storage NbS (focused on temporarily holding and storing stormwater, for reused or released in a controlled manner to sewers or receiving channels) and **3)** Water conveying NbS (focused on redirecting excess stormwater away from vulnerable areas and minimize the risk of overflow). A land suitability evaluation was done to identify potential places for all the three types of NbS implementation in Glasgow City's urban setting and further in 'vacant and derelict land.' This research was done mainly by collecting secondary data (both qualitative and quantitative) from literature review, official and open sources, primary information supported by experts' opinion. Relative importance of one attribute compared to another was carried out through the multi-criteria AHP analysis. Data processing and analysis were done using Geographic Information

System (GIS) software to map the identified possible opportunity sites in the Glasgow City region.

6.1: Key Conclusions

The following major conclusions were drawn accordingly from **conceptual understanding-**

- Flooding is a naturally occurring event, where urban surface water flooding is triggered by a physical process in the earth system and rapid urbanization, that has substantial negative influences on societies and ecosystems. In general, due to the complex connection of drivers and responses, surface floods are increasing over time, resulting in its potential increase of consequences. Thus, it needs a multi-functional management approach (Lennon *et al.*, 2014), which can be met through sustainable use of nature which is referred to as ‘Nature-based Solution (NbS)’ (Chiu *et al.*, 2021). Though this NbS is getting popular worldwide with different terminologies developed based on local conditions and histories of climate-risk management history, the basic concept of NbS in context of urban flood management is yet to get sufficient attention.
- Implementing NbS in urban areas is most of the time challenged by limited space, where utilizing VDLs can be a promising solution (Qiao *et al.*, 2018). But the success and effectiveness of these solutions heavily depend on the specific characteristics of the site where they are implemented. Thus, to maximize benefits and minimize the negative impacts of NbSs in managing stormwater effectively, site-specific tailoring is required (Cheng *et al.*, 2017) in urban VDL for finding potential and appropriate location for the interventions. Successful implementation of natural flood mitigation strategies in urban vacant area can improve water quality, habitat protection and enhance community value (Brody & Highfield, 2013), also can create room for public interaction and build ecosystem communication.
- This study was focused on seven important environmental criteria: Land Cover, Percentage of impermeable area (PIMP), Proximity to existing drainage features, Proximity to flood

prone area, Soil Texture, Topography and Proximity to urban green areas data. According to the AHP analysis, among the selected environmental criteria, surface slope and proximity to flood-prone areas had the most significant impact on the final suitability mapping for NbS, followed by percentage of impermeable area (PIMP) and soil texture. On the other hand, proximity to urban green areas can be considered as the least important criterion.

From the **contextualization**, it was found that,

- Glasgow has a satisfactory suitability to accommodate all the three types of NbS, where it showed maximum optimal suitability for retention-based rather than conveyance-based NbS and storage-based NbS. Glasgow city showed moderate suitability for storage-based and conveyance-based NbS over retention-based NbS.
- While considering vacant and derelict areas, almost 2% land of total Glasgow city territory was found moderately suitable for storage and conveyance-based NbS, and 1% for retention-based NbS. Though the optimal suitability for NbS in compared to overall city territory was found nearly 0.1%, but of 9.38 km² vacant and derelict land, 5% were considered as optimally suitable for both storage-based and conveyance-based NbS. Like the opportunity site in Glasgow city, vacant and derelict areas also showed almost no low suitability for NbS creation.
- To find a suitable location for any specific purpose, the methods considered showed fluency while considering multiple attributes at once. While in this study, site suitability analysis was carried out in context of urban surface water flood management, the following table 6.1 showed the SWOT analysis on the process of finding suitable opportunity site for NbS implementation using MCA-AHP and GIS application.

Table 6.1: SWOT analysis on the process of suitable site selection for NbS creation using MCA-AHP and GIS application.

Strengths	Opportunities
<ul style="list-style-type: none"> ● Nature-based solutions approach can have multiple benefits along with surface flood management, such as improved biodiversity and recreational opportunities. ● The use of AHP allows for a structured and systematic approach to decision-making in prioritizing and selecting suitable attributes effectively. ● ArcGIS is a powerful tool for spatial analysis, which provides accurate data visualization and the ability to integrate multiple layers of information for better decision-making. ● The project involves the integration of environmental science expertise, GIS, and decision-making methodologies, which can lead to more comprehensive and well-informed decisions. 	<ul style="list-style-type: none"> ● The successful identification of suitable NbS sites offers an opportunity to bolster the community's resilience against the growing threat of climate change like floods. ● Successful implementation can serve as a model for other regions facing similar flood risks, promoting sustainable flood management globally. ● This initiative opens doors for fruitful collaborations between academia, governmental bodies, research institutions, and environmental NGOs, uniting efforts towards a common goal and maximizing the project's impact fostering a holistic approach to flood mitigation.
Weaknesses	Threats
<ul style="list-style-type: none"> ● The success of the project heavily relies on the availability and quality of data for surface elevation model, flood risks, land use, and other relevant factors. Inaccurate or insufficient data could compromise the results. ● Implementing AHP and ArcGIS processes requires skilled experts and specialized software. A lack of resources and engagement from NbS experts during AHP survey could impede the project's progress and results. ● Despite its structured approach, MCA-AHP may still be influenced by the judgment and preferences of experts involved, leading to potential bias in site selection. 	<ul style="list-style-type: none"> ● Future changes in climate, land use, or urban development may introduce uncertainties that could impact the effectiveness and longevity of selected nature-based solutions. ● Limited financial and technical resources may impede the widespread adoption of MCA-AHP and ArcGIS analysis, particularly in smaller municipalities or developing regions. ● Working with spatial data and sensitive information in ArcGIS may raise privacy and security concerns, requiring robust data management and protection measures.

6.2: Limitations and Future Scope

Key limitations and further scope of research observed from this work are listed below-

- The question on how effective the selected VDLs could be at reducing volume of surface water runoff and the ownership authorization analysis of the available land in Glasgow city was out of this work. Further assessment of this issue might help to create a more fruitful decision in using VDLs for sustainable urban flood management.
- Future changes in climate, land use, or urban development may introduce uncertainties that could impact the effectiveness and longevity of selected nature-based solutions. Assessment of the uncertainty of future preservation of NbS measure would benefit for building long time flood management resilience.
- This study focused on seven environmental factors of Glasgow. Future studies should attempt to extend the analysis of more environmental criteria while considering site suitability for NbS.
- Limited research was found on the economic costs and benefits evaluation of NbS vs hard engineering structure when adopted for building resistance to urban floods. Therefore, research on cost-efficiency and advantages of NbS practice for flood management may provide its basic and clear understanding to promote NbS uptake.
- The creation of an NbS catalogue with uniform and comprehensive database and metadata models for NbS is among the other research needs. There is a substantial gap between the science, policy, and practice of NbS that calls for more research to investigate and create a bridge that can improve the commercial potential of NbS above simply grey methods.

Finally, though some academic researchers are talking about the effectiveness of nature-based solutions (NbS) in flood control, overall study on their adoption in planning and practice has been limited (Grace *et al.*, 2021; Moosavi *et al.*, 2021), especially due to lack of knowledge on site specification. The suitability of a place for NbS focused on specific role depends on the local context, including the topography, soil, and land use and most importantly availability of land in the area (Qiao *et al.*, 2018.). At the end, this research can contribute to the urban planners, sustainability decision-maker, environmental managers, and policy maker with the knowledge on urban flooding, nature-based solutions, sustainable flood risk reduction and available opportunity site selection analysis process while seeking to manage urban surface water flood and to enhance urban resilience.

REFERENCES:

Ashley, R., & Ashley, S., 2017. Urban surface water flooding: A review of causes and impacts. *Journal of Flood Risk Management*, 10(2), 195-211.

Byrne, L. B., Geraldi, N. R., & Walsh, C. J., 2021. Managing the water quality impacts of extreme rainfall events in urban streams with sustainable drainage systems. *Journal of Environmental Management*, 288, 112418. doi: 10.1016/j.jenvman.2021.112418

Charlesworth, S., Warwick, F. and Lashford, C., 2016. Decision-making and sustainable drainage: Design and scale. *Sustainability*, 8(8), p.782.

Cheng, C., Yang, Y.E., Ryan, R., Yu, Q. and Brabec, E., 2017. Assessing climate change-induced flooding mitigation for adaptation in Boston's Charles River watershed, USA. *Landscape and Urban Planning*, 167, pp.25-36.

Cheng, W., Chen, H., Zhou, X., Wang, R., Zeng, C., & Lu, X., 2017. Green infrastructure and ecosystem services in the urban area: a review of the international literature. *Frontiers of Environmental Science & Engineering*, 11(2), 1-11. <https://doi.org/10.1007/s11783-017-0901-6>.

Chiu, Y.Y., Raina, N. and Chen, H.E., 2021. Evolution of flood defense strategies: Toward nature-based solutions. *Environments*, 9(1), p.2.

Christman, Z., Meenar, M., Mandarano, L. and Hearing, K., 2018. Prioritizing suitable locations for green stormwater infrastructure based on social factors in Philadelphia. *Land*, 7(4), p.145.

CIRIA., 2015. The SuDS Manual (C753). Retrieved from <https://www.ciria.org/ItemDetail?iProductCode=C753&Category=BOOK>

Çoban, İ., 2021. *Source-pathway-receptor-consequence conceptual model for flooding and tsunami at the ayamama river and coastal area* (Master's thesis, Middle East Technical University).

Cohen-Shacham, E.; Walters, G.; Janzen, C.; Maginnis, S., 2016. *Nature-Based Solutions to Address Societal Challenges*; IUCN: Gland, Switzerland.

Dhakal, K.P. and Chevalier, L.R., 2016. Urban stormwater governance: The need for a paradigm shift. *Environmental management*, 57, pp.1112-1124.

Debele, S.E., Kumar, P., Sahani, J., Marti-Cardona, B., Mickovski, S.B., Leo, L.S., Porcù, F., Bertini, F., Montesi, D., Vojinovic, Z. and Di Sabatino, S., 2019. Nature-based solutions for hydro-meteorological hazards: Revised concepts, classification schemes and databases. *Environmental Research*, 179, p.108799.

Department for Communities and Local Government, 2018. National Planning Policy Framework. Retrieved from <https://www.gov.uk/government/publications/national-planning-policy-framework--2>

Faraj, B.A. and Hamaamin, Y.A., 2023. Optimization of Locations for Bioswales Stormwater Management Using BMP Siting Tool-Case Study of Sulaymaniyah City-KRG-Iraq. *Journal of Engineering*, 29(1), pp.76-92.

Ferreira, C.S., Kalantari, Z., Hartmann, T. and Pereira, P., 2021. Introduction: Nature-Based Solutions for Flood Mitigation. In *Nature-Based Solutions for Flood Mitigation: Environmental and Socio-Economic Aspects* (pp. 1-7). Cham: Springer International Publishing.

Ferreira, C.S., Kalantari, Z., Seifollahi-Aghmiuni, S., Ghajarnia, N., Rahmati, O. and Solomun, M.K., 2021. Rainfall-runoff-erosion processes in urban areas. In *Precipitation* (pp. 481-498). Elsevier.

Glasgow City Council, 2021. Glasgow Climate Adaptation Plan 2022-2030. Glasgow, UK.

Gonzalez-Ollauri, A. and Mickovski, S.B., 2017. Plant-Best: A novel plant selection tool for slope protection. *Ecological Engineering*, 106, pp.154-173.

James D Miller, Gianni Vesuviano, John R Wallbank, David H Fletcher, Laurence Jones, 2023. Hydrological assessment of urban Nature-Based Solutions for urban planning using Ecosystem Service toolkit applications, *Landscape and Urban Planning*, Volume 234, 104737, ISSN 0169-2046, <https://doi.org/10.1016/j.landurbplan.2023.104737>.

Jia, H., He, Y., & Liu, Y., 2019. Assessment of urban surface flood vulnerability based on an integrated framework of urbanization and climate change. *Science of the Total Environment*, 646, 1329-1342.

Kabisch, N., 2019. Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, 24(2), 1-17.

Kabisch, N., Frantzeskaki, N. and Hansen, R., 2022. Principles for urban nature-based solutions. *Ambio*, 51(6), pp.1388-1401.

Kapetas, L. and Fenner, R., 2020. Integrating blue-green and grey infrastructure through an adaptation pathways approach to surface water flooding. *Philosophical Transactions of the Royal Society A*, 378(2168), p.20190204.

Köppen, W., 1884. The warm zones of the earth, considered according to the duration of the hot, temperate, and cold time and according to the effect of heat on the organic world. *Meteorological Journal*, 1(21), pp.5-226.

Lashford, C., Rubinato, M., Cai, Y., Hou, J., Abolfathi, S., Coupe, S., Charlesworth, S. and Tait, S., 2019. SuDS & sponge cities: a comparative analysis of the implementation of pluvial flood management in the UK and China. *Sustainability*, 11(1), p.213.

Lennon, M., Scott, M. and O'Neill, E., 2014. Urban design and adapting to flood risk: the role of green infrastructure. *Journal of Urban Design*, 19(5), pp.745-758.

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Li, Y., Wang, L., Yang, X., & Yu, R., 2021. Impacts of Sustainable Drainage Systems (SuDS) on the reduction of urban flood volume and frequency: A case study of Chengdu, China. *Water*, 13(6), 784. doi: 10.3390/w13060784.

Liquete, C., Udias, A., Conte, G., Grizzetti, B., & Masi, F., 2016. Integrated valuation of a nature-based solution for water pollution control. Highlighting hidden benefits. *Ecosystem Services*, 22, 392-401.

Lohpaisankrit, W., Hiranwattananon, T., & Tumma, N., 2021. Application of a rainfall-runoff model for flood generation in the Huai Sangka catchment, Thailand. *Engineering and Applied Science Research*, 48(2), 121–130.

Mensah, H. and Ahadzie, D.K., 2020. Causes, impacts and coping strategies of floods in Ghana: A systematic review. *SN Applied Sciences*, 2, pp.1-13.

Met Office., 2022. Glasgow Climate Averages. Available at: <https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages>.

Miller, J. D., & Miller, J. E., 2016. Urbanization and flood response: Lessons from Houston. *Journal of Contemporary Water Research & Education*, 157(1), 4-12.

Mubeen, A., Ruangpan, L., Vojinovic, Z., Sanchez Torrez, A. and Plavšić, J., 2021. Planning and suitability assessment of large-scale nature-based solutions for flood-risk reduction. *Water Resources Management*, 35(10), pp.30

Muthanna, T.M., Sivertsen, E., Kliewer, D. and Jotta, L., 2018. Coupling field observations and geographical information system (GIS)-based analysis for improved sustainable urban drainage systems (SUDS) performance. *Sustainability*, 10(12), p.4683.

Newman, G., Dongying, L., Rui, Z. and Dingding, R., 2019. Resilience through regeneration: The economics of repurposing vacant land with green infrastructure. *Landscape architecture frontiers*, 6(6), p.1

O'Donnell EC, Thorne CR.,2020. Drivers of future urban flood risk.Phil.Trans. R. Soc. A378: 20190216. <http://dx.doi.org/10.1098/rsta.2019.0216>

Pacetti, T., Cioli, S., Castelli, G., Bresci, E., Pampaloni, M., Pileggi, T. and Caporali, E., 2022. Planning Nature Based Solutions against urban pluvial flooding in heritage cities: A spatial multi criteria approach for the city of Florence (Italy). *Journal of Hydrology: Regional Studies*, 41, p.101081.

Pina, R., Ochoa-Rodriguez, S., Simões, N., Mijic, A., Sa Marques, A., and Maksimovic, Č., 2014. Semi-distributed or fully distributed rainfall-runoff models for urban pluvial flood modelling?.

Qiao, X.J., Kristoffersson, A. and Randrup, T.B., 2018. Challenges to implementing urban sustainable stormwater management from a governance perspective: A literature review. *Journal of Cleaner Production*, 196, pp.943-952.

Qin, Y., 2020. Urban flooding mitigation techniques: A systematic review and future studies. *Water*, 12(12), p.3579.

Sahani, J., Kumar, P., Debele, S., Spyrou, C., Loupis, M., Aragao, L., & Di Sabatino, S. 2019. Hydro-meteorological risk assessment methods and management by nature-based solutions. *Science of the Total Environment*, 696, 133936.

Sanches, P.M., and Pellegrino, P.R.M., 2016. Greening potential of derelict and vacant lands in urban areas. *Urban Forestry & Urban Greening*, 19, pp.128-139.

Sánchez, R., José, E.S., Feroso, J., Gómez, S. and González, M., 2023. Types of nature-based solutions for water, their functions and suitability. In *Regional Perspectives of Nature-based Solutions for Water: Benefits and Challenges* (pp. 11-34). Cham: Springer International Publishing.

Scottish Government, 2010. Designing Streets: A Policy Statement for Scotland. <https://www.transport.gov.scot/media/9839/designing-streets-policy-statement.pdf>

Scottish Government, 2011. The Water Environment (Controlled Activities) (Scotland) Regulations 2011. <https://www.legislation.gov.uk/ssi/2011/209/contents/made>

Scottish Government, 2021. Designing Streets: A Policy Statement and Design Guidance for Scotland. <https://www.transport.gov.scot/media/16284/designing-streets-2021.pdf>

Scottish Government, 2021. Transforming Our Water: Proposals for Legislation to Modernise the Management of Surface Water. <https://www.gov.scot/publications/transforming-water-proposals-legislation-modernise-management-surface-water/pages/6/>

Senes, G.; Ferrario, P.S.; Cirone, G.; Fumagalli, N.; Frattini, P.; Sacchi, G.; Valè, G., 2021. Nature-Based Solutions for Storm Water Management—Creation of a Green Infrastructure Suitability Map as a Tool for Land-Use Planning at the Municipal Level in the Province of Monza-Brianza (Italy). *Sustainability*, 13, 6124. <https://doi.org/10.3390/su13116124>

UK Government, 2021. Non-Statutory Technical Standards for SuDS. Retrieved from <https://www.gov.uk/government/publications/non-statutory-technical-standards-for-sustainable-drainage-systems>.

Warner, D., 2023. Nature Based Solutions for Water Management in England: Contribution to Biodiversity Net Gain in Urban Areas. In *Regional Perspectives of Nature-based Solutions for Water: Benefits and Challenges* (pp. 67-99).

WHITE, I., 2013. The more we know, the more we know we do not know: Reflections on a decade of planning, flood risk management and false precision. *Planning Theory and Practice*, 14, 106-114.

World Bank, 2021. A Catalogue of Nature-based Solutions for Urban Resilience. Washington, D.C. World Bank Group

Yao, Y.; Zhang, S.; Shi, Y.; Xu, M.; Zhang, J.; Zhang, Y.; Zhao, J., 2021. Landscape Pattern Change of Impervious Surfaces, and Its Driving Forces in Shanghai during 1965–2010. *Water* 2021, 13, 1956. <https://doi.org/10.3390/w13141956>

Alberti, M., et al. (2018). A framework for urban ecology: advancing urban ecosystem science and management. *Frontiers in Ecology and the Environment*, 16(1), 1-9.

Kabisch, N., et al. (2019). Nature-based solutions to climate change mitigation and adaptation in urban areas: perspectives on indicators, knowledge gaps, barriers, and opportunities for action. *Ecology and Society*, 24(2), 1-17.

Zhang, Y., Li, Y., Li, X., Li, B., & Li, J., 2019. Application of AHP in identifying suitable locations for sponge city construction in urban areas. *Journal of Cleaner Production*, 234, 148-157.

Zhou, Q., Leng, G., Su, J., & Ren, Y., 2018. Comparison of urbanization and climate change impacts on urban flood volumes: Importance of urban planning and drainage adaptation. *Science of The Total Environment*. doi:10.1016/j.scitotenv.2018.12.184

Zölch, T., Henze, L., Keilholz, P. and Pauleit, S., 2017. Regulating urban surface runoff through nature-based solutions—an assessment at the micro-scale. *Environmental research*, 157, pp.135-144.

Appendix I

Questionnaires for three types of NbSs sent to experts and one sample response

“IDENTIFYING POTENTIAL OPPORTUNITY SITES in vacant and derelict land for NATURE-BASED SOLUTIONS (NBS) against urban flooding.”

This questionnaire aims to collect expert input on the relative importance of different environmental criteria related to siting water retention NBS in urban vacant and derelict land.

Water Retention NBS involve holding storm-water in the ground whilst reducing surface runoff and providing other benefits (e.g., urban greenery, host wildlife, recreational opportunities etc.). For example-



INSTRUCTIONS

Twelve Environmental criteria relevant to siting water retention NBS were shortlisted: [Environmental criteria for water retention Nbs.docx](#)

Please, following the relative importance scale and example provided, rate the relative importance of one criterion respect to another by completing the pairwise matrix below.

Please, fill matrix comparing criteria featuring in the rows with those appearing in the columns.

Scale	Numerical Rating (More Important)	Reciprocal (Less Important)
Strongly	5	1/5
Moderately	3	1/3
Equally	1	1

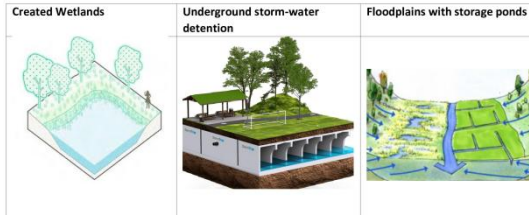
Attributes	Land cover	Soil Texture	Topography
Land cover	1	5	1
Soil Texture		1	1/5
Topography			1

- Land cover strongly more important than soil texture – score given = 5
- Land cover is equally important than topography – score given = 1
- Soil texture is strongly less important than topography – score given = 1/5

“IDENTIFYING POTENTIAL OPPORTUNITY SITES in vacant and derelict land for NATURE-BASED SOLUTIONS (Nbs) against urban flooding.”

This questionnaire aims to collect expert input on the relative importance of different environmental criteria related to siting water storage Nbs in urban vacant and derelict land.

Water storage Nbs involves storing stormwater runoff to provide water source for non-potable uses or allow water to infiltrate or evaporate whilst providing other benefits (e.g., urban greenery, host wildlife, recreational opportunities etc.). For example-



INSTRUCTIONS

Twelve Environmental criteria relevant to siting water storage Nbs were shortlisted: [Environmental criteria for water storage Nbs.docx](#)

Please, following the relative importance scale and example provided, rate the relative importance of one criterion respect to another by completing the pairwise matrix below.

Please, fill matrix comparing criteria featuring in the rows with those appearing in the columns.

Scale	Numerical Rating (More Important)	Reciprocal (Less Important)
Strongly	5	1/5
Moderately	3	1/3
Equally	1	1

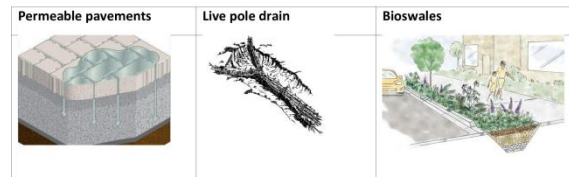
Attributes	Land cover	Soil Texture	Topography
Land cover	1	5	1
Soil Texture		1	1/5
Topography			1

- Land cover strongly more important than soil texture – score given = 5
- Land cover is equally important than topography – score given = 1
- Soil texture is strongly less important than topography – score given = 1/5

“IDENTIFYING POTENTIAL OPPORTUNITY SITES in vacant and derelict land for NATURE-BASED SOLUTIONS (NBS) against urban flooding”

This questionnaire aims to collect expert input on the relative importance of different environmental criteria related to siting water conveyance NBS in urban vacant and derelict land.

Water conveyance NBS strive to convey stormwater runoff away from flood-prone areas whilst providing other benefits (e.g., urban greenery, host wildlife, shade provision etc.). For example-



INSTRUCTIONS

Seven Environmental criteria relevant to siting water conveyance were shortlisted: [Environmental criteria for water conveyance Nbs.docx](#).

Please, following the relative importance scale and example provided, rate the relative importance of one criterion respect to another by completing the pairwise matrix below.

Please, fill matrix comparing criteria featuring in the rows with those appearing in the columns.

Scale	Numerical Rating (More Important)	Reciprocal (Less Important)
Strongly	5	1/5
Moderately	3	1/3
Equally	1	1

Attributes	Land cover	Soil Texture	Topography
Land cover	1	5	1
Soil Texture		1	1/5
Topography			1

- Land cover strongly more important than soil texture – score given = 5
- Land cover is equally important than topography – score given = 1
- Soil texture is strongly less important than topography – score given = 1/5

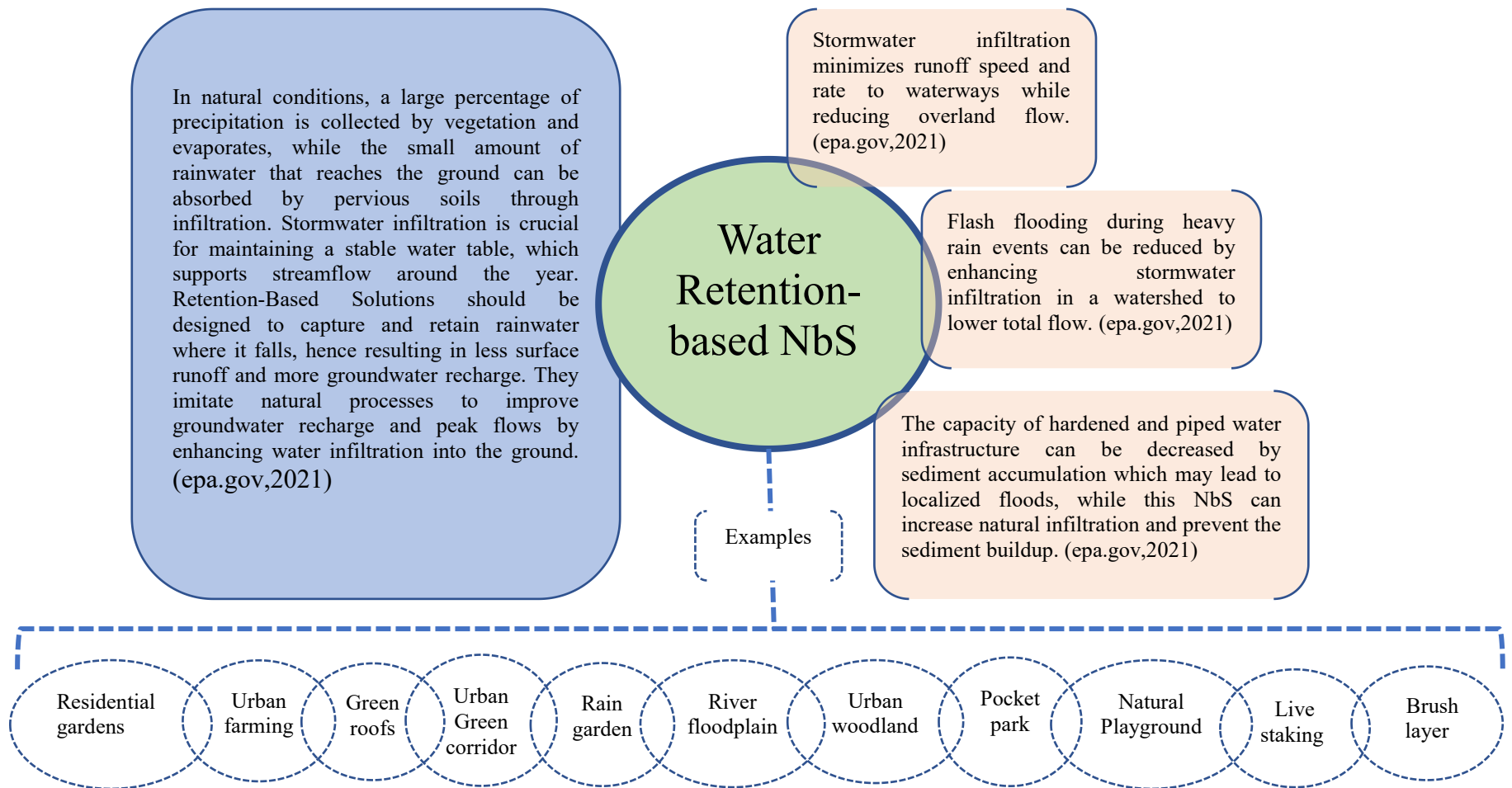
Please fill the following matrix of pair-wise relative importance of environmental Criteria-

Environmental Criteria	Land Cover	Percentage of impermeable area (PIMP)	Proximity to existing Drainage features	Proximity to flood prone area	Soil Texture	Topography	Proximity to urban green areas
Land Cover	1						
Percentage of impermeable area (PIMP)		1					
Proximity to existing drainage features			1				
Proximity to flood prone area				1			
Soil Texture					1		
Topography						1	
Proximity to urban green areas							1

Environmental Criteria	Land Cover	Percentage of impermeable area (PIMP)	Proximity to existing Drainage features	Proximity to flood prone area	Soil Texture	Topography	Proximity to urban green areas
Land Cover	1	1/5	3	5	1	1/5	3
Percentage of impermeable area (PIMP)	5	1	3	5	1	1/5	3
Proximity to existing drainage features	1/3	1/3	1	5	1	3	3
Proximity to flood prone area	1/5	1/5	1/5	1	1	3	1
Soil Texture	1	1	1	1	1	1	1
Topography	5	5	1/3	1/3	1	1	1
Proximity to urban green areas	1/3	1/3	1/3	1	1	1	1

Appendix II

Detail on three classes of NbSs, functions in surface water flood management and examples-



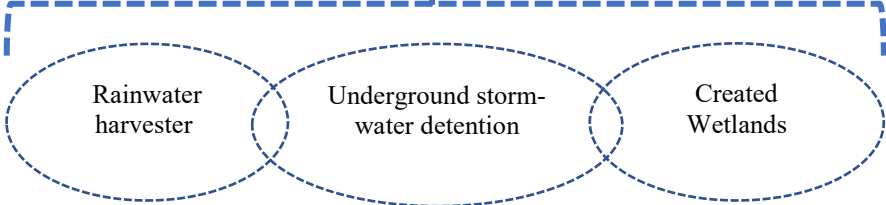
Storage-Based Solutions aim to temporarily store rainwater and slowly release it over time. This helps in reducing the immediate impact of heavy rains on the stormwater system and prevents flash floods. This can be an useful tool for capturing the increased volume and rate of surface water runoff and channeled water from upland impervious surfaces and buildings. Localized floodwater storage detains and retains floodwater, which can provide temporary storage of water for future use or slowly release in watercourse as the flood risk decreases. (epa.gov,2021)

Water Storage-based NbS

Successful floodwater storage-based NbS protects urbanizing floodplains and mitigates localized flooding by storing rainfall and keeping water from burdening pipe networks or prevent damage caused by pooling in streets or basements.(epa.gov,2021)

Adequate floodwater storage allows for groundwater recharge and the overall regulation of water flows, reducing instances of flooding. (epa.gov,2021)

Examples



Water from rain events, snow and ice melt, and natural springs is collected and conveyed naturally according to the laws of hydrodynamics. While due to human intervention, these systems can no work to efficiently move water across the landscape, conveyance-Based Solutions can work by safely transporting excess water from one place to another. They help manage the flow of stormwater, reducing the speed and volume of water that reaches waterways and stormwater infrastructure. (epa.gov,2021)

Water Conveyance -based NbS

Decreasing the amount of runoff that reaches streams can keep stream flow rates within the stream channels conveyance capacity and prevent downstream flood events. (epa.gov,2021)


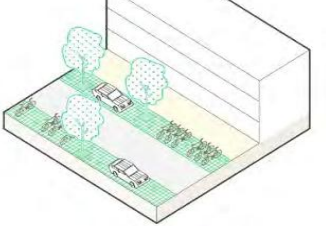
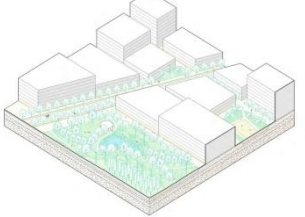
Waterways are more resilient alternatives to hardened infrastructure such as pipes and culverts that are more susceptible to failure during flood and earthquake events. (epa.gov,2021)

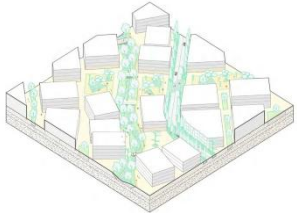

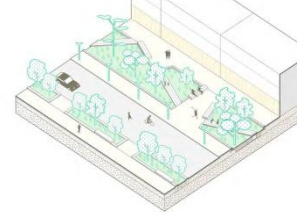
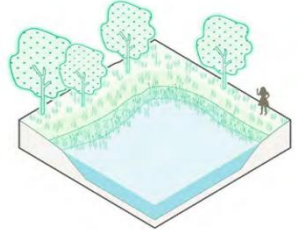
Examples


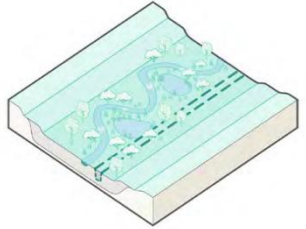
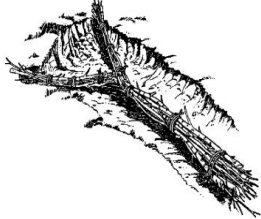
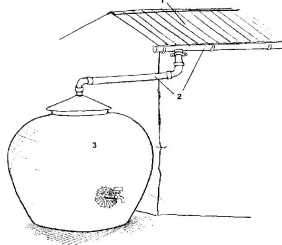
- Permeable pavements
- Live pole drain
- Bio-swal
- Vegetated riprap/ Cribwal
- River re-meandering

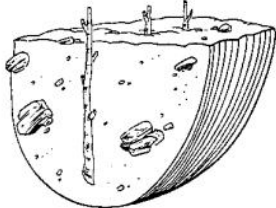
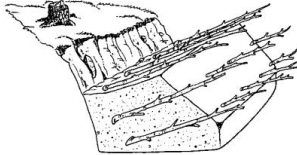
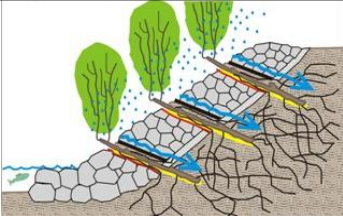
Appendix III

Different NbS and how they work for urban flood management

NbS	Pictorial view	How it helps
Green roofs		<ul style="list-style-type: none"> ● Reduce the amount of runoff by evapo-transporating and absorbing rainfall. ● Reduce the amount of water that enters the drainage system
Permeable pavements	 <p data-bbox="621 984 982 1016">(Source: World Bank. 2021)</p>	<ul style="list-style-type: none"> ● Allow water to soak through them, ● Reducing the amount of runoff that enters the drainage system
Urban open green area (Natural Playground/ pocket park/residential gardens/Urban farming/ Urban woodland)	 <p data-bbox="621 1253 982 1286">(Source: World Bank. 2021)</p>	<ul style="list-style-type: none"> ● Reduce the amount of runoff by intercepting and absorbing rainfall as well as by enhanced evapo-transporation ● Can retain rainwater ● Reduce the amount of water that enters the drainage system

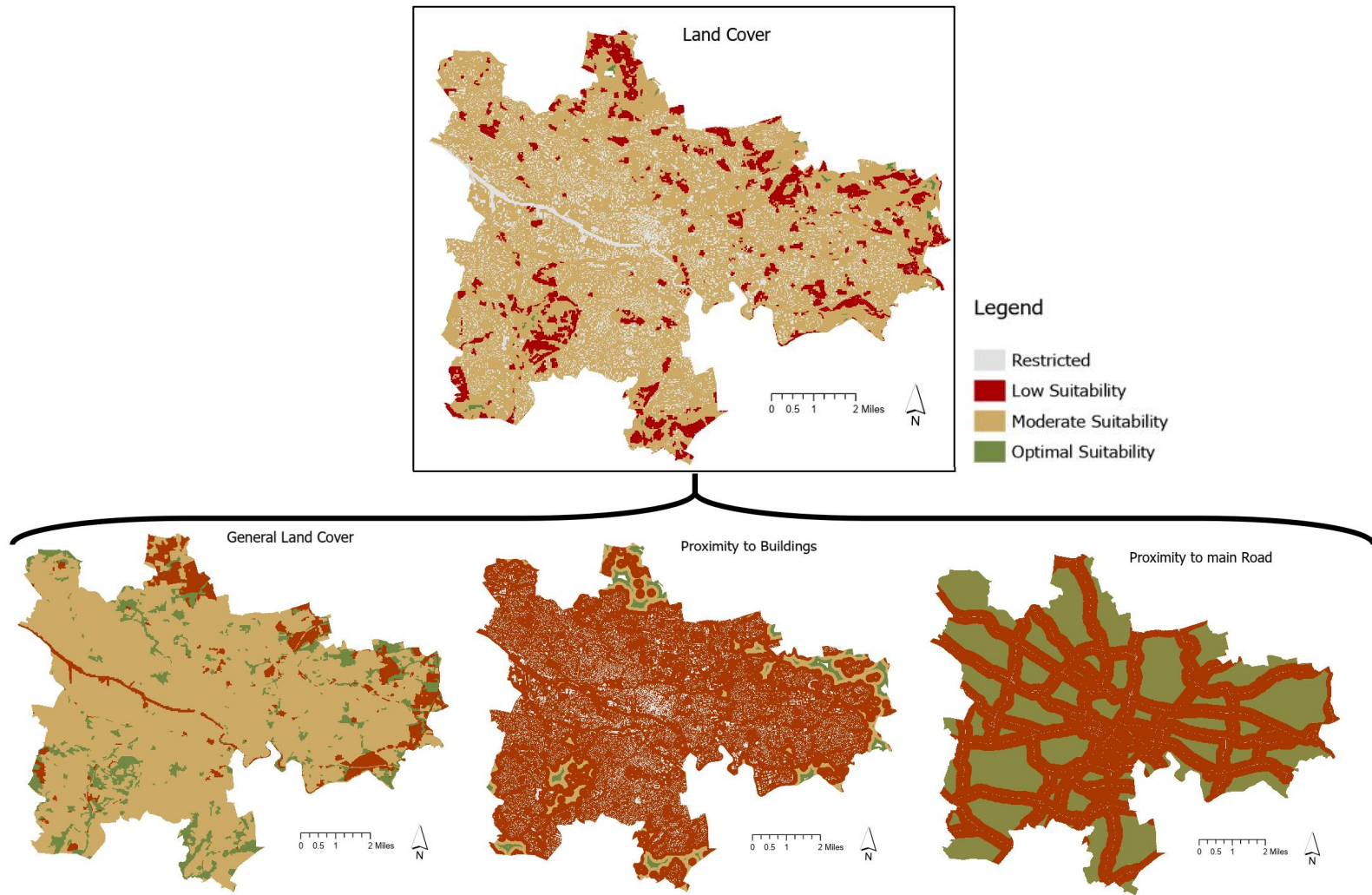
<p>Urban Green corridor</p>	 <p>(Source: World Bank. 2021)</p>	<ul style="list-style-type: none"> ● Reduce the amount of runoff by intercepting and absorbing rainfall as well as by enhanced evapotranspiration rate ● Improve connectivity of runoff with drainage system
<p>Rain gardens</p>		<ul style="list-style-type: none"> ● Capture and store rainwater during heavy rainfall ● Allow water to infiltrate into the ground. ● Reduce the amount of runoff by intercepting and absorbing rainfall as well as by enhanced evapotranspiration rate ● The roots layer can absorb and retain water, thus reducing runoff.
<p>Bio-swales</p>	 <p>(Source: World Bank. 2021)</p>	<ul style="list-style-type: none"> ● Help to reduce the velocity of runoff, ● Allow water to infiltrate into the ground. ● Reduce the amount of runoff by intercepting and absorbing rainfall as well as by enhanced evapotranspiration rate ● The roots layer can absorb and retain water, thus reducing runoff.
<p>Created Wetlands</p>	 <p>(Source: World Bank. 2021)</p>	<ul style="list-style-type: none"> ● Absorb large amounts of water like natural sponges ● Collect stormwater from surrounding area and detain water for a long period of time

<p>Floodplain</p>	 <p>(Source: World Bank, 2021)</p>	<ul style="list-style-type: none"> ● Absorb water during high water events. ● Provide space for water to store and flow during high water events.
<p>River re-meandering</p>	 <p>(Source: World Bank, 2021)</p>	<ul style="list-style-type: none"> ● Allows the river to flow more freely and naturally, it can deposit sediment and create new habitats that can absorb and store floodwater ● Slow down the water flow and increase the volume of water stored in the river channel.
<p>Live pole drain</p>	 <p>(Polster, 1999)</p>	<ul style="list-style-type: none"> ● Reduce the risk of flooding by capturing and redirecting stormwater runoff during heavy rainfall events and increasing evapotranspiration. ● Slow down and filter the stormwater flow before the water is discharged.
<p>Rainwater harvester</p>	 <p>(Worm et Hattum, 2006)</p>	<ul style="list-style-type: none"> ● By capturing and using (for irrigation, flushing toilets, or other non-potable uses) rainwater, it helps to reduce the amount of storm-water runoff that enters the sewer system.

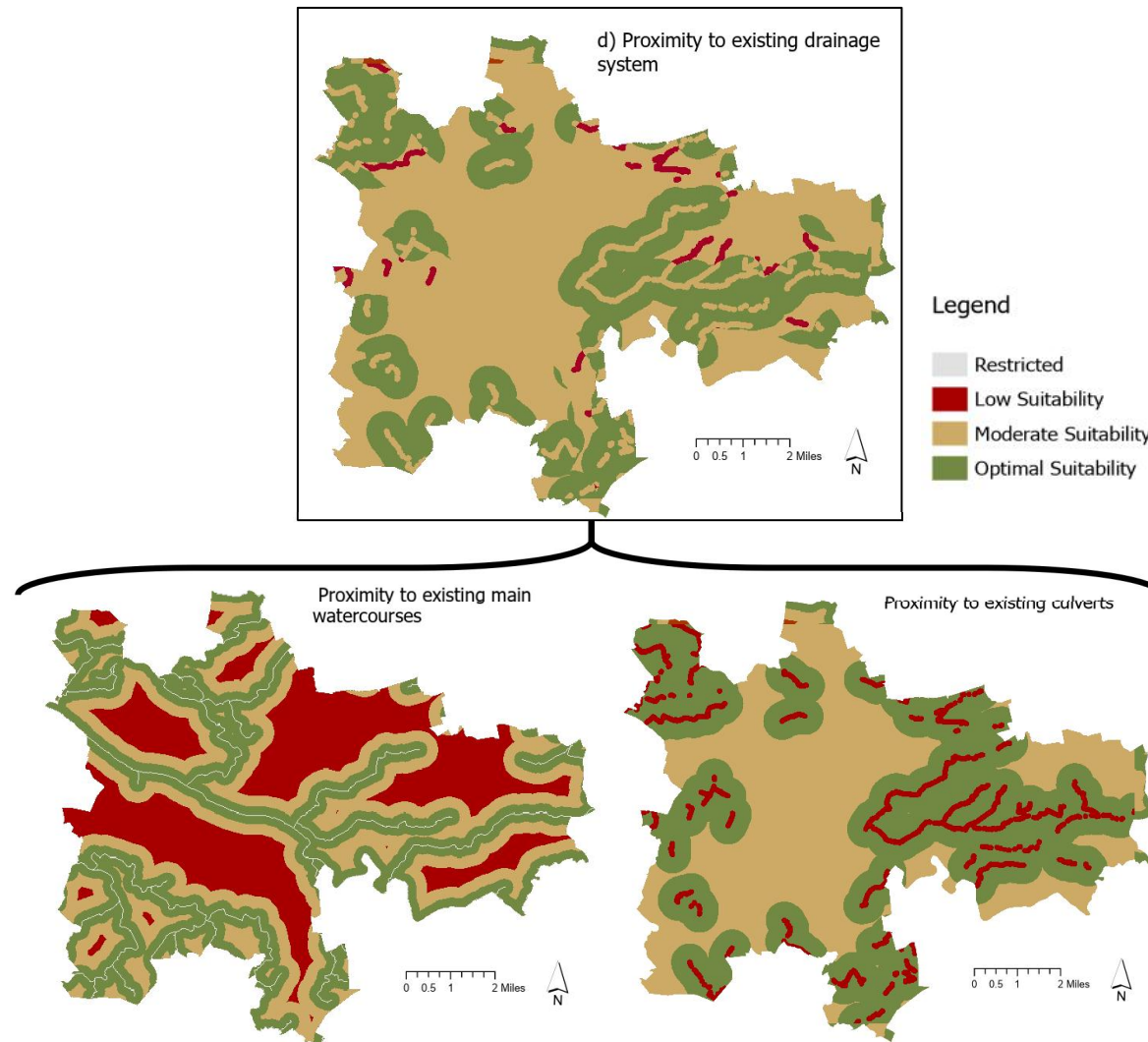
<p>Live staking</p>	 <p>(Polster, 1999)</p>	<ul style="list-style-type: none"> ● The cuttings of live staking can root and grow into new plants, creating a natural barrier that helps to slow the movement of floodwaters. ● The roots layer can absorb and retain water, so reduce runoff.
<p>Brush layer</p>	 <p>(Polster, 1999)</p>	<ul style="list-style-type: none"> ● Attenuating the stormwater runoff. ● Reduce the risk of flooding by capturing and redirecting stormwater runoff during heavy rainfall.
<p>Vegetated Cribwalls</p>	<p>riprap/</p> 	<ul style="list-style-type: none"> ● The layer of riprap stones and boulders can act as a physical barrier to slow down and absorb the energy of floodwaters. ● The vegetation layer planted on top of the riprap can help to absorb water and reduce surface runoff. ● Allow water to infiltrate into the soil, which can help reduce the amount of surface runoff and recharge groundwater aquifers.

Appendix IV

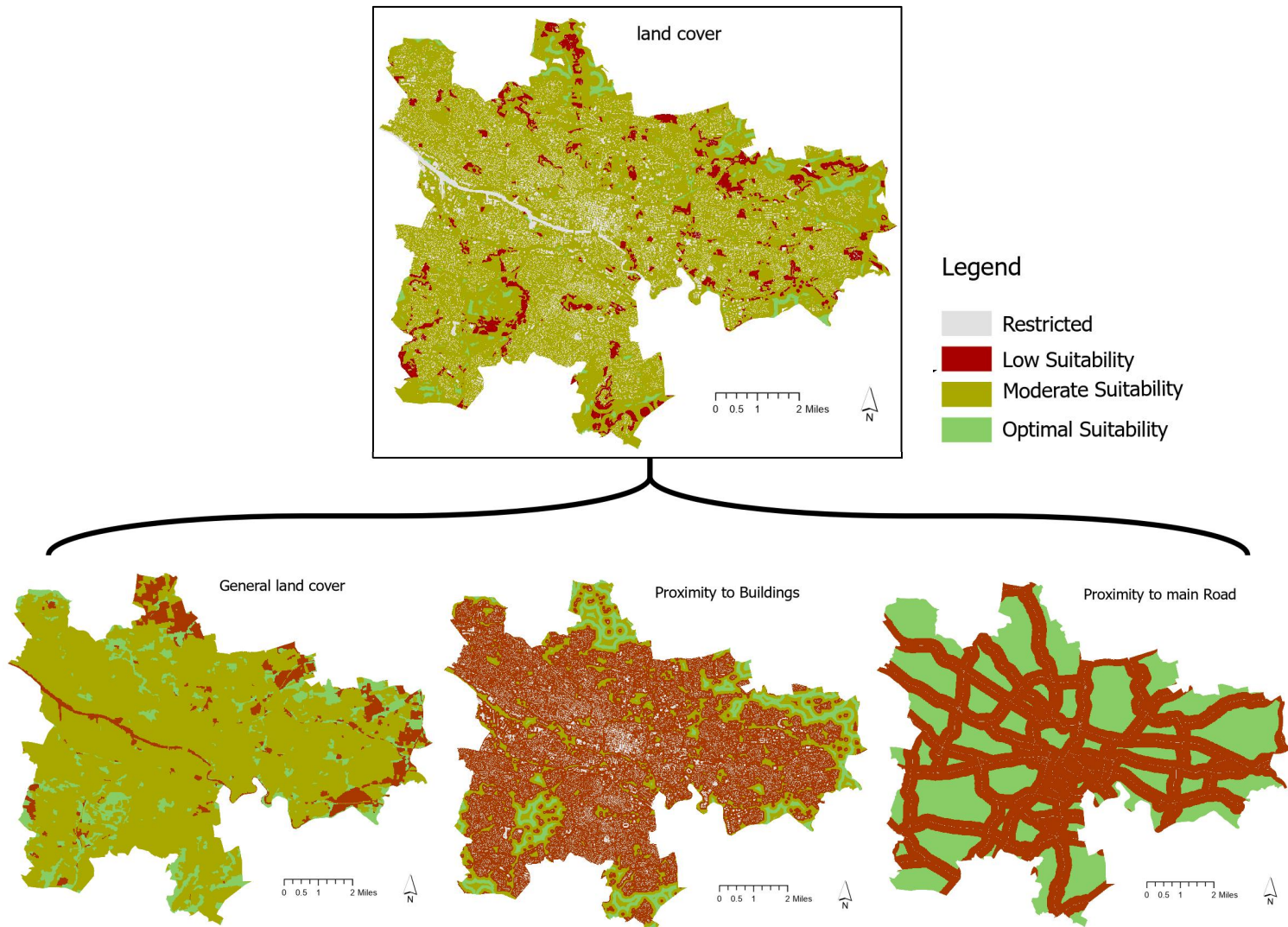
A) Subdivisions of Land Cover Data analysis for Retention-based NbS



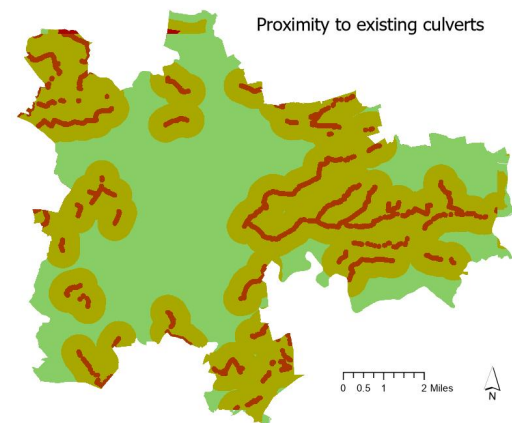
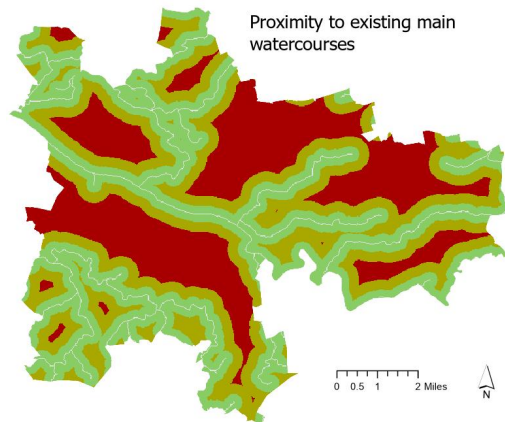
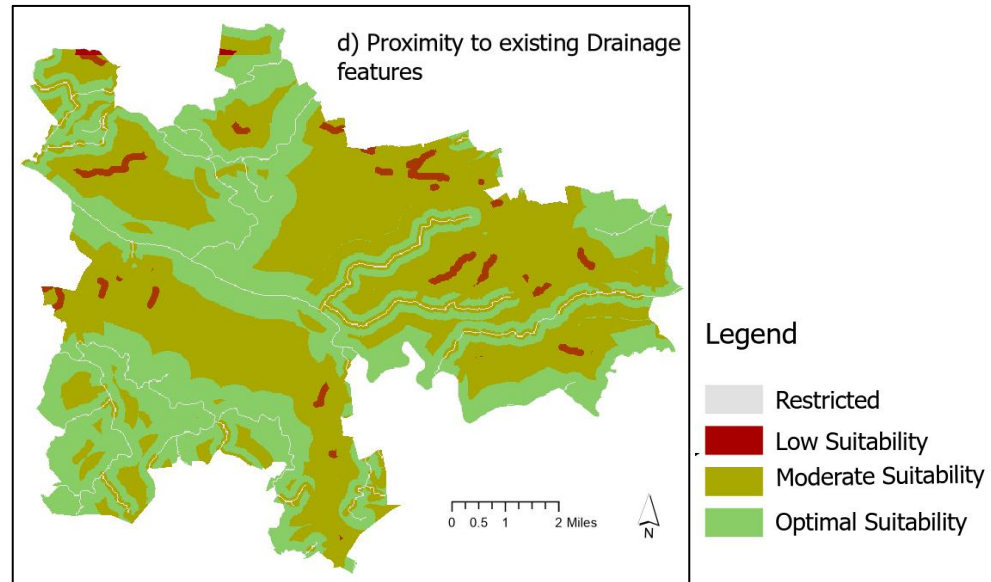
B) Subdivisions of Proximity to existing drainage system data analysis for Retention-based Nbs



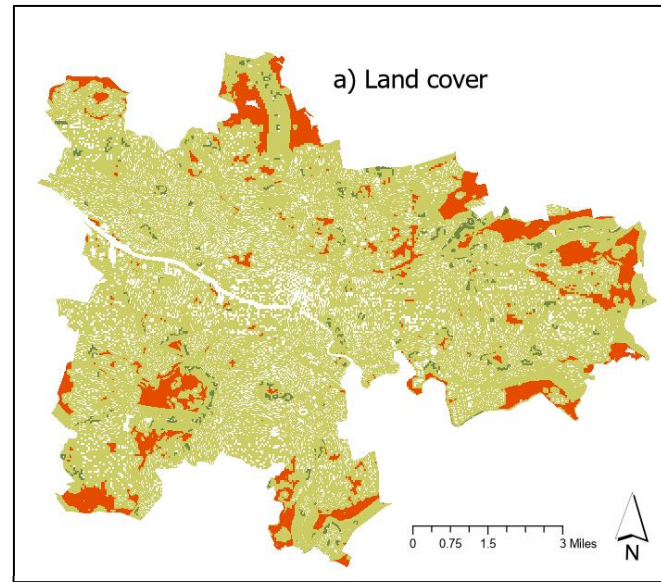
C) Subdivisions of Land Cover data analysis for Storage-based Nbs



D) Subdivisions of Proximity to existing drainage system data analysis for Storage-based NbS

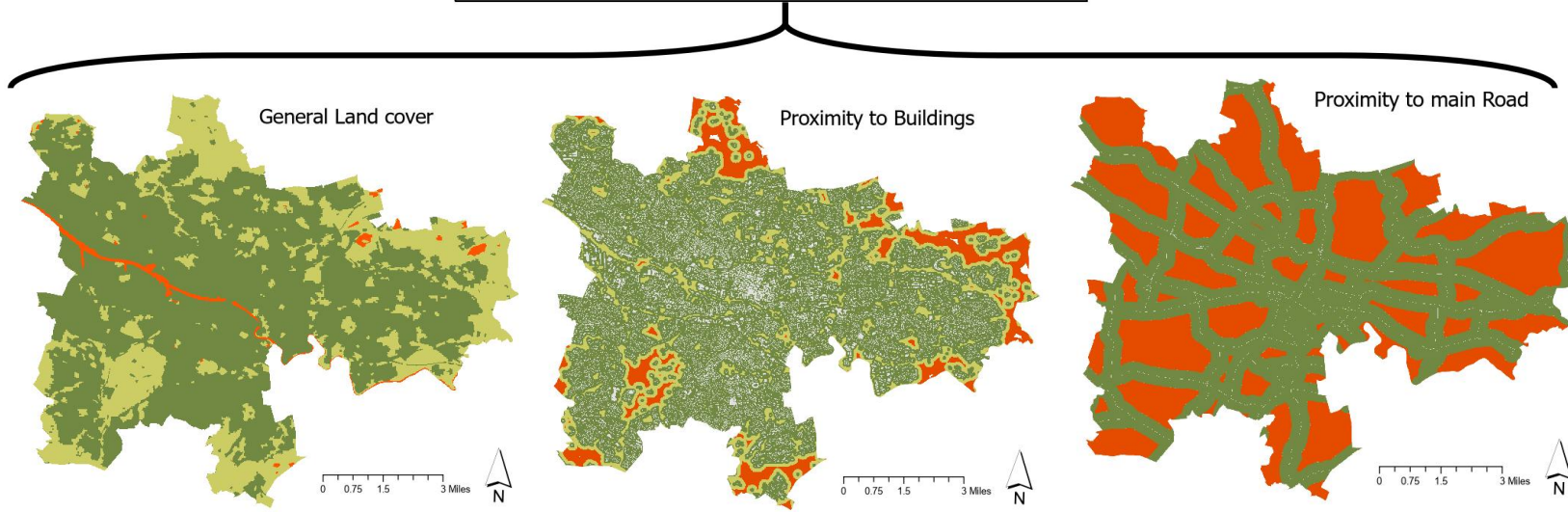


E) Subdivisions of Land Cover data analysis for Conveyance-based Nbs



Legend

- Restricted
- Low Suitability
- Moderate Suitability
- Optimal Suitability



F) Subdivisions of Proximity to existing drainage system data analysis for Conveyance-based NbS

