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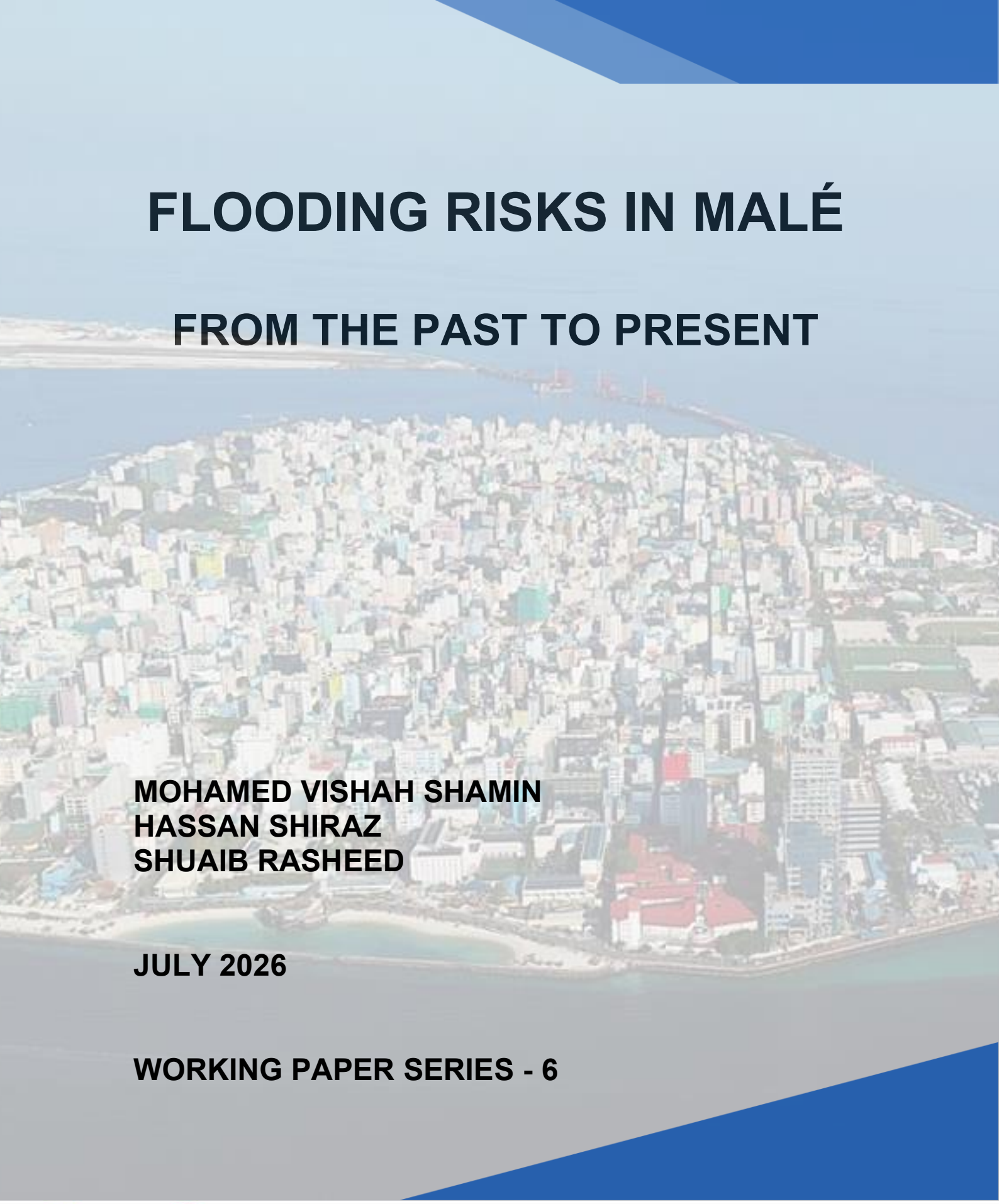
GRANT / SUBVENTION: - RESILIENCE TO CLIMATE VULNERABILITY AND ENVIRONMENTAL RISK (RECOVER) WITH A FOCUS ON SMALL ISLANDS

FLOODING RISKS IN MALÉ

FROM THE PAST TO PRESENT



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COVER PHOTO

Photo of Malé, capital of Maldives
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AUTHORS' DECLARATION

The authors of this publication declare that the views and opinions expressed herein are solely those of the authors and do not necessarily reflect the official policies or positions of the RECOVER Project, its affiliated institutions, the FCDO, IDRC or the governments of the United Kingdom or Canada.

The content provided is based on the authors' analysis, research, and interpretation, and any errors or omissions are the responsibility of the authors. The authors declare that there are no conflicts of interest related to this publication.

This working paper is a slightly revised version of the thesis submitted by Mohamed Vishah Shamin to The Maldives National University (MNU) in partial fulfilment of the requirements for the Bachelor of Civil Engineering (Honours) degree, with minor editorial revisions made to improve clarity and overall presentation while preserving the original research findings.

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THE RECOVER PROJECT

RECOVER stands for 'Resilience to climate vulnerability and environmental risk' with a focus on small islands. Addressing the needs and the unique challenges of Small Island Developing States (SIDS) that are on the frontlines of climate change, the RECOVER Project aims to address climate change adaptation through a multi-risk and multi-sector approach. By conducting pilot projects in three small island states- the Maldives, Mauritius, and Seychelles- RECOVER will co-develop scalable and systems-changing climate resilience approaches to enhance understanding of small island climate adaptation capacities and possibilities. RECOVER is led by the University of Waterloo in Canada in partnership with implementing partners in activity countries: the Maldives National University, the University of Mauritius and Sustainability for Seychelles (S4S).

RECOVER is funded and supported by the Climate Adaptation and Resilience (CLARE) programme. CLARE is a £110m, UK-Canada framework research programme, aiming to enable socially inclusive and sustainable action to build resilience to climate change and natural hazards. CLARE is an initiative jointly designed and run by the UK Foreign Commonwealth and Development Office and Canada's International Development Research Centre. CLARE is primarily funded by UK aid from the UK government, along with the International Development Research Centre, Canada.

Through long-term commitments and partnerships worldwide, and needs-driven, action-focused research, CLARE links up short-and long-term issues, providing a better understanding of the risks associated with climate, supporting early action to reduce impacts of climate variability whilst enabling long-term, sustainable, and equitable economic and social development in a changing climate.

EXECUTIVE SUMMARY

Flooding is a recurrent problem in Malé, the capital city of the Maldives, where high population density and rapid urbanization exacerbate the impacts of heavy rainfall. This study assesses the city's flood risk through a combination of long-term rainfall analysis, recent flood incident records, and an evaluation of the city's stormwater system in terms of its capacity to manage flood events. The Gumbel Extreme Value Distribution (Type I) was applied to rainfall data of Hulhulé station for the period of 1993 to 2024 to determine return periods for extreme rainfall events.

Flood incident records from the National Disaster Management Authority (NDMA) for the period 2023-2024 were reviewed to quantify both human and economic impacts. The capacity of the existing drainage system was assessed based on a stormwater design study conducted by Royal HaskoningDHV, which simulates the system's performance under a 5-year return period (RP5) rainfall event.

The results indicate that Malé experiences an average annual rainfall of approximately 2,013 mm, with extreme daily events becoming increasingly clustered in recent years. The 31st December 2023 storm, which produced 192.7 mm of rain within 24 hours corresponded to a 25-50-year return period, exceeding the design assumptions of the existing stormwater network. NDMA records confirm that this and similar events have resulted in relief expenditure amounting to hundreds of thousands of Maldivian Rufiyaa (MVR).

Hydraulic simulations from the design study revealed that, during a 5-year return period event, inundation depths of 0.3-0.4 m may persist for up to 16 hours, indicating that the system remains under-designed. By combining hydrological analysis, flood incident data and infrastructure performance assessment, this study demonstrates that Malé's stormwater system is insufficient to address current rainfall risks. The findings highlight the urgent need to revise design standards to accommodate higher return periods, improve flood incident reporting, and adopt adaptive stormwater management practices. These measures are critical to reducing the physical and socio-economic impacts of flooding in Malé.

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1. Introduction

1.1 BACKGROUND STUDY

Malé, the capital of the Maldives, is a densely populated island city with a low elevation that faces increasing flooding risks from both rain-induced pluvial flooding and coastal flood events caused by storm surges and high tidal volumes, the former being significantly more frequent. The city has become more flood-prone due to rapid urbanization, land reclamation projects and infrastructure expansion, all of which have modified natural water drainage routes (Amores et al., 2021; Wadey et al., 2017).

The stormwater management system (SWM) often experiences operational failure as rainfall runoff exceeds its capacity, resulting in repeated flooding events (Royal HaskoningDHV, 2023; Limthongkul et al., 2022). Climate change, combined with rising sea levels, further exposes the city to severe storm surges whose intensity is increasing while simultaneously undermining traditional flood protection measures (IPCC, 2021; Knutson et al., 2020).

1.2 STATEMENT OF PROBLEM

Malé has become increasingly flood-prone due to rapid urbanization, outdated drainage systems and impacts of climate change (Mahmoud & Gan, 2018). Waterlogging occurs across the city as a result of rainfall runoff alongside limited land space and ineffective stormwater management (Limthongkul et al., 2022). Rising sea levels and coastal storm surges produce additional flooding risks that threaten business operations, infrastructure and residents (Amores et al., 2021; World Bank, 2022). Although land reclamation projects and seawalls were designed to protect coasts from erosion and storm damage, they have altered wave patterns that cause increased flooding in certain areas (Wadey et al., 2017; Rangel-Buitrago et al., 2019). Flood risk evaluation is constrained by the outdated flood zone map, which hinders accurate identification of vulnerable locations and prevents the development of effective stormwater management improvements (World Bank, 2022).
The study will focus on two main areas:

1. Historical and present flooding patterns in Malé due to rainfall.
2. A critical evaluation of current stormwater drainage systems.

An analysis of historical rainfall trends will provide data-driven insights to support Malé's future planning and infrastructure development.

1.3 OBJECTIVE OF THE STUDY

This study aims to analyze and understand flooding risks in Malé through the following objectives:

1. To conduct a long-term rainfall analysis of Malé and examine its relationship with flood events.
2. To assess the effectiveness of the stormwater management system in Malé through rainfall analysis.

1.4 RESEARCH QUESTIONS

1. How have long-term rainfall patterns in Malé (1993-2024) varied in terms of annual totals and extreme daily events?
2. What return-period rainfall intensities can be derived from the rainfall record, and what do these indicate for stormwater management planning? How are recent extreme rainfall events (2023-2024) associated with documented flood incidents in Malé?
3. How effective is Malé's upgraded stormwater drainage system in managing the rainfall extremes identified in the analysis?
4. What policy and design measures are needed to strengthen Malé's flood resilience considering projected increases in rainfall intensity and continued urban growth?

1.5 SCOPE OF THE STUDY

This study focused exclusively on flooding risks in Malé, examining both pluvial and coastal flooding with a primary focus on the former. The research covered a 10-year period to analyze historical flooding trends. Data was collected from historical flood records, rainfall data, and existing stormwater infrastructure assessments. It does not include detailed hydrodynamic modeling of storm surges.

2. LITERATURE REVIEW

2.1 FLOODING PATTERN IN MALÉ

Natural and artificial factors create worsening flood conditions in Malé. Malé faces heightened flood risks due to its low elevation and high urban density, both of which increase vulnerability to rising sea levels and heavy rainstorms. Climate change related elements play a significant role in coastal flooding including both stronger storm surges along with altering wind-wave conditions. Human activities have exacerbated the situation by engaging in development projects such as land reclamation and improper design of drainage systems thus disrupting island waterways. The subsequent sections evaluate the research studies that investigate Malé's flooding triggers along with studies on adaptative approaches and risk evaluation.

2.1.1 Mean Sea Level Rise and Wind-Wave Impacts

In the study conducted by Amores et al. (2021), mean sea level rise (MSLR) and wind wave dynamics are investigated on the flooding patterns in the Maldives with the use of global climate models and local hydrodynamic simulations. Specifically, Malé, the capital city, is of greatest concern on account of its densely populated condition and reclamation of a large proportion of its land. The paper identifies the main drivers of coastal flooding in terms of storm surges, monsoonal wind patterns, and a localized wave amplification. Increased frequency and severity of coastal inundation events are expected in Malé without major mitigation actions in the coming decades based on the findings. Amores et al. (2021) performed a multi scale modeling by integrating global climate projections and local detailed coastal models. These included Global Climate Models (GCMs) that made large scale projections of MSLR on the basis of different greenhouse gas emission scenarios. The hydrodynamic simulations used were high resolution numerical models used to simulate wind wave interactions and coastal flooding processes in Malé. Validation of the model output was done by historical data analysis, in which records from tide gauge and past flooding events were studied to validate the model outputs and to examine long term trends. Future flooding risks were estimated based on scenario-based predictions that took into account variations in wave height as well as storm intensities. By using this mixed method approach, they were able to understand not only present risks but also future flood risks in Malé and gain insight into localized flood dynamics. Their findings revealed that rising sea levels have the power to increase flood frequency even from relatively modest wave events which have until now posed little risk of inundation. Amores et al. (2021) showed that coastal alterations, including land reclamation and seawalls, change the character of the wave and may increase flooding risk in certain areas. Extreme weather events are projected to lead to more severe flooding episodes and as a result storm surges would have a more prominent role in future inundation.

2.1.2 Historical Coastal Flooding Assessment

The Maldives, as a low-lying island nation, is subjected to the threat of coastal flooding; with implications to its urban areas such as Malé. Wadey et al. (2017) conducted a detailed assessment of historic coastal flooding events in terms of their causes, frequency and long-term consequences. Research shows that floods in Malé have been mainly caused by storm surge, high tide, and wave overtopping, and that extreme events are happening more frequently due to climate variability and anthropogenic coastal modification. In addition, the study discusses past efforts to mitigate flooding and challenges to future urban development in flood prone areas. Wadey et al. (2017) have applied a multi-faceted approach to understand past flooding events

and their implications for the Maldives. Tides Gauge Records, Government reports, and eyewitness accounts were used to reconstruct flood incidents in Malé and other islands in the past. Meteorological and oceanographic data was used to understand the influence of past flood events by storm surges, extreme high tides and wave activity. The impact was evaluated by assessing major flooding events through damage to infrastructure, coastal defenses, as well as community displacement. In reviewing past and present coastal protection strategies it pointed out the gaps in flood resilience planning and how improved coastal adaptation measures are needed. Historical records indicated that the frequency and intensity of flooding have increased substantially and more so in urbanized islands such as Malé. The study demonstrates that storm surges, extreme high tides and wave overtopping were the dominant factors responsible for past floods. Coastal Modifications such as in Figure 1 (Land reclamation and seawall construction of an Industrial Village area in Malé), which have intervened with natural patterns of flooding, sometimes increase the risk of flooding in certain areas.

Figure 1 - Land Reclamation of Industrial Village in Male' (Ministry of National Planning, Housing and Infrastructure, 2016)

Wadey et al. (2017) highlighted that the exposure of the city to flooding is increasing as more urban expansion takes place in the flood prone areas together with deficient drainage systems and old coastal defenses. The findings highlighted that there exists a pressing need for better flood management which should be carried out through the implementation of better nature-based solutions, more effective drainage and adaptive urban planning strategies.

2.1.3 Land Raising as an Adaptation Strategy

Given increasing sea level rise (SLR) threat to low lying nations like the Maldives, land reclamation has been proposed as a solution to coastal flooding. Brown et al. (2020) studied the impact of land raising as a long-term adaptation strategy with a focus on an artificial island in the Maldives. The effect of elevation change on flooding patterns, the magnitude of flood risk for land raising, and tradeoffs between large scale reclamation projects were investigated. According to the findings, while land raising can offer transitory flood defense, it brings new problems such as modified

hydrodynamics, enhanced susceptibility to wave action and ecological effects. In order to understand how land rising affects coastal flooding, Brown et al. (2020) used a modeling and observational approach. Wave and corresponding hydrodynamic simulations were conducted to determine the effects that changes in land elevation would have on the propagation of waves, the behavior of storm surge and flood risk. The study compared the flood patterns of both natural, low-lying islands and artificially raised, high land and gave a comparative analysis of the vulnerability and resilience of the two types of islands. Field observations and data collection were used by the researchers to validate model predictions and to evaluate the reduction of flooding on the artificial island due to land raising. The study also ran through various sea level rise scenarios to determine whether land raising would be sustainable as a type of flood mitigation strategy in the long term. This research identified various essential outcomes which demonstrate the effectiveness of land raising techniques for coastal flood reduction. For example, artificial elevation of island surfaces results in decreased flood occurrences during moderate storm surge. However, adjacent regions experience more erosion damage because artificial alterations of water flow patterns occur when land elevation changes as the process increases wave strength. As a result, the adjacent regions in lower elevations become more prone to more adverse flooding incidents. High-elevation areas obtain better protection against direct flooding though they lose their natural barriers when adapted to higher levels as this exposes areas at risk to severe wave acts during extreme weather. Sustainability issues exist because land raising cannot be a long-term solution as rising sea levels will eventually lead to the need for more land raising or additional flood protection systems. Large-scale land reclamation projects combined with raising initiatives result in damage to marine ecosystems which leads to negative environmental impacts while causing displacement of communities as well as social repercussions.

2.1.4 Complex Causes of Flooding

The history of flooding in the Maldives is related to climatic, oceanographic and human induced factors. Research conducted by University of Southampton (2017) shows these causes to be complex, not only from sea-level rise but also from dynamic interaction with wave activity, monsoonal patterns, coastal modification and land cover change factors.. The research emphasizes the need for a systematic flood management that takes into account natural and artificial effects. According to University of Southampton researchers (2017), the cause of the flood event was analyzed using a "multi-disciplinary approach" and data was collected through a site visit. The triggering of flooding was evaluated by instrumental measurements of wave heights, tidal variations and storm surges. Simulations were run to study the interaction between oceanographic forces (e.g., wind-driven waves, tidal forces) and coastal infrastructure. The flood dynamics were investigated with respect to urban expansion, land reclamation, and seawall construction. Critical factors contributing to flooding of Malé were revealed by the study. The south west monsoon presents strong winds, high waves, and increases the chance of coastal inundation especially during high tide (University of Southampton, 2017). Human activity including land reclamation and artificial seawalls increases rather than decrease wave setup, such that in addition to causing flooding, waves add to the flooding water level in certain regions. Coastal Flooding can be seen occurring near the Artificial Beach area periodically as depicted in Figure 2.

Figure 2 - Coastal Flooding near Artificial Beach, Male' (Auzam, 2019)

Flood events are not all the same as the study discovered that fluctuation in the degree of flooding is not uniform throughout all islands. Local topography and urban planning decisions can determine how intense flooding will be. Long-term sea level rise is just one of many concerns for Malé, because short term events like storm surges are more likely to pose an immediate threat. The research highlights that the solution to flooding should be based on a combination of engineering solutions, improved urban planning, and creating space for nature-based flood defenses.

2.1.5 Quantitative Risk Assessment

Sea-level rise (SLR) poses one of the most significant long-term threats to the Maldives, with potential consequences for infrastructure, livelihoods, and overall economic stability. A risk assessment conducted by the World Bank (2022) measures quantitative effects of SLR in the Maldives through analysis of threatened urban zones and economic damage along with necessary adaptation approaches to decrease vulnerability. Malé experiences higher risks of flooding because it is the island with the highest population density and has minimal height above sea level while continuing to expand and build critical infrastructure by the coast. Data science gives direction to essential adaptation policies which should focus on creating urban environments that resist disasters and invest money in protecting infrastructure and implementing nature-based solutions. World Bank (2022) used high-resolution topographic and bathymetric data to analyze potential flood scenarios as they relate to different sea-level rise projections about sea-level rise through geospatial modeling. An economic evaluation was performed to measure how flooding would affect structures alongside infrastructure and elements from the tourism sector. They used different greenhouse gas emission scenarios which served to generate multiple projections regarding future sea levels. A Cost-Benefit Analysis of adaptation strategies was performed including seawalls along with land raising and nature-based solutions to establish their financial sustainability and performance. The study demonstrates that Malé, alongside other Maldivian islands, faces intense risks from sea-level rise. They predict that high emissions will lead to widespread inundation of Malé city and urban islands across the Maldives between 2070 and 2100 (World Bank, 2022). The economic sector faces major financial harm together with

infrastructure deterioration when coastal flooding occurs. The research establishes that postponing adaptive actions would heighten economic losses and demands substantial financial investments into flood defense structures as a proactive response. World Bank (2022) established that restoring coral reefs, protecting mangroves and reinforcing sand dunes are effective and sustainable practices to combat flood risks. There are many organizations focused on the restoration and rehabilitation of coral reefs in different regions of the Maldives as seen in Figure 3. Long-term resilience depends on national development planning which requires climate risk assessments (World Bank, 2022).

Figure 3 - Coral Reef Restoration (Save the Beach The Maldives, 2025)

2.1.6 Urban Heat Island Effects and Pluvial Flooding Amplification

An Urban Heat Island (UHI) effect is present when the urban area of an island is hotter than the rural regions. As a result of UHI in Malé, the city air warms up, which can cause floods to happen more often. A study conducted by Li et al. (2021) investigated short periods of intense rain that sometimes result from UHI. The researchers examined the movement of stormwater out of heat-affected areas of nearby South Asian cities and towns by using images from satellite thermal imaging, radar information and a Weather Research and Forecasting (WRF) Hydro model. Those areas of the city that received the greatest heat anomalies had around 15-25% higher hourly rainfall and caused local cloudburst activity. In UHI zones, surface runoff is likely to increase because both non-porous land and poor drainage can keep water from being absorbed. In Malé, roads are more likely to become flooded after rain due to congestion and the lack of space. Climate-smart approaches must be used in developing our building and zoning policies to help address the UHI effect. Li et al. (2021) write that using specular construction materials, permeable roads and green or roof gardens is necessary. Results indicated that the heaviest UHI-driven rain often occurs during rush hour. Dealing with UHI lowers the heat and also aids in handling flood impacts.

2.1.7 Coastal Sediment Transport Disruption and Flood Hazard Zones

Alterations to the movement of coastal sediments are an overlooked aspect of why low-lying island cities are at risk from flooding caused by seawalls, groynes and new port constructions. Rangel-Buitrago et al. (2019) assessed the disruptive influence of coastal engineering on natural drift of sand and the resulting rise in flood danger. More than 50 case studies spanning island and coastal cities around the world (including the Indian Ocean) were examined. Results were supported by satellite-based observations of sea levels and models examining the distribution of sediments to study the lasting outcomes of building hard infrastructure. In Malé, land reclamation and seawalls have inadvertently stopped sediment from moving along the shore, causing down-drift locations to suffer sediment starvation. During storm surges, erosion and wave overtopping impact these regions, reducing the protection that was already available from natural coastal buffers. Rangel-Buitrago et al. (2019) showed that changes in nearshore sediment can shift wave energy upward during high tides, allowing what could have been a minor storm to end up as a harmful flood event. The study recommends using sediment for building up the beaches, flexible sand dunes made from geotextiles and mangroves and coral reefs to help control waves. Furthermore, they recommend that all future coastal construction should be preceded by numerical simulations of how sediment moves in the water. In Malé, we need to ensure that sediment flow projections are added into EIAs for any changes to coastal infrastructure. The study shows that protection today can be provided by structures, but safe and reliable coasts will require the repair and upkeep of natural processes by sediments.

2.1.8 Cyclonic Events and Changing Flood Return Periods

Tropical cyclones are increasing in both frequency and intensity because of climate change and forecasting flood risk with return periods is far less reliable, mainly for island nations such as the Maldives. Knutson et al. (2020) analyzed storm surge data from past and recent climate model simulations to show how rising sea levels and storms are now posing new threats to coastal communities. Scientists report that extreme weather events were expected once in a hundred years but are now happening about every 40 years or so in many tropical places. Because of its equatorial position, Malé often only feels what is left of cyclones and because of sea-level rise, subsidence and weak early warning systems, the city is at greater risk. Knutson et al. (2021) combined Coupled Model Intercomparison Project Phase 5 (CMIP5) global predictions and local wave and tide observations to estimate flood extent and surge height for Representative Concentration Pathways (RCPs) 4.5 and 8.5. Outcomes demonstrate that cyclonic residues that are not major can still cause surges of two to three meters in urban coastal regions when spring tides occur at the same time. They pointed out that historic standards for designing drainage could now be obsolete because of the new flood patterns. To make hazard maps more accurate, they advise governments to rebuild flood models according to the latest climate trends. In addition, the study recommends using methods such as raising the road level, adding several-use seawalls and factoring climate change into zoning and insurance options. Since growth in Malé is happening close to the ocean and the population is dense, cyclonic risks must be taken into account in both building and non-building approaches to planning to support future flood resilience and the safety of people's livelihood.

2.1.9 Impact of Land Use Change on Urban Flooding in Coastal Cities

In Malé and other small, crowded islands, how land is used has a significant impact on urban water management. Mahmoud and Gan (2018) investigated how faster growth development of more land has led to more severe bouts of flooding in cities. Using land use data from satellites, rainfall records and the Soil & Water Assessment Tool (SWAT) model, the researchers discovered that much larger peak discharge rates were caused by urban growth in coastal cities over two decades. According to the study, changing vegetation and the transition of open areas to built areas raised runoff by 40% and lowered the area's capacity to recharge groundwater by 20%. When applied to a case like Malé that has little green space, these points are especially important. Fragmented development and unplanned zoning cause the stormwater system's drainage to be slow and leads to blocked areas. In Malé, since much of the land is constructed, these problems are increased by a lack of natural drainage areas. Mahmoud and Gan (2018) recommend using watershed information in city designs and relying on green techniques such as bioswales, rain gardens and grass areas on roofs for urban water management. The study stresses that close coordination between planning bodies, drainage teams and agencies responsible for the environment is necessary to match land use practices with the ability to manage stormwater.

2.1.10 Wave Overtopping Risk in Coral-Fringed Islands

Rising seas, stronger storm surges, and frequent flooding places the Maldives at significant risk (World Bank, 2024). Storlazzi et al. (2018) looked at how the health of coral reefs, land elevation and the design of coastal defense structures together affect the chance of overtopping in atoll islands' shorelines. Various techniques, including fieldwork, reef profiling, satellite data, ocean tank testing and modelling, were used to learn how changes in reefs and urban redevelopment cause flood risks for low-lying atolls. A major result was that healthy coral reefs control nearly all the waves, preventing that energy from reaching the land. However, when reefs are degraded by factors such as coral bleaching, fishing methods, dredging or sedimentation, they offer only limited protection from the sea, leaving more work for sea barriers. Because reefs have been replaced by manmade barriers in places like Malé, larger waves overtop and more land near the sea is carried away. A Slotted Waveguide Antennas Model (SWAN) was used to study how various reef health conditions and storm situations affect the surrounding ocean. It was found that at high tide together with moderate swell, the area 200 meters inland could become flooded when the slopes behind the reef were made steeper by human activity. The researchers tested how vertical and sloped seawalls behave as waves in the North Atlantic increase or decrease. Although these structures protect the area for a short time, their shiny surfaces increase chances of backwater scouring and risk weakening the foundations near them. Such negative effects become especially worrying in reclaimed areas such as Malé and Hulhumalé, where the properties of the underlayers are not always steady. The findings supported the use of modern measures alongside patches and barriers that let nature thrive such as fake reef assembly, moving live coral and built barriers designed to lower the effect of waves. Some of the recommendations provided by Storlazzi et al. (2018) are: closely monitoring reef health with surveys and UAV maps, designing coastal protection structures that can easily change as sea levels rise and including reef health measures in national flood early warning systems. The research shows that if nothing is done to coordinate both natural and man-made systems, wave overtopping will give rise to greater hazards in Malé, where it is not possible to move important structures inland.

2.2 STORMWATER MANAGEMENT SYSTEM IN MALÉ

The continued flooding of different neighborhoods in Malé occurs due to obsolete stormwater infrastructure combined with insufficient areas for natural water absorption. Government bodies together with international assistance have launched initiatives to modernize stormwater infrastructure in order to strengthen urban flood defenses. These initiatives include groundwater recharge improvement as well as disaster preparedness for climate-related events. The subsequent sections analyze these developments focusing on construction strategies, instructions for managing groundwater resources and a climate risk survey for the capital city.

2.2.1 Construction of Malé Stormwater Management System

Urban flooding occurs frequently in Malé because the capital city receives heavy rainfall and its drainage systems lacks sufficient capacity. The Maldivian government launched an extensive stormwater management project to enhance the drainage system of Malé's urban areas in 2024 (Ministry of Finance, 2024). The initiative works to decrease flood dangers along with boosting water movement capability and preventing areas from becoming flooded. Flash floods occur after heavy rainfall on most roads of Male' including major roads as seen in Figure 4.

Figure 4 - Flash flood of a Major Road in Malé (Moosa, 2024)

The upgraded drainage system exists as a key element of general climate resilience approaches decreasing the effect of weather extremes on built infrastructure and local community welfare systems. The project implements an organized series of steps as described by the Ministry of Finance (2024). International Competitive Bidding (ICB) opened up the contract for both domestic and international construction companies to obtain international expertise and high-quality construction standards. They have outlined drainage infrastructure projects for new system development and pipeline enhancement alongside modern stormwater management strategy implementation to boost flood protection capabilities (Ministry of Finance, 2024). Multiple

stakeholders were consulted throughout the project from government institutions combined with engineering teams and urban planning specialists and community members working to create systems that function well for technical needs as well as community requirements. Multiple anticipated results and probable obstacles emerged as the project progressed. A better flood control system has been designed as part of the updated drainage infrastructure to minimize flooding incidents which impact the low-lying populated neighborhoods of Malé (Ministry of Finance, 2024). Modern stormwater management implementation within the project serves to manage excess rainwater with improved effectiveness while protecting the environment from degradation. The improved stormwater infrastructure offers dual benefits as it protects land and municipal facilities from flooding while boosting locality resistance to floods (Ministry of Finance, 2024). The project will support the rapid urbanization of Malé by combining flood control measures into urban development processes. The Ministry of Finance (2024) has acknowledged implementation difficulties including system integration with existing drainage networks, construction interruptions, as well as the need for long-term network maintenance for optimized performance.

2.2.2 Groundwater Improvement Measures

The small coastal islands found within the Maldives experience major groundwater challenges from limited water supply and high exposure to saltwater intrusion. Ministry of Environment (2021) has developed a guideline on improving the groundwater conditions with specific methods which help increase sustainable infiltration techniques for both groundwater recharge and quality improvement. The guide can be used as a resource for efficient groundwater management solutions and presents different methods to improve groundwater recharge performance while minimizing water losses. It promotes rainwater capture through rooftop collection methods to help fill freshwater reserves and suggests road drainage systems that enable absorption of rainwater in to the soil as recharge instead of releasing water as waste to the sea. The guideline stresses on active participation of community in both establishing and sustaining groundwater enhancement strategies (Ministry of Environment, 2021). The deployment of proposed groundwater restoration techniques will create various advantages by increasing water supply and quality while ensuring environmental sustainability. The successful long-term results depend on solving existing challenges. Sustainable infiltration methods for groundwater recharge increase freshwater supply by refilling underground water reserves. Water recharge projects function as a method to defend against salinity intrusion because they maintain the freshwater and saltwater distribution layers and combat water pollution risks. The wastewater filtration process that occurs through infiltration leads to enhanced water purity in groundwater. These techniques function as appropriate tools for urban planners to combine into city designs that boost overall sustainability. The implementation of the system faces challenges because it requires addressing financial constraints as well as technical limitations and maintenance needs (Ministry of Environment, 2021).

2.2.3 Climate-Related Disasters Survey

The Maldives is vulnerable to climate-related disasters because it is only few meters above sea level and increasingly experiences severe weather conditions. A Japan International Cooperation Agency (JICA) survey evaluated disaster risks for Malé while investigating suitable disaster prevention methods (JICA, 2021). This study attempted to enhance disaster readiness through the evaluation of historical occurrences and existing structures and identified future conditions which could pose threats. Various data collection methods enabled researchers to gather information about climate-based disasters while reviewing local emergency readiness levels. Data collection also included acquisition of information from agencies and local organizations involved

in disaster risk management while experts physically checked the state of coastal protections and urban drainage systems during field inspections. Discussion sessions with officials as well as residents from the area gave information about disaster consequences and readiness levels in the community (JICA, 2021). Several challenges were identified during the study, and specific strategies were developed to enhance disaster resilience. The low-lying nature of Malé exposes the community to extreme storm surge risks that have resulted in severe floods and substantial property destruction during past events. In addition, the existing drainage networks of Male' area prove insufficient to manage heavy precipitation since they are unable to drain excess water effectively. The protection of Malé's coast requires immediate strengthening of seawalls combined with other coastal defenses to decrease flood risks. Early Warning Systems provide effective extreme weather event preparation to communities. Ultimately, long-term disaster response capabilities require better development of institutional and community preparedness. The study demonstrates that Malé needs better infrastructure and early warning systems in addition to community readiness to reduce climate emergency dangers.

2.2.4 Urban Waterlogging Dynamics and Drainage Capacity Constraints

The continuous flooding in Malé is largely attributed to a combination of factors including its low-lying coastal setting, outdated drainage system that is unable to handle heavy rain and inadequate integration of ocean and coastal management. Limthongkul et al. (2022) conducted a study focused on determining what causes efficiency problems in the drainage systems of tropical megacities and recommended ways to address them. The researchers combined site-specific bell analyses, simulations with Storm Water Management Model (SWMM) and gathered feedback from urban water managers in several cities in Southeast Asia that are similar to Malé in climate, urban population and land use. The investigation found that in older areas of the cities, over 40% of stormwater infrastructure did not meet design standards because of abundant sediment, lack of maintenance, structural damage and buildings moving closer to pipes. In addition, problems were created by misplaced manholes, graded inlets that often-caused blockages and a lack of storage systems for water during rainfall peaks. Where traffic pushes cars together down narrow roads lined by tall buildings, both speed and flow decrease, causing water on the roads or streets to pool and take longer to clear after two storm events. It was discovered that when rainfall of a return period of 10 years occurs, the local drainage network might flood, producing 25 to 35% more runoff than it can carry. Old stormwater arrangements were found to be ineffective because they only move stormwater without storing or using it for other purposes. Limthongkul et al. (2022) recommends an approach that adds dual-drainage layouts, elevated side inlets, underground storage tanks located under roads or parks and scattered green infrastructure, including vegetated swales and permeable parking zones. In trial areas where these actions were implemented, the top water levels decreased by roughly 40% and water drainage times decreased due to system diversification. In Malé, as the area is congested, the authors propose incorporating asset condition assessment, flood vulnerability analysis and modular improvements to drainage as part of the city's routine planning activities. Moreover, they recommend collaboration of urban planners, water utilities and environmental regulators ensure hydraulic elements are incorporated into the design and development.

2.2.5 Nature-Based Solution and Sustainable Drainage in Small Island Nations

Since urban areas of low-lying island nations like the Maldives face growing challenges from flooding, heat stress and loss of biodiversity, nature-based solutions (NBS) have appeared as an

effective way to manage stormwater and provide a range of other benefits at the same time. Wamsler et al. (2021) investigated the use of NBS in small island developing countries, using Sri Lanka as a case study and also applyed the findings to the Maldives. The study used participatory urban planning methods, including computer modelling for water and implemented various Sustainable Drainage Systems (SuDS) processes in practice such as vegetated bioswales, rain gardens, permeable paving and multi-use retention basins. They installed the green infrastructure at schools, in public parks and alongside streets to see what effect it had on limiting floods, absorbing water, removing pollutants and community reactions. At locations like Malé that have many city features, bioswales and rain gardens were proposed to manage stormwater runoff, slow it down and protect water quality by catching sediment and nutrients. Figure 5 shows the effectiveness of rain gardens, bioswales and permeable paving in reducing the amount of runoff. According to Wamsler et al. (2021), these flood buffers effectively tackle floods and enhance how the area is regulated by weather, how it looks and the type of habitats available in the city. They added that successful implementation largely depends on the community and their capacity to maintain and design the project. In pilot areas with local people involved, the systems always worked well and were maintained. On the other hand, when public involvement was missing such projects suffered neglect, blockages and poor performance. In places where physical space is limited, adding rooftop gardens and growing plants on building walls could be part of the solution, while incorporating rainwater harvesting units into existing construction makes sense where space is also an issue. They argue that local government ordinances should bind permits for development to monitor compliance with stormwater regulations and suggest that such development could attract financial rewards. According to the study, combining traditional engineering with natural solutions gives the most dependable and affordable strategy for managing urban stormwater during periods of climate change and rising sea levels.

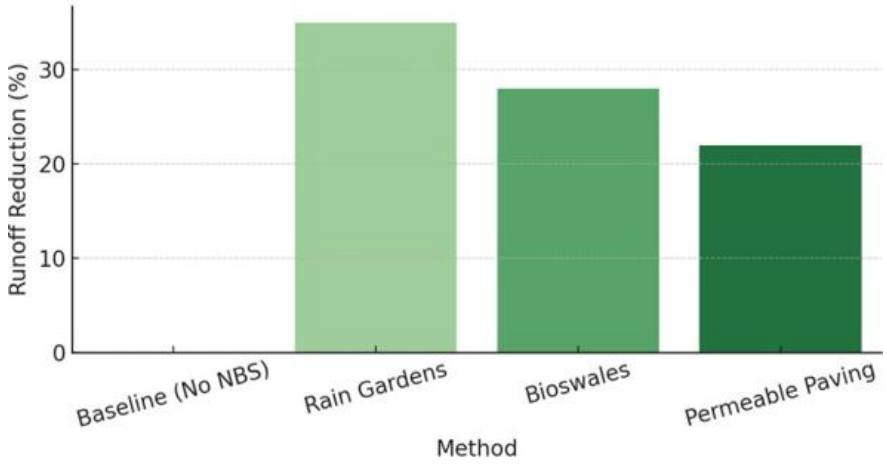

Figure 5 - Effectiveness of Nature-Based Solutions (Wamsler et al. 2021)

2.2.6 Smart Stormwater Infrastructure and Sensor-Based Management

Due to the uncertain nature of rainfall and space constraints for new drainage areas, smart stormwater systems offer an effective approach to flood management in densely urban parts of Malé. Roldin et al. (2020) published an overview discussing how to use Real-Time Control (RTC) technologies in stormwater networks to boost their reliability. The research studied several RTC applications in Europe, Asia and North America, evaluating their success by means of case studies, simulated control algorithms and cost analysis. An RTC system depends on many

sensors and actuators to monitor water levels, analyze weather forecasts, monitor the flow of runoff and adjust gate controls to control water storage and release during storms. Using these systems, traditional pipe-and-storage infrastructure becomes active and is managed to allow for slowing, moving, or holding traffic as needed. In a project conducted in Copenhagen, RTC drainage resulted in a 40% decrease in combined sewer overflows and more than a 30% decline in urban surface flooding for 20-year storm conditions. The comparison between before and after RTC is shown in Figure 6. It was noted by the study that RTC fits well in urban areas that have limited space and old structures. Malé would thus be a strong candidate for an RTC system because building more infrastructure is challenging due to limited space and remodeling old infrastructure would be beyond available funds. Roldin et al. (2020) also described how using machine learning improves RTC systems, allowing them to estimate hydraulic flow and adjust efficiency for different types of urban drainage. They also mentioned problems with bringing warehouse operations online such as sluggishness in the water industry, problems linking data and the necessary coordination among water utilities, IT experts and municipal engineers. According to the Roldin et al. (2020), Malé should begin by monitoring flows and modelling stormwater, then pilot RTCs in flood areas, moving on to expanding RTCs to whole urban districts and installing decision support systems. When RTC is backed by smart code and GIS asset management, it can become the core system for a new stormwater management technique that is practical, adapted to changing climate and ready to respond in real time to changes in a city.

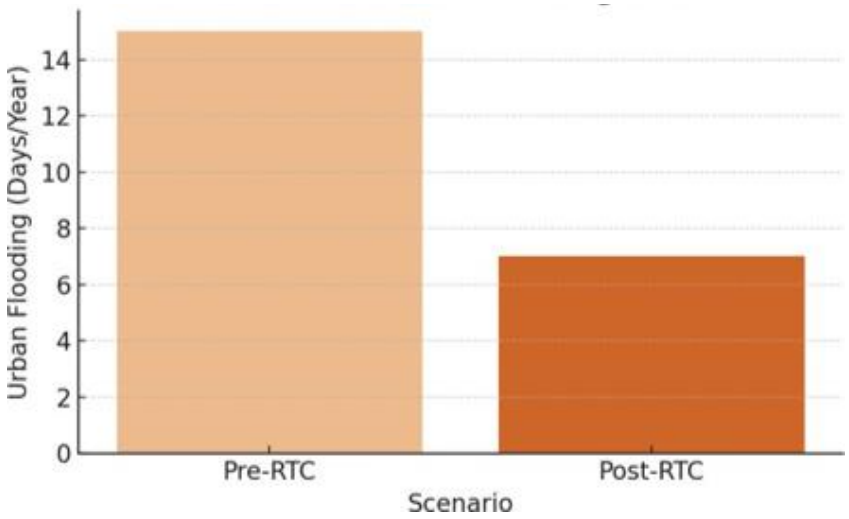

Figure 6 - Reduction in Urban Flooding with RTC

2.2.7 Integrated Urban Stormwater Planning and Climate Resilient Design

Rising rates of urbanization and climate change mean that cities must now include climate-resilient strategies for managing stormwater during urban development. In their publication, Fletcher et al. (2018) argue that integrating stormwater planning is especially vital for small island nations such as the Maldives, since space for new infrastructure is scarce and climate change causes more regular and severe heavy rainfall. The importance of including stormwater management in early urban planning through to infrastructure design is stressed to ensure drainage is both effective and adaptable. According to the Fletcher et al. (2018), cities should consider using hydrological modelling, projecting future climate events and evaluating several options in drainage network planning to address possible flooding. Case studies from Australian and Southeast Asian cities are used to show that poor urban planning together with ageing drainage systems can make situations worse during strong storms. Integrated city planning is proven to have measurably

raised the ability to withstand flooding, as illustrated in Figure 7. Because of more intense urban runoff in some places, 10-year storms are now happening every 3 to 5 years. For Malé, since there are many buildings close together and a large area of reclaimed land, these results are especially important. Fletcher et al. (2018) points out that if blue-green infrastructure—for example, vegetated swales, detention ponds and green roofs—and grey infrastructure are used together, rainwater runoff can be cut down and flood protection increased. The authors state that including flood resilience in city master planning allows cities to save resources in the future and would result in fewer and lower damage expenses during flooding. According to them, adding decentralized water management systems, stormwater collection, simple green infrastructure and local flood control to older city areas can help cities like Malé where land and resources are limited. Their results point out that integrating urban planning with method to confront climate and stormwater hazards requires co-operation not only between analysts but also among water utilities, those who develop cities and organizations that focus on environmental issues.

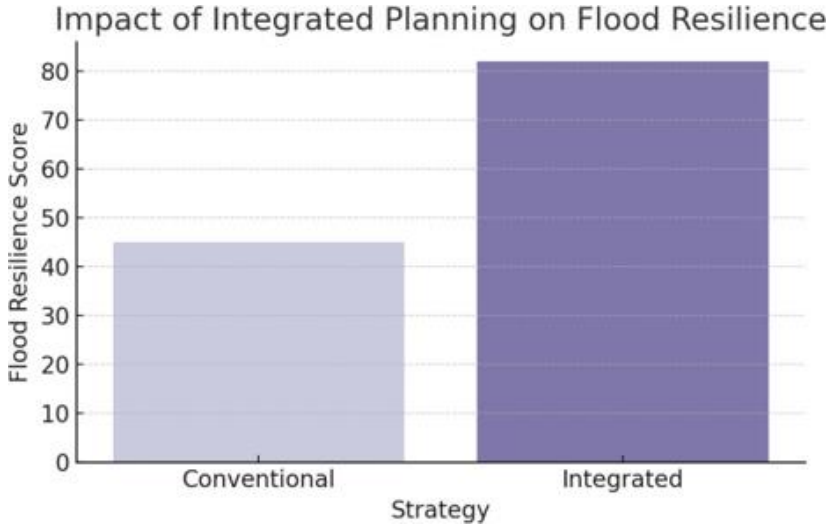

Figure 7 - Impact of Integrated Planning on Flood Resilience

2.2.8 Community-Based Flood Governance and Localized Stormwater Strategies

Since main infrastructure in places like the Maldives is hampered by many geographic, economic and operational issues, local solutions managed by communities are very helpful for improving the nation's resilience. Alam and Rabbani (2017) examined how involving communities in planning and localizing stormwater responses helped reduce urban floods in Dhaka wards similarly impacted by population density, poor drainage and seasonal flooding. They realized key findings by blending Participatory Rural Appraisal (PRA) with surveys, maps of local waters and a study of local authorities to learn how communities manage waterlogging themselves when services are not available. It was clear that household-made soak pits, handled drain systems, elevated pathways and localized water pumps played a major role in reducing flooding in these under-served communities. Thanks to these steps, drainage was possible for residents of informal settlements where municipal help was rarely given during heavy monsoon rains. Additionally, where community-based water committees (CBWCs) organized quick fixes, exchanged

knowledge and kept in contact with city agencies, recovery was faster, damage costs were lower and the community felt more united. Many respondents in the study said they put more trust in their neighbors' initiatives than in government authorities, who were viewed as acting only when there was a problem. This understanding matters greatly for Malé, due to the issues faced by its stormwater authorities: delays caused by government processes, a lack of resources and the need to serve many kinds of users. The authors recommend adopting neighborhood-based stormwater management, involving the community and small-scale investments, because it makes response faster, fairer and helps lower the city's overall maintenance costs. Community-based models are proven to greatly boost both the regular operation and reliability of drainage systems, as illustrated in Figure 8. Alam and Rabbani (2017) point out that decentralized projects are better suited for solving problems that are unique to each ward's infrastructure. They suggest that to give these benefits structure, CBWCs must be brought into the regular water management system by means of training workshops, microfinance and cooperative budgeting. They believe infrastructure designers should give neighborhoods the ability to change their drainage systems based on their setup and conditions. In Malé, this involves giving wards the authority to build up micro-drainage systems, keep decentralized rainwater tanks clean and be a part of local flood mapping with free tools. The research suggests that models where local efforts support the main city processes are best able to offer inclusive and responsive flood management to small island cities facing challenges from both rapid urbanization and climate change.

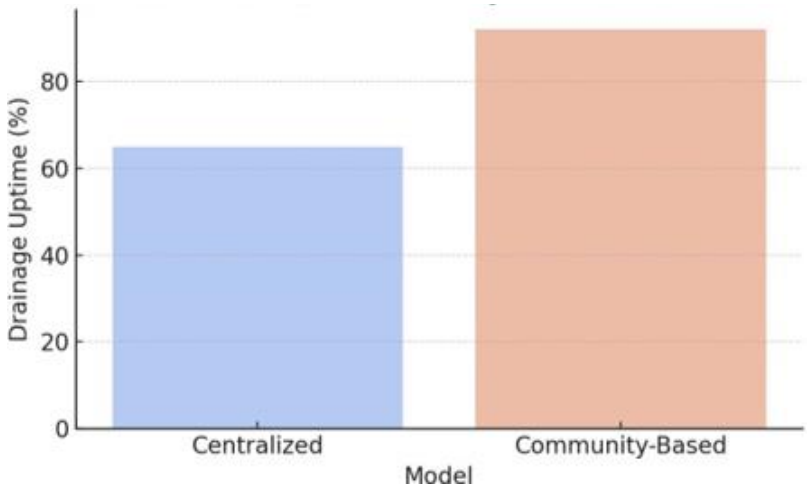

Figure 8 - Effectiveness of Community-Based Governance

2.2.9 Decentralized Water Reuse Systems for Urban Flood Mitigation

Major construction projects are thwarted by land scarcity and low water availability plus climate-related flooding. Using stormwater around the city instead of discharging it to the sea can increase the amount of fresh water available and decrease the chance of neighborhood flooding. A study conducted by Sgroi et al. (2018) examined the potential, quality of use and benefits for the environment of using small amounts of greywater and rainwater in crowded coastal areas by looking at Mediterranean island cities. Field readings of decentralized systems installed in hotels, schools and multi-unit residential buildings, together with data on water flows, contaminant levels removed and user reviews, were used for simulations to predict how the neighborhood would respond to less rainwater. According to the authors, coupling onsite greywater reuse units with rainwater tanks could cut stormwater sent to sewers by up to 40% when heavy rain occurs briefly

in urban islands. The researchers also recorded that the demand for drinking water was significantly reduced by up to 30% after those functions were done with greywater. This advantage is displayed in Figure 9 which illustrates the water savings realized from greywater use. These results are very important for Malé, since its water systems are under pressure from a growing population. Decentralized systems are structured in modules, so building them does not require excavation or setting up main centers. According to Sgroi et al. (2018), having gravel, activated carbon and membrane filters, UV disinfection and smart controls for saving water based on when people are at home and weather reports worked best. Sgroiet al. (2018) showed that a greywater system complies with WHO standards and that most users are content once the system is properly cared for. The group estimated that the expenses for the systems can be covered through lower water bills and requiring less from the city's sewer systems. The authors recommend that Malé include decentralized reuse in the building codes, gives tax advantages for those who use it and considers these systems when certifying green infrastructure. The placement of such systems in different neighborhoods could help stabilize stormwater levels and cooperate with present drainage systems. The investigation found that implementing water reuse at the neighborhood level offers climate-smart resilience for compact cities with limited availability of land and water.

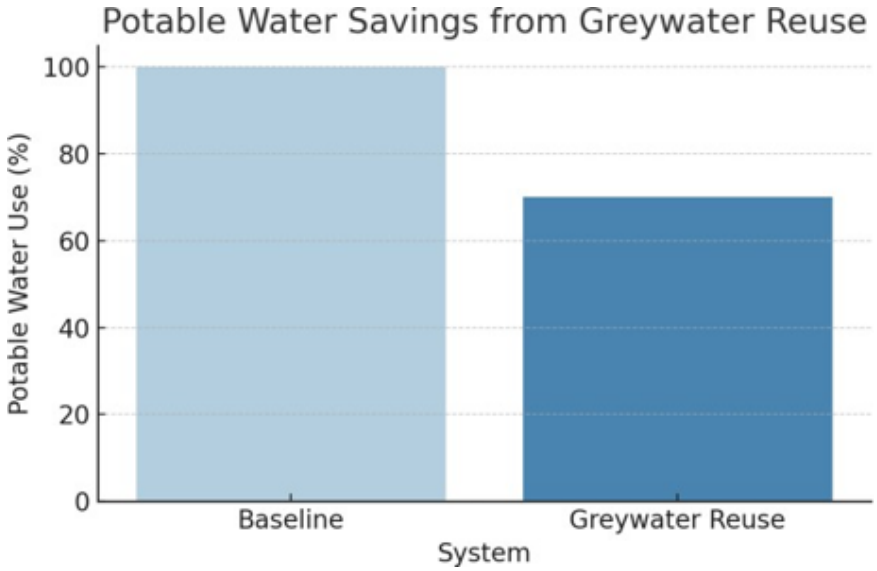

Figure 9 - Potable Water Savings from Greywater Reuse

2.2.10 Adaptive Retrofitting of Existing Infrastructure for Flood Resilience

In areas such as Malé, where infrastructure that has been around for decades fails to meet present-day climate challenges, it becomes important to use adaptive retrofitting to strengthen flood protection at a reduced cost. Bacchin et al. (2019) conducted a global review exploring how cities in Asia, Latin America and Europe have introduced retrofitting processes to make stormwater systems stronger under issues of territory, financing and urban planning. By looking at over 30 cases in detail, the team combined data from field monitoring, simulations and interviews with stakeholders to decide on retrofit strategies that were efficient for water, reliable financially and safe for the environment. Installed systems included modules that trap pollutants in gravel lining roads and squares, layering of permeable paving over existing surfaces, raised inlets with devices controlling water volume and adjusting pipe slopes by adding cured-in-place liners. A case from Manila which is similar to Malé in climate and shape, revealed that using

adjustable weirs and flow valves in a phased approach cut street flooding from storms by nearly half over three years, with no problems for drivers or for underground systems. Figure 10 shows how flood depth decreases when infrastructure improvements are made.. Unlike other cities, Malé's overcrowded lands prevent the addition of large detention basins. Bacchin et al. (2019) recommends installing small retention units into the sidewalks, park areas and below community facilities. They said that for retrofitting to be effective, municipalities must keep detailed drainage inventories, assess drainage conditions regularly and choose performance-based over strict design standards. The authors suggest that adaptive retrofitting should be part of national urban resilience strategies and that disaster risk funding instruments such as resilience bonds and insurance support can help. If applied to Malé, this would involve blending standard infrastructure audits with what citizens report about flooding, to help with planning that is direct and open to everyone. According to the authors, while retrofitting is no silver bullet, it offers a realistic and widespread way to slowly adjust old infrastructure to deal with changing climate conditions, particularly for islands crowded with buildings.

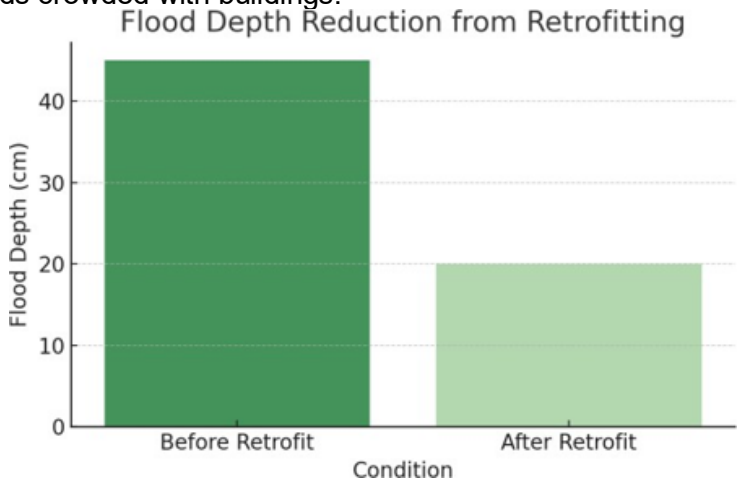

Figure 10 - Flood Depth Reduction from Retrofitting

3. METHODOLOGY

The approach adopted in this study involved a detailed analysis of flooding risks in Malé. In line with the research objectives, the methodology was designed to analyze long-term rainfall records and to review the performance of the existing stormwater management system in Male'.
Rather than applying predictive models or designing new interventions, the study focused on collecting and analyzing data to understand how floods have evolved overtime and how existing infrastructure has responded. This was carried out using simple analytical techniques and open-source materials to ensure transparency and reproducibility. The statistical techniques used for the analysis of the data is presented in detail in the results section.

3.1 STUDY DESIGN

The study followed a longitudinal approach, examining trends in flood incident data, rainfall records from 1993-2024 and the performance of the current stormwater system over a ten-year window (2014-2024). The methodology emphasizes the use of data analysis techniques to assess flood vulnerability. Overall, the study design is observational and analytical in nature.

3.2 DATA COLLECTION

All information for this study was obtained from secondary sources, including official government reports, environmental reviews, meteorological datasets and institutionally maintained flood records. The key categories of data inputs are as follows:

- Flood incident records obtained from National Disaster Management Authority (NDMA) case registries (2016-2024)
- Rainfall records from the Maldives Meteorological Service (MMS) (1993-2024).
- Drainage and stormwater infrastructure plans from the Royal HaskoningDHV (2023) report.

3.3 STORMWATER INFRASTRUCTURE ASSESSMENT

The analysis evaluates the suitability and effectiveness of the existing stormwater infrastructure in Malé. The objective is to determine whether the network adequately responds to storm events and flooding in flood-prone areas.

3.4 STUDY LIMITATIONS

Several limitations are inherent in the design and methodology of this study:

- Prior to 2023, missing or poorly maintained event logs in the flood incident case registries and outdated flood zone maps limited the availability and quality of historical information.
- The study was unable to monitor pipeline flows, water levels or rainfall at the required speed in real-time.
- Variations in both in clarity and accuracy of base maps across different institutions introduced uncertainties.

- Since this study is observational, no simulation modelling or flow-based hydrodynamic estimates are undertaken.

3.5 ETHICAL AND INSTITUTIONAL CONSIDERATIONS

All data utilized in this research is obtained from government bodies, official reports and academic literature. Sources were appropriately referenced in accordance with institutional requirements. No human subjects or fieldwork were involved in the course of this research.

4. RESULTS AND ANALYSIS

4.1 RAINFALL ANALYSIS

4.1.1 Data Source & Pre-processing

Rainfall data covering the period 1993-01-01 to 2024-12-31 was obtained from the Maldives Meteorological Service (MMS). Measurements were taken at the MMS Hulhulé station, which is located close to Malé. Since no other long-term dataset is available in or near Malé, this dataset was used for the analysis. The data were recorded as hourly rainfall amounts and were compiled into daily and annual totals for hydrological analysis. These data were further re-sampled into daily, annual and annual maximum rainfall data, enabling a thorough evaluation of rainfall variability, intensity, and extremes across multiple time scales.

Quality control procedures included are parsing and validating timestamps; converting non-numeric rainfall values to numeric; setting negative values to missing; removing rows with missing time or rainfall data; and ensuring chronological ordering of records. Daily totals were calculated by exact summation of hourly values and duplication avoided. These procedures were applied uniformly across the entire record to ensure consistency and reproducibility.

4.1.2 Annual Rainfall Trends

To assess long-term variability, the annual rainfall totals were calculated and plotted against time. This is a common approach used in hydrological studies that illustrates both interannual variability and long-term changes (Wijayewardene, Herath, & Takeuchi, 2018). The results indicated that the average annual rainfall was approximately 2013.1 mm with a total of 66,433.48 mm recorded between 1993 and 2024 as shown in Figure 11. Considerable year-to-year variability was observed with some years exceeding the mean while others recorded less than 1,500 mm. This variability is likely influenced by monsoonal patterns and El Nino-Southern Oscillation (ENSO)-related fluctuations, consistent with the global assessments of rainfall variability in tropical island regions (IPCC, 2021). In addition, Chowdhury et al. (2025) reported that ENSO and IOD exert a strong influence on seasonal climate variability in the Maldives. Such analysis provides a reference baseline against which extreme rainfall events can be evaluated.

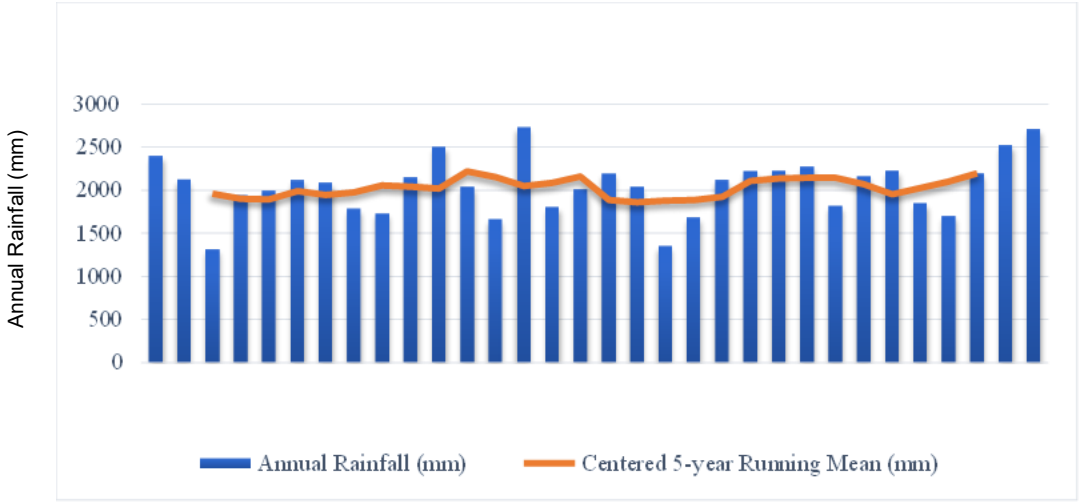

Figure 11 - Annual Rainfall Totals for Hulhule' Station (1993-2024)

4.1.3 Distribution of Daily Rainfall Intensities

The frequency distribution of the daily rainfall was analyzed by plotting a histogram of the daily sums as shown in Figure 12. Most of the events occurred in the range 0-100 mm/day. This technique can be used to categorize rainfall into light, moderate and heavy intensities, which is critical for characterizing the rainfall regime. The results indicate that most days recorded less than 10 mm/day, while approximately 2.05% of the days recorded over 50 mm/day. Although rare, these high-intensity days made a disproportionately large contribution to annual totals and often coincided with flood events in Malé. The distribution is positively skewed, a pattern typical in tropical climates where a small number of convective storms dominate the hydrological cycle (Falkland & White, 2020). The rationale for applying this method is that average annual rainfall does not adequately capture the extremes most relevant to urban flood risk, whereas intensity distribution provides a more direct link between rainfall attributes and hydrological hazards.

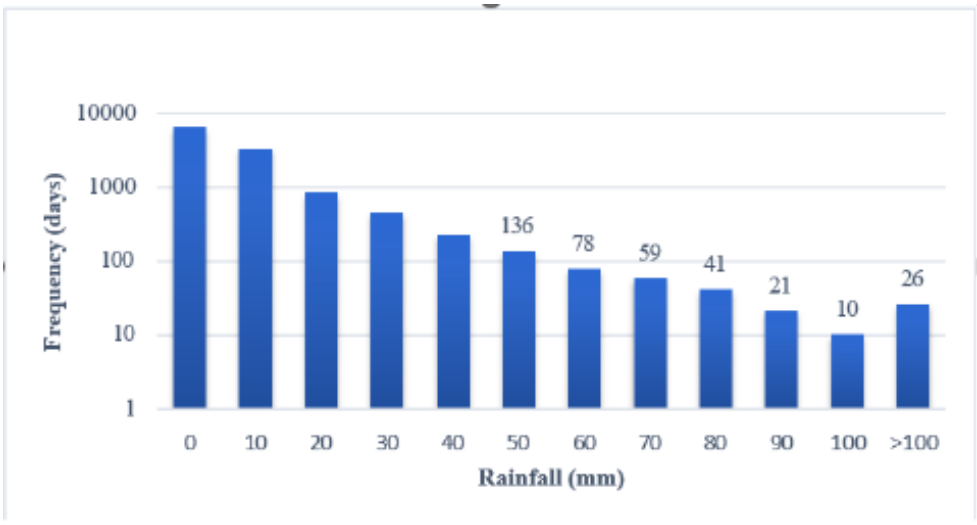

Figure 12 – Frequency Distribution of Daily Rainfall for Hulhule' Station (1993-2024)

4.1.3 Identification of Extreme Daily Events

Extreme rainfall days were identified by ranking daily rainfall totals in descending order to determine the highest rainfall days. This is a straightforward yet effective method that allows comparison with documented flood events, as extreme rainfall is the primary cause of flooding in Malé. The highest daily rainfall values recorded were 192.7 mm on 31 Dec 2023, 170.4 mm on 18 Oct 2005 and 165.8 mm on 17 Jul 2022. Figure 13 illustrates the maximum annual daily rainfall. The identification of such events highlights their rarity while also providing empirical benchmarks against which reported flood incidents can be validated.

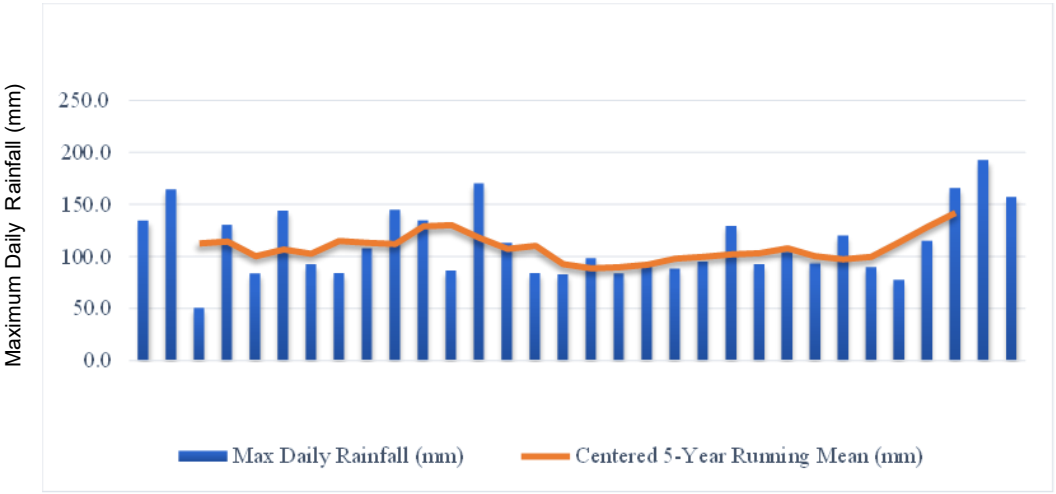

Figure 13 - Annual Rainfall Maxima for Hulhule' Station (1993-2024)

4.1.5 Extreme Rainfall Frequency Analysis

The probability of occurrence of rare but critical rainfall events was determined through a frequency analysis of the annual maximum daily rainfall using Gumbel Extreme Value Type I distribution (EV1). This type of statistical approach is widely applied in hydrology to estimate the magnitude of rainfall events with respect to specific return periods (Chow, Maidment, & Mays, 1988).

The equation used is $XT = \bar{X} + KT \cdot \sigma$, where XT is the rainfall intensity with a return period T (mm/day), $\bar{X}$ is the mean of annual maximum daily rainfall series, σ is the standard deviation of the annual maximum daily rainfall series, and KT is the frequency factor based on Gumbel distribution. The frequency factor is defined as: $KT= (yT - \bar{y})/sy$ where yT is the reduced variate with a return period T calculated as $yT = -\ln[-\ln(1 - 1/T)]$, $\bar{y} = 0.5772$ is the Euler-Mascheroni constant (mean of the Gumbel distribution), and $sy = 1.2825$ is the standard deviation of the reduced variate. This method is particularly suited to modeling the distribution of annual maxima and is widely used in the hydrological design of stormwater infrastructure.

The method of moments was applied to estimate the location (μ) and scale (β) parameters of the Gumbel EV1 distribution using: $\beta = s \cdot \sqrt{6}/\pi$ and $\mu = \bar{x} - \gamma\beta$ ($\gamma = 0.577215664901533$, $\bar{x}$ = sample mean of annual maxima, s = sample standard deviation). This estimation ensures consistency between the reported mean and variance of the data and the return-period magnitudes in design calculations. A Gumbel EV1 Probability Plot (Figure 14) compares the observed maxima with the

fitted Gumbel distribution, demonstrating that the Gumbel model provides a good fit for extreme rainfall.

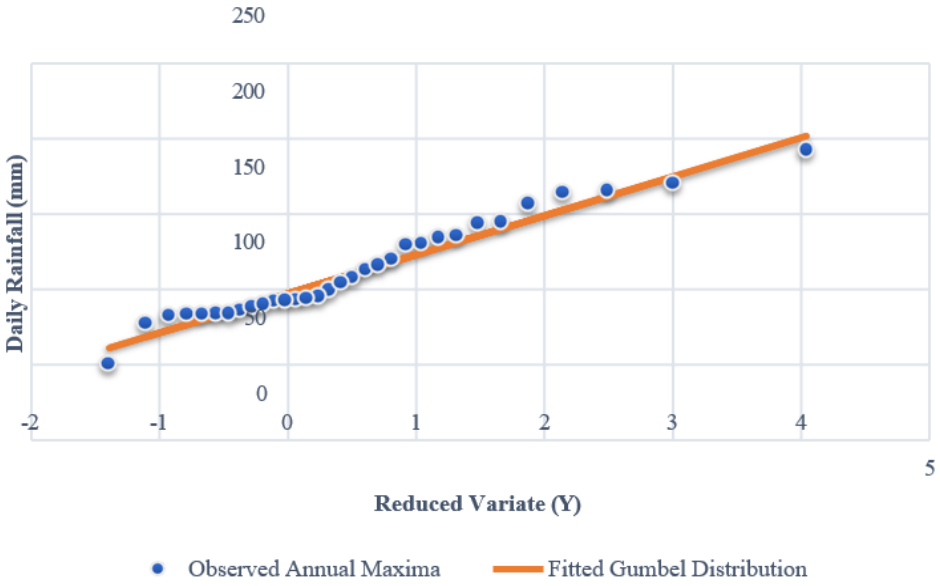

Figure 14 - Gumbel EV1 Probability Plot (1993-2024)

Estimated daily rainfall magnitudes for selected return periods (RP) (based on 1993-2024 AMS) is provided in Table 1. In this context, the maximum daily rainfall recorded was 192.7 mm on 31 Dec 2023, which lies between the estimated RP25 (180.68 mm) and RP50 (198.86 mm) events, and is therefore considered rare and design relevant in Malé.

Table 1 – Estimated Daily Rainfall for Return Periods

Return Period (years)	Rainfall (mm/day)
2	107.5
5	136.79
10	156.18
25	180.68
50	198.86
100	216.90

4.2 ASSESSMENT OF STORMWATER MANAGEMENT SYSTEM

The performance of Malé's stormwater management system was evaluated using the Official Detailed Design Report prepared by Royal HaskoningDHV (2023) as a benchmark for system capacity. This design study provides the most comprehensive assessment of the existing drainage network and is directly relevant for understanding how the city's infrastructure responds to the extreme rainfall events identified in this research.

4.2.1 Design Basis

The system was modelled using InfoWorks ICM (v11.0), a 1D-2D hydrodynamic model capable of simulating both subsurface drainage and overland flooding. The design was based on an RP5, 12-hour rainfall event, in accordance with the Maldives National Guideline for Stormwater Drainage (2021) (Royal HaskoningDHV, 2023). The rainfall design inputs were derived from Hulhulé station Intensity-Duration-Frequency (IDF) curves. As shown in Figure 15, the IDF curves illustrate the rainfall intensities across various return periods.

The report also stated that higher return periods for RP25 and RP50 were not considered in the final sizing. However, independent rainfall analysis in this study demonstrated that recent observed extremes (e.g. 31 December 2023, 192.7 mm in 24hrs) fall within this range. This indicates a mismatch between the design assumptions and current hydrological realities.

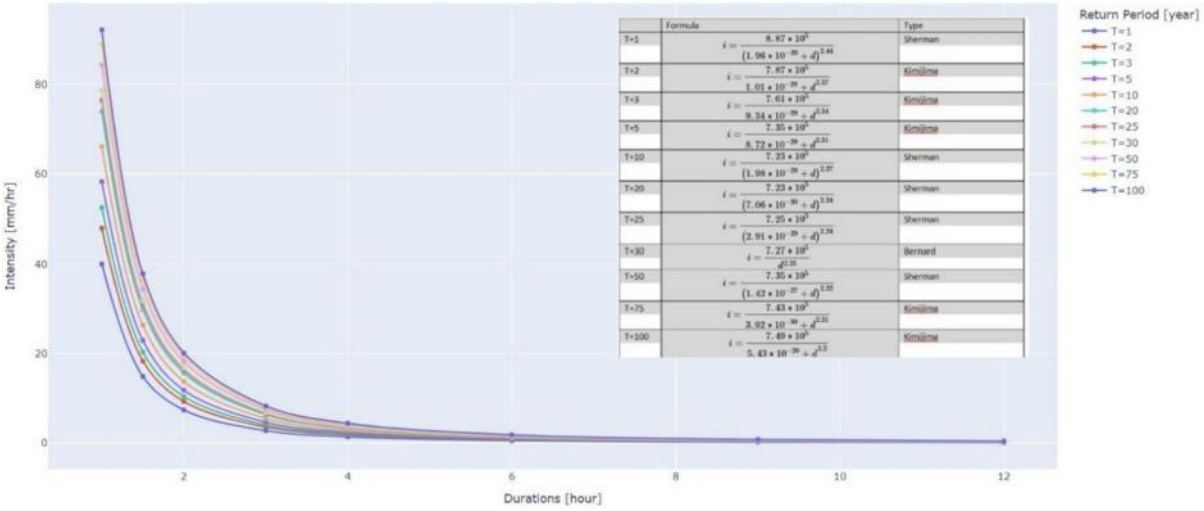

Figure 15 - Intensity Duration Frequency (IDF) Curves in Malé (Royal HaskoningDHV, 2023, Figure 5)

4.2.2 Pipe Diameters, Outfalls and Standards

The drainage system is designed around six large diameter outfall pipes through which stormwater is discharged directly into the sea (Royal HaskoningDHV, 2023). The outfall diameters vary between 1.2 – 2.4 m, depending on catchment size and flow requirements. The proposed system

also incorporates roadside inlets and manholes, spaced to connect with the new outfall pipes (Royal HaskoningDHV, 2023). Standard manhole designs comply with BS EN 1917 (2002) while gully tops and gratings are compliant to BS EN 124-1 (2015). In contrast, the existing smaller gutters (400 mm x 600 mm) and soak pits in the city are identified as inadequate due to clogging, silting, and conflicts with underground urban utilities.

4.2.3 Pumping Stations and Limitations

The majority of the stormwater management system relies on gravity outflow. However, pumping stations have been introduced in low-lying reclaimed areas to address shallow groundwater and tidal backflow (Royal HaskoningDHV, 2023). The capacity and corresponding catchment lengths are presented in Table 2 below.
Operational challenges such as maintenance requirements, high energy consumption, and groundwater intrusion reduce the overall effectiveness of these pumping stations. These vulnerabilities are consistent with NDMA flood incident reports, which highlight persistent waterlogging in the same zones.

Table 2 - Pump Capacity Details

Pump Capacity Details		
PS ID	PUMP CAPACITY	CATCHMENT LENGTH (m)
LS-01	21kW + 21kW	298
LS-02	21kW + 21kW	339
LS-03	09 kW	339
LS-04	09 kW	129
LS-05	09 kW	127
LS-06	09 kW	219
LS-07	21kW + 21kW	557
LS-08	09 kW	325

Pump Capacity Details		
PS ID	PUMP CAPACITY	CATCHMENT LENGTH (m)
LS-09	09 kW	112
LS-10	09 kW	433
LS-11	09 kW	266
LS-12	09 kW	579
LS-13	09 kW	248
LS-14	09 kW	205
LS-15	21kW + 21kW	651
LS-16	21kW + 21kW	722

4.2.4 Hydraulic Performance

Hydraulic modelling results (Royal HaskoningDHV, 2023, Figures 19-29) show that during an RP5 event, significant inundation still occurs in the central low-lying area where runoff from both the old city and reclaimed zones join together. Simulated flood depths ranged from 0.3-0.4 m and persisted for up to 16 hours after rainfall. This outcome aligns with independent Gumbel EV1 analysis which indicates that rainfall events 25-50-year return periods (as of 2012) have already been observed in recent years. Therefore, although the system was designed for RP5, actual rainfall extremes and NDMA flood records demonstrate that return levels exceeding beyond RP25 are now relevant. These findings confirm that the system, despite being recently upgraded, remains under-designed relative to current climate variability.

5. DISCUSSION

5.1 RAINFALL CHARACTERISTICS (1993-2024)

The rainfall analysis for the period January 1993 to December 2024 provides a detailed description of both long-term and short-term variability in precipitation patterns in the study area. The data indicates significant annual variations in rainfall amounts, with values ranging from relatively low rainfall years to years of extreme rainfall. Such variability is consistent with the influence of monsoon circulation systems, the intertropical convergence zone, and episodic climatic events such as the El Niño-Southern Oscillation (ENSO) which have been shown to affect rainfall anomalies across the Indian Ocean basin (McPhaden et al., 2006).
Annual accumulations reveal rainfall is distributed throughout the year, though inter-annual variability is high. Some years recorded more than 2,800 mm while others fell below 2,000 mm, illustrating the limitations of relying solely on mean annual values for hydrological planning. The analysis further shows that extreme wet years have become more clustered in recent decades with 2023 and 2024 being significantly high. This suggests a possible intensification of rainfall, consistent with climate change projections for the South Asian monsoon region, which indicate a trend toward more intense and concentrated rainfall patterns (IPCC, 2021).

Daily rainfall distribution highlights the dominance of low to moderate-intensity events, interrupted by occasional high-magnitude rainfall. An analysis of the largest daily rainfall events identified several days with totals exceeding 150 mm, with the maximum occurring in December 2023. Importantly, the clustering of extreme daily events in the past decade is of particular concern for urban flood risk, as such events are often the direct catalysts of severe flooding in low-lying cities like Malé (McPhaden et al., 2006; IPCC, 2021). The fact that these extremes occur during both the southwest and northeast monsoon underscores that heavy rainfall is not seasonal but can occur throughout the year (IPCC, 2021).

The application of the Gumbel Extreme Value Type I (EV1) distribution to the daily rainfall data provides estimates of rainfall magnitudes for various return periods. The 2-year return level, typically used as a design parameter, was estimated at approximately 107.5 mm/day, reflecting an event likely to occur frequently. In contrast, the 50- and 100-year return levels exceed 190 mm/day, which is substantially greater than the median annual maxima (Chow et al., 1988). While such events are rare, they cannot be ruled out within the planning horizon for critical infrastructure. This has significant implications for stormwater drainage design and flood preparedness, particularly given the low land elevation of the study area and its high vulnerability to rapid run-off accumulation (Royal HaskoningDHV, 2023).

5.2 IMPLICATIONS OF RAINFALL EXTREMES

Statistical evidence showing the prevalence of moderate rainfall and occasional extreme storms has major implications for the resilience of urban infrastructure and the long-term water management planning. Malé and nearby islands are vulnerable to both high annual totals and single-day extreme events, many of which exceed the current stormwater drainage capacity. For example, rainfall events exceeding 150 mm in 24 hours have been recorded more than once in the past decade, with magnitudes far beyond the capacity of conventional urban drainage systems in small islands (Butler & Davies, 2011).

From a design perspective, Gumbel-derived return levels are critical for engineering applications. At present, the infrastructure in Malé is designed only for the 5-year return period, which fails under more severe but still probable storms. By contrast, 25-year design requires capacity for around 180 mm/day rainfall while the 100-year design level is approximately 217 mm/day. The compact, impermeable urban surface of Malé directs these high rainfall volumes into rapid runoff creating severe ponding and localized flooding within minutes. This highlights the need for stronger design standards, not only for the average conditions, but also for extreme events that are becoming more frequent under climate change.

From a risk management perspective, the clustering of extremes in recent years raises concerns about the adequacy of relying solely on historical data to predict future conditions. While the 1993-2024 record is relatively reliable, climate change projections indicated that rainfall extremes in the Maldives and South Asia will likely increase in frequency and intensity (IPCC, 2021). This uncertainty implies the need for conservative safety margins in designs. Furthermore, the potential for compound risks such as heavy rainfall with high tides or storm surges could adversely affect flooding impacts. However, this study did not consider such interactions, as only rainfall data were analyzed.

Another implication relates to urban resilience and emergency preparedness. Rare extreme rainfall events can cause disproportionately high social and economic disruption in Malé, where population density exceeds 65,000 persons per square kilometer and open land for temporary flood storage is limited (World Bank, 2020). Under these conditions, flooding can damage property, disrupt transportation, contaminate freshwater lenses, and pose significant public health risks.

Therefore, rainfall analysis must not be considered as an academic exercise but as the foundation for adaptive management strategies like stormwater network upgrades, investments in real-time flood warning systems, and the adoption of green infrastructure solutions such as permeable pavements and rain gardens.

5.3 FLOOD INCIDENT REPORTS (2023-2024)

The NDMA case registries for the period 2023-2024 provide an important source of evidence linking extreme rainfall with flood-related disruption in Malé (NDMA, 2024). While records from earlier years in the registry lack sufficient detail for quantitative analysis, the data for 2023 and 2024 are detailed enough to emphasize both the frequency of the flooding events and their associated impacts. The clustering of incidence during this period may be partly due to improved reporting systems but may also reflect an actual increase in the frequency of extreme rainfall events.

One of the most notable events was the heavy rainfall on 31st December, 2023, which resulted in nearly 193 mm in 24 hours (MMS, 2024; NDMA, 2024). Although this event technically occurred in 2023, it was recorded in NDMA reports in early 2024, reflecting a lag in administrative processing. Statistically, this event is significant because it corresponds to 25-50-year return period storm according to the Gumbel EV1 rainfall analysis, underscoring both the rarity and severity of the event. Moreover, records of widespread impacts from this storm further validate the rainfall analysis presented in the previous section of this study (NDMA, 2024).

The registries also show that hundreds of people were affected by flood events, with relief assistance often amounting to several hundred thousand Maldivian Rufiyaa (MVR) (NDMA, 2024). Although NDMA reports list both households and individuals, the number of individuals affected

provides a more reliable measure, as household sizes vary and reporting is inconsistent. These impacts demonstrate the vulnerability of Male's dense population to short but intense rainfall events. In practical terms, even the inundation of few streets can prevent thousands of people from accessing workplaces, schools, or essential services given the compact urban fabric (World Bank, 2020).

The provision of relief aid further illustrates that flood management in Malé remains largely reactive. Assistance is provided after flooding occurs to compensate for damages, rather than being prevented through adequate drainage capacity or proactive preparedness measures (Royal HaskoningDHV; NDMA, 2024). This aligns with this study's broader observations that the existing stormwater system is inadequate to avoid the impacts of rare but increasingly frequent extreme rainfall events.

5.4 STORMWATER SYSTEM CAPACITY AND LIMITATIONS

The official stormwater system design prepared by Royal HaskoningDHV (2023) provides the most comprehensive technical evaluation of Male's drainage network. The system was designed based on a 5-year return period (RP5), using a 12-hour rainfall event consistent with national guidelines. However, this design standard is no longer adequate when compared with observed extremes. Rainfall analysis conducted in this study has shown that events corresponding to RP25-50 have already occurred, most notably the storm on 31 December 2023. This mismatch highlights that the newly designed infrastructure cannot provide the level of protection that is now required.

The drainage system consists of six major outfalls that discharge stormwater directly into the sea, with pipe diameters ranging from 1.2 m to 2.4 m. These are supported by roadside inlets and manholes designed in accordance with BS EN 1917 and BS EN 124-1 standards. However, both field observations and the design report highlight the vulnerability of these structures to clogging, siltation, and conflicts with other urban utilities. Hydraulic modelling conducted in the design study showed that, even under an RP5 event, water depths of 0.3-0.4 m could remain in central low-lying areas for up to 16 hours. This simulated outcome is consistent with NDMA records, which show repeated incidents of flooding in these zones.

Pumping stations were introduced in reclaimed areas to address shallow groundwater levels and tidal backflow, but they have limited capacity and are vulnerable to maintenance issues and power interruptions. The design report notes capacities ranging from 9 kW to 42 kW per station, yet NDMA incidents records indicate that waterlogging still occurs during high-intensity storms. This may be attributed not only to pump limitations but also to bottlenecks in upstream pipes and inlets, which restrict flow before it reaches the pumping stations.

Taken together, these findings demonstrate that Malé's upgraded stormwater system has provided an improved baseline but still falls short of addressing current flood risks. The system was designed for a return period that no longer reflects the intensity of rainfall events now being experienced, and operational shortcomings further exacerbate this under-design. As a result, the system leaves significant residual flood risk even when functioning as intended.

5.5 INTEGRATED POLICY RECOMMENDATIONS

A synthesis of the findings provides several important policy recommendations for policymakers:

1. Upgrade stormwater infrastructure design criteria. Drainage networks, road elevations, and pumping stations should be upgraded to withstand at least 25- and 50-year rainfall events given that such magnitudes have already been observed in recent years.
2. Mainstream rainfall return-period data into urban planning. Urban master plans and zoning regulations should mandate on-site stormwater retention and infiltration measures for new developments, thereby reducing direct load on the municipal drainage system.
3. Strengthen monitoring and institutional coordination. Enhanced data-sharing between the Maldives Meteorological Service (MMS), Malé City Council, and the Ministry of Environment is essential to integrate real-time rainfall and flood information into operational decision-making and emergency response.
4. Develop compound risk management strategies. Flood management frameworks must account for interactions between extreme rainfall, tidal peaks, and storm surges, which together exacerbate flood severity and urban disruption.
5. Adopt adaptive planning approaches. Infrastructure planning should incorporate climate change projections and uncertainty margins to avoid maladaptive investments and ensure flexibility in future upgrades.

6. CONCLUSION

This study analyzed flooding risks in Malé by combining three core analyses: rainfall patterns over the period 1993-2024, flood incident records from NDMA (2023-2024), and the performance of the city's stormwater management system as assessed in the Royal HaskoningDHV (2023) official design report.

The rainfall analysis revealed a high degree of interannual variability, with an average of about 2,013 mm per year, but also a clustering of extreme daily events in recent years. The highest observed event of 192.7 mm on 31 December 2023 lies between the 25-50-year return levels, confirming the re-emergence of higher rainfall extremes in Male (MMS, 2024). Gumbel EV1 frequency analysis showed that 2-5-year storms are quite frequent, but higher return period events have already been observed within the available data record (Chow et al., 1988). This indicates that design assumptions based on short return periods underestimate present hydrological realities.

Flood incident reports from NDMA (2024) provided evidence of the direct human and economic consequences of these extreme rainfall events. In 2023-2024 alone, hundreds of people were affected, with relief assistance amounting to hundreds of thousands of MVR (NDMA, 2024). These reports supported the rainfall analysis, as large hydrological events corresponded with significant flood damage. However, the fact that reliable reporting has only been available for the last two years highlights systemic challenges in long-term data collection and institutional record keeping.

The stormwater infrastructure assessment revealed a significant mismatch between design assumptions and actual conditions. While the stormwater management system was modelled for a 5-year return period rainfall, current extremes already fall within the 25-50-year range. Hydraulic simulations in the design study by Royal HaskoningDHV (2023) showed ponding of up to 0.4 m, even under RP5 rainfall intensities, lasting for as long as 16 hours. These outcomes are consistent with NDMA incident reports. Furthermore, limitations in pumping capacities, reliance on gravity outflows and vulnerability to maintenance problems further reduce the system’s effectiveness.

Taken together, these results show that Male's existing stormwater system, despite recent upgrades, remains under-designed relative to the observed rainfall extremes. The combination of high population density, impermeable urban surfaces and extreme rainfall events yields disproportionately severe impacts, even from localized flooding. Without revised design standards, stronger data collection mechanisms, and improved planning, Malé will continue to face high levels of disruption from both pluvial and coastal flooding.

This study contributes to the pool of knowledge on Male's flooding risks by providing an integrated perspective - linking long-term rainfall data, recent flood incident reports and system capacity evaluations. The findings highlight the need to shift stormwater design criteria to at least 25-50-year return periods, enhance the reporting of flood incidents and incorporate compound risk assessments that include tidal and storm surge interactions. By pairing hydrological data with infrastructure realities, this study underscores the importance of adaptive and forward-looking planning to safeguard Malé’s population and urban infrastructure from future flood risks.

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Appendices

The full set of appendices accompanying this thesis is available through the Metabolism of Islands repository and can be accessed at https://metabolismofislands.org/.