Promoting Green Urban Development in Africa:

Enhancing the relationship between urbanization, environmental assets and ecosystem services

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PREFACE AND ACKNOWLEDGMENTS

This study forms one of the case studies of a larger study on Green Urban Development commissioned by the World Bank and co-funded by The Nature Conservancy. Anchor Environmental Consultants (Anchor) was subcontracted by AECOM to undertake case studies in three cities: Kampala, Uganda; Dar es Salaam, Tanzania; and Durban, South Africa. Each city was consulted as to the focus of the case study. In the case of Dar es Salaam, the city requested a study to evaluate the potential costs and benefits of rehabilitating the Msimbazi River and catchment to address the flooding problems associated with this river system. This study builds on the preparation of an Environmental Profile for Dar es Salaam by AECOM, as well as on earlier work on flooding in the city led by one of our team members, Raffaele de Risi.

The study was led by Drs Jane Turpie of Anchor Environmental Consultants and Timm Kroeger of The Nature Conservancy. Gwyneth Letley and Katherine Forsythe of Anchor and Dr Liz Day of Freshwater Consulting Group undertook the ecological and green urban design aspects of the study and associated costings. Dr Raffaele de Risi of Bristol University and Dr Francesco de Paola of Naples University undertook the hydrological and hydraulic modelling and flood damage estimates.

We are grateful to the Dar es Salaam municipal staff for their interest and support of this project, in particular to local World Bank consultant Amy Faust for her valuable inputs and assistance with data collation and to Mary Bitekerezo (social development specialist) for her advice on resettlement. Nancy Lorenzo Garcia of the World Bank kindly provided detailed land cover data.

Thanks to Roland White and Chyi-Yun Huang of the World Bank and Diane Dale, Brian Goldberg and John Bachmann of AECOM for inputs and discussions during the project planning phase, as well as to Elizabeth Tellman (Arizona State University) and Daniel Auerbach (U.S. EPA) for their technical guidance on hydrological aspects.

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EXECUTIVE SUMMARY

Introduction

Rapid urbanisation is taking place at an unprecedented rate throughout the world, with the rate of growth often outpacing urban planning and the capacity of city managers. As a result, existing natural areas within cities, which provide a range of benefits to urban dwellers are becoming smaller and degraded, and problems such as flooding, air pollution and water pollution are becoming worse in many places. African cities often lack the resources to deal with these problems. However, a number of studies have suggested that investing in the maintenance or restoration of natural infrastructure in many cases may not only address given problems at comparable or lower cost than conventional engineering projects, but also generate multiple additional benefits that ultimately translate into cost savings and increased human wellbeing.

Meanwhile, great strides have been made in the design of sustainable mechanisms to deal with urban environmental issues, stormwater flows and the attendant pollution problems, and management and planning of cities is increasingly taking a holistic approach that includes the use and conservation of semi-natural and natural areas within cities as part of a green urban development strategy. One of the challenges of green urban development will be to find the right balance between ecological infrastructure (natural systems), "green" (= environmentally friendly) built infrastructure, and conventional ("grey") built infrastructure.

Dar es Salaam, located on Africa's Indian Ocean Coast, faces a multitude of environmental problems. Prominent among them is the problem of flooding in and around the city centre, which frequently brings the city to a standstill, as well as causing infrastructural damage. Many factors have contributed to this problem, including unplanned informal settlements in the upper catchment and floodplain areas, a lack of drainage and a lack of solid waste management. The impacts of flooding are also exacerbated by high levels of pollution in the rivers, which increases the risks associated with flooding. In consultations for this study, stakeholders in Dar es Salaam identified the Msimbazi River as being among the most degraded ecosystems in the city and also the source of the most serious flooding problems.

The aim of the study was to explore the potential costs and benefits of undertaking a green urban development approach, including catchment-to-coast restoration measures, to ameliorate flood risk in the Msimbazi River catchment.

The overall approach was to model current flooding and expected annual losses (EAL) in the Msimbazi catchment and to determine the potential change in these after implementation of a range of stormwater management scenarios involving different combinations of feasible measures. The scenarios were then compared in terms of their net present value (NPV), internal rate of return (IRR) and return on investment (ROI).

Study area

Dar es Salaam, the most populous city in Tanzania, has undergone rapid population growth and currently has a population of more than 4.36 million. Much of this growth has taken the form of unplanned residential areas which now account for 75% of the urban area, and many houses have been built in areas previously considered unsuitable, such as on floodplains and river banks. The infrastructure of the city, which is governed by five municipalities (Kinondoni, Ilala, Ubungo, Kigamboni and Temeke), has not been able to keep up with this growth. Most residents still lack access to public services including sanitation and waste collection. During the rainy season, intense rainfall events often cause flooding in certain areas of the city. Of the four main river systems, the problems are greatest in the Msimbazi river catchment, which floods parts of the city centre. This study therefore focuses on the Msimbazi river system.

The Msimbazi catchment covers approximately 300 km^2 and extends across the Kinondoni and Ilala municipalities and beyond the western boundary of the city. Once an important water resource, it is now highly polluted with both solid waste and effluents. While the lower catchment is highly urbanised, further upstream land cover becomes increasingly agricultural, and the source of the Msimbazi falls within the Pugu Forest Reserve. The main river has two tributaries, the Ubungo, which flows through a largely cultivated landscape with some woodland/bushland and urban areas, and the Sinza, which flows through a mainly urbanised catchment and joins the Msimbazi closer to its estuary.

The catchment is densely populated, with densities increasing towards the city centre. At the source, large areas of the Pugu Forest have been deforested due to charcoal production and agriculture. In the upper catchment, agricultural areas, dump sites and quarries border on the river and have degraded the riparian vegetation. Further down the catchment, some floodplain areas are occupied by dense unplanned settlements, and others are heavily used for cultivation. The mid to lower reaches enter more densely populated areas which also include an abattoir and other industries

along the river banks. In the lower catchment, where the Ubungo and Sinza Rivers join the Msimbazi, the surrounds are heavily populated and while there is little residential development in the floodplains, these areas are used for agriculture and appear to have been disconnected from the river channel to some extent by berms. In the Msimbazi estuary, there still exists a large remnant mangrove stand of approximately 0.5 ha. The Msimbazi river system is highly contaminated and pollutant levels exceed many standards for drinking, irrigation and contact with skin. Pollution levels at the river mouth in some cases are over 1000 times the levels considered safe for human contact. The largest contributors to water pollution are inadequate on-site sanitation systems and industrial areas without sewers.

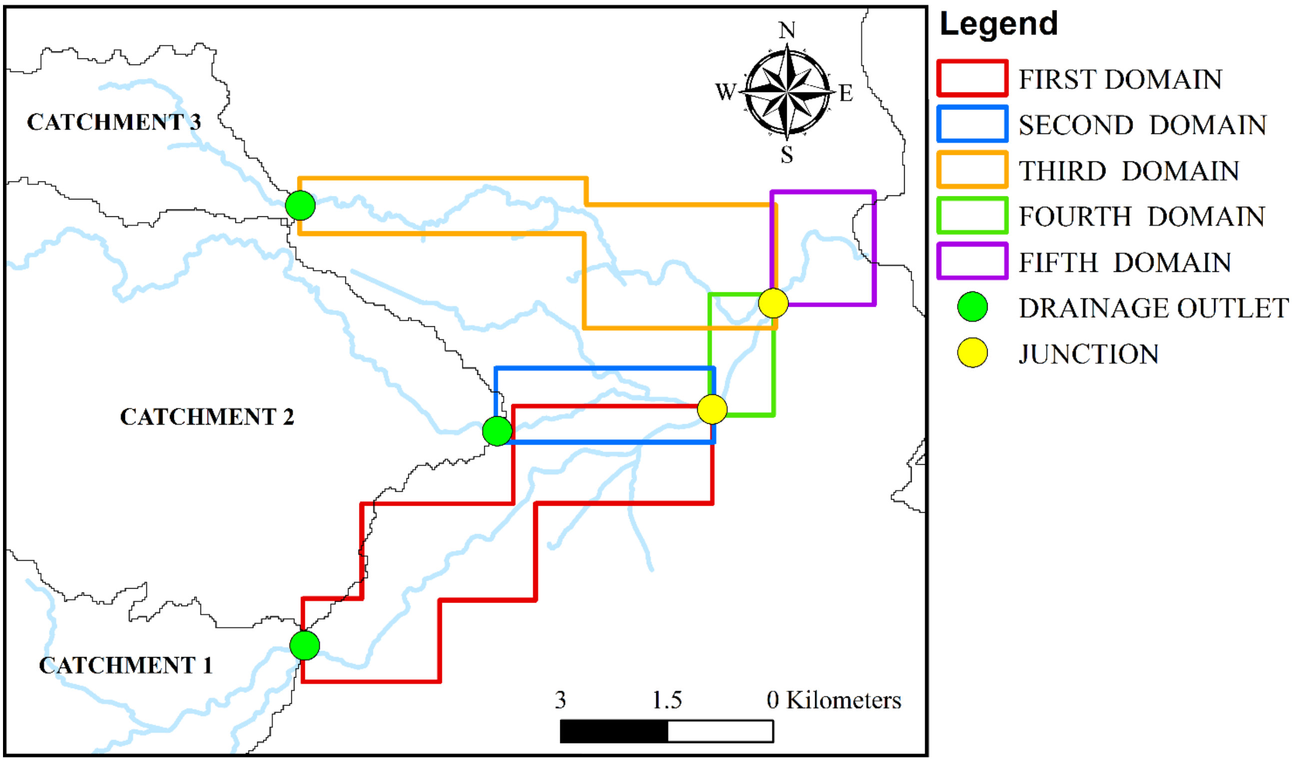
Modelling flood risk in the Msimbazi catchment

Flood risk assessment comprises three phases: hazard, exposure and vulnerability assessment. The hazard is generally assessed through physically-based hydraulic models, providing the flood depth and the velocity for each point within the study area, also accounting for the presence of buildings, infrastructure and soil characteristics. Established methods are computationally demanding, and require significant amounts of data. For developing country contexts, simplifications in modeling hypotheses and assumptions are generally adopted. In this study, flood risk is modelled using a physically-based method. Exposure assessments require identification of the elements at risk, including all the elements of human, built and natural environments at risk in the flooding area. Finally, given the characterization of the built environment, vulnerability analysis can be carried out in order to quantify the adverse effects of flooding. A vulnerability analysis provides infrastructure fragility functions, representing the probability of reaching or exceeding predefined damage states, for a given level of flood intensity. The combination of hazard and vulnerability returns the mean annual rate of exceedance of a specific limit state. This rate can then be used to calculate the probability of exceedance in a given time window, by adopting a reasonable probability distribution describing the event occurrence. This probability can then be combined with the exposed value in order to quantify the flood risk in the predefined time window in terms of economic losses or in terms of number of casualties. The final result is generally expressed as the expected annual loss (EAL).

In the flood hazard assessment, rainfall intensity-duration-frequency (IDF) curves, geologic and land-use information were used to characterize the hydrograph, leading to the calculation of the discharge (Q) and the total water volume (i.e. the area under the hydrograph) for different return periods. This information, together with the topographic map of the zone of interest was used in a two-dimensional diffusion model in order to generate the maps of maximum water height and velocity for each node of a lattice covering the zone of interest for a given return period (the flood hazard map).

Historical rainfall data was obtained from the single meteorological station in the area, located at Dar es Salaam International Airport at 55 m above sea level. We chose five rainfall durations (1, 3, 6, 12, and 24 hours), the typical values adopted. Hydrologic basin modelling was then carried out in order to produce hydrographs for each of the three sub-catchment areas of the Msimbazi river system at the points where they enter the main built environment. The geographic characteristics of the catchments were used to estimate the concentration times of 9.79 hours, 7.80 hours, and 4.16 hours for the main Msimbazi and the Ubungo and Sinza contributory catchments, respectively. Although it is preferable to use a more comprehensive, distributed or semi-distributed model to estimate the design hydrograph, the lack of data with which to calibrate such models dictated the choice of a relatively simple tool – the classic Curve Number Method. The Curve Number is a function of the major runoff producing watershed characteristics, and is fairly well documented for its inputs (soil, land use/treatment, surface condition, and antecedent soil moisture condition (AMC). Our analysis assumed conservatively (based on the historic record) that the AMC class at the beginning of the modelled extreme rainfall events was AMC III.

In the next step, the flood discharge estimated using the hydrograph was propagated through the zone of interest in order to delineate the flood prone areas for various return periods. Flood routing in two dimensions was accomplished by means of the commercial software FLO-2D, a flood volume conservation model based on general constitutive fluid equations of continuity and flood dynamics, i.e. shallow water equations or Saint-Venant equations. The flow is considered variable in space and in time, and the bottom friction is evaluated using Manning's formula. The Manning's coefficients were assigned to computational cells based on a literature review. Conservative estimates of 0.04 and 0.02 were assumed for natural and for urban areas, respectively. The drainage systems not already incorporated in the 2 m DEM (e.g. the sewage system) were omitted due the lack of available data on these systems. In order to optimize computational time, the analysis domain was divided in five sub-domains (ES Figure 1). We then estimated the mean annual frequency of exceeding a given flood height at any point within each domain (flood hazard curves).



ES Figure 1 Flood domains used in the hydraulic analysis

Detailed spatial building information was obtained from OpenStreetMap.com, and intersected with GIS data on Urban Morphology Type to identify the type of each building at risk. The buildings at risk in the analysis domain were identified by intersecting the map of all buildings with the maximum extent of the baseline flood inundation. A total of 12,744 buildings fell within this area. Sixty-two potential combinations of available characteristics were recognized. From these, three main structural types were identified: informal masonry (89.5%), formal masonry (8.8%), and reinforced concrete frame (1.7%). Next, the vulnerability of each type of structure was described using published fragility functions, which evaluate the probability of reaching or exceeding specific damage states for a given hazard intensity. These functions were derived in prior studies in Dar es Salaam and elsewhere.

After estimating the flood hazard curves for each of the buildings at risk, we summarised the flood risk assessment as the mean annual rate of exceedance of a given limit state (critical water height) for a structure beyond which it no longer fulfills a specified functionality. We then estimated the expected annual losses from flooding in the form of damages to buildings, based on the estimated degree of damages and replacement value of the buildings.

Evaluation and selection of potential urban stormwater management options

Urban drainage management has changed significantly over the last few decades, from a conventional ‘rapid disposal’ approach to a more integrated and sustainable ‘design with nature’ approach. There has been a proliferation of related approaches going under terms such as Integrated Urban Water Management (IUWM), Water Sensitive Urban Design (WSUD), urban stormwater Best Management Practices (BMPs), Sustainable Urban Drainage Systems (SUDS) and Low Impact Development (LID). These describe a number of measures to address flooding and/or water quality problems. These tend to be categorised into passive and active structural and non-structural measures, and the active measures, which seek to reduce the effects of urbanisation on the quantity and quality of catchment runoff, can be further categorised into source, local and regional controls, as summarised in ES Figure 2.

Passive structural measures for conveyance

- Drains, swales
- Modify river channel – widen/deepen/levees
- Hydraulic bypass

Active structural measures ("Green engineering")

Source controls

- Permeable pavement
- Infiltration trenches
- Sub-surface soakaways
- Green roofs
- Rainwater harvesting

Local controls

- Vegetated swales
- Filter strips
- Sand filters
- Bio-retention areas

Regional controls

- Detention basins
- Treatment wetlands

Non-structural measures

- Policies, laws and enforcement (sanitation, effluents, litter)
- Solid waste management, river cleaning programmes
- Riparian buffers
- Catchment conservation areas

ES Figure 2 Different types of measures used in stormwater management
Source: This Study

While conveyance measures tend to be highly effective for reducing flood exposure/risk, they achieve little water quality improvement, vary in terms of cost-effectiveness and generally produce relatively small co-benefits. Indeed, they are more likely to lead to externalities such as damage to aquatic ecosystems. "Green" measures (that seek to ameliorate the impacts of urban development on quantity and quality of flows) also vary in their cost-effectiveness and may have to be applied in combination and/or at scale for effective flood protection, but are important for water quality. They also present much greater opportunities for delivering co-benefits, such as water supply (in the case of rainwater harvesting) and the provision of sports and recreational opportunities. The latter is particularly the case for the vegetated options which have greater aesthetic appeal. Green measures include both engineering solutions and the protection or restoration of natural systems in riparian and catchment areas. Within flood prone areas, conservation of natural green infrastructure such as riparian buffers and functional floodplain areas can potentially enhance the value of development setbacks and conveyance measures. Non-structural measures can also be considered "green".

This study sought to find a suitable set of "green" measures that could be implemented in combination to address flooding problems in Dar es Salaam, while also contributing to a green urban development path for the city. Each intervention was assessed on their limitations and requirements as well as their suitability for application in the Msimbazi catchment in Dar es Salaam. The rapid expansion of Dar es Salaam city and the lack of control over settlement patterns, especially in the floodplain areas of the lower catchment, has resulted in increased stormwater runoff, reduced water quality coming from the catchment, and reduced capacity of the floodplain to accommodate and convey flows. The nature and pattern of development in the catchment and flood receiving areas therefore severely constrains both the range of options that could be considered to offset flooding problems and their potential efficacy. Significant manipulation of flow regime in the upstream catchment and/or better conveyance from the flood prone areas is required to improve water quality and address flooding in Dar es Salaam.

Conventional flood conveyance methods are not only expensive but would be difficult to establish in this catchment because of the size of the floods that need to be contained. Very few of the active structural options were considered feasible. In some cases this was because of the low location in the catchment of the building structures they would be associated with, or because of the unsuitable soils. Rainwater harvesting would have limited flood benefits in Dar es Salaam, as the tanks would fill up early in the rainy season. A much better option is to have large-volume storage systems able to absorb high-rainfall events and slowly release the stored water. Thus the potential for detention basins was explored. Swales were also considered for implementation in the lower catchment, high residential, flood prone areas where they could convey rainfall and runoff out of these areas as quickly as possible.

Among the most feasible options identified were the protection, restoration and/or enhancement of natural systems. There are substantial areas of degraded forest in the catchment that could be restored, and floodplains lower in the catchment have been artificially disconnected from the river, greatly reducing their potential for flood mitigation and co-benefits. Restoring the natural hydrological connectivity of the river system will provide numerous ecological benefits and the deepening of the floodplain in the lower catchment provides an opportunity to develop a wetland park which would provide inner city recreational green open space area. Furthermore, there are a number of floodplain areas in the mid-lower catchment areas that could be enhanced to improve their water holding

capacity at the same time as providing other benefits such as erosion control and provision of areas for agriculture and wetlands. The idea of a mixed use enhanced riparian and floodplain area was developed based on the concept of a combination of riparian zone rehabilitation and floodplain enhancement measures that store and retard flows but which could easily include opportunities for beneficial uses, including sports fields, agricultural lots and parks as well as active riparian buffer zones/ conservation corridors. Whilst these beneficial uses of the floodplain could potentially raise initial costs, it is expected that they are likely to reduce opportunities for unplanned resettlement of the floodplain. In addition, a community-based river cleaning programme was included as an essential measure to help deal with the problem of solid waste in the river system that leads to the clogging of drainage infrastructure such as culverts and channels. This could be considered as an interim measure until proper municipal waste collection and management services are implemented.

The extent and location of each physical intervention was estimated using Google Earth and GIS land cover maps in combination with the criteria and limitations described for the interventions to identify the most suitable areas within the catchment for implementing each specific stormwater management measure. The costing of the selected interventions was based on a wide range of information sources collated from literature and various green urban development projects offered in other parts of the world.

The extent and cost of each proposed GUD intervention is shown in ES Table 1. The total initial investment cost of the GUD interventions was estimated to be approximately $40 million with annual maintenance costs in the order of $1.6 million. Just more than 40% of the total investment cost is for the mixed-use enhanced riparian and floodplain areas, which cover almost 500 ha and detain 5 million m^3 of runoff. In addition, costs associated with the resettlement of households from the 60 m River Reserve areas were estimated to be in the order of $44 million. Whilst the River Reserve areas are considered protected areas in which no development is allowed, these areas have not been clearly demarcated or enforced by government. Therefore, unless government acts to enforce this law, people who have settled informally in these areas might need to be resettled in order to execute certain GUD interventions. However, it is important to note that compensation payments are likely to be counterproductive, as they could encourage rent-seeking behaviour in this and other such reserve areas in the future. The costs associated with this scenario are therefore much higher as a result of the River Reserve areas not having been maintained and protected.

Scenario analysis

Five combinations of stormwater management measures were included in the analysis:

1. Riparian setbacks in the flood prone area;
2. Green urban development measures (GUD);
3. GUD measures + riparian setbacks in the flood prone area;
4. GUD measures + additional detention basin(s); and
5. GUD measures + detention basin(s) + riparian setbacks in the flood prone area.

The scenarios are a combination of interventions that either reduce exposure to flooding, reduce flood risk, or a combination of both (ES Table 2). By removing people from flood prone areas within riparian setback buffers the number of people and structures exposed to flooding is reduced. By implementing GUD and additional storage interventions the flood hydrograph is lowered and flood risk is reduced.

ES Table 1 Estimated extent and cost of the proposed GUD interventions

Intervention	Extent (ha)	Initial / construction cost (US$)	Annual maintenance cost (US$)
Swales to improve drainage in flood prone areas	10	1 800 000	108 000
Catchment reforestation in Pugu Forest Reserve	776	845 000	17 000
Mixed use enhanced riparian and floodplain areas (~1m deep)	488	28 000 000	1 036 000
Rehabilitated floodplain and wetland park (~2m deep)	15	3 130 000	94 000
Enhanced floodplain-recessed gardens (~1m deep)	51	5 360 000	107 000
Community-based river cleaning project	-	1 000 000	250 000
Total without resettlement costs	1340	40 135 000	**1 612 000**
Relocation with compensation		44 000 000	
Total with maximum resettlement costs		84 135 000	1 612 000

Source: adapted from TEEB 2010

ES Table 2 Scenarios 1-5 and their estimated costs

		Reduce exposure →	
		No interventions in flood prone areas	People and structures removed from 60m buffer in flood prone areas
Reduce flood risk ↓	No interventions in catchment		Scenario 1 $62.6 million
	GUD interventions in catchment[1]	Scenario 2 $84 million	Scenario 3 $138.5 million[2]
	GUD with additional storage	Scenario 4 $124 million	Scenario 5 $178.5 million

[1] GUD: (a) restoration of forests in upper catchment, (b) rehabilitated and enhanced riparian and floodplain areas in middle catchment, (d) river cleaning in middle catchment, (c) floodplain rehabilitation in lower catchment, (e) swales in flood prone areas.

[2] This is less than the sum of 1 and 2 since the number of buildings at risk in the buffer is reduced, and so a reduced number of households need to be resettled.

ES Table 3 Impacts of Scenarios 1 to 5 on expected annual losses (EAL), and the percentage change in EAL.

		Reduce exposure →	
		No interventions in flood prone areas	People and structures removed from 60m buffer in flood prone areas
Reduce flood risk ↓	No interventions in catchment	Baseline US$47.30 million	Scenario 1 US$37.24 million (-21%)
	GUD interventions in catchment	Scenario 2 US$28.87 million (-39%)	Scenario 3 US$23.16 million (-51%)
	GUD with additional storage	Scenario 4 US$27.78 million (-41%)	Scenario 5 US$21.64 million (-54%)

Modelling the effect of the riparian setback involved removal of buildings from within 60 m of the rivers, therefore changing the number of buildings exposed to flooding. The effect of catchment restoration, which improves infiltration capacity of soils, was modelled by changing the antecedent soil moisture condition from the baseline, wettest AMC III to the moderately moist AMC II, resulting in a change in the input hydrograph. For the floodplain storage area, we used a simple approach of removing from the stream flow the discharge accumulated in the floodplain storage.

The different scenarios were evaluated in terms of their return on investment (ROI), that is, the ratio of benefits and costs. Benefits were taken as the difference in net present value of EAL under each scenario versus the baseline. Costs were calculated as the net present value of the life-cycle costs of implementation of the mitigation measures, based on a review of the literature. A discount rate of 6% was used.

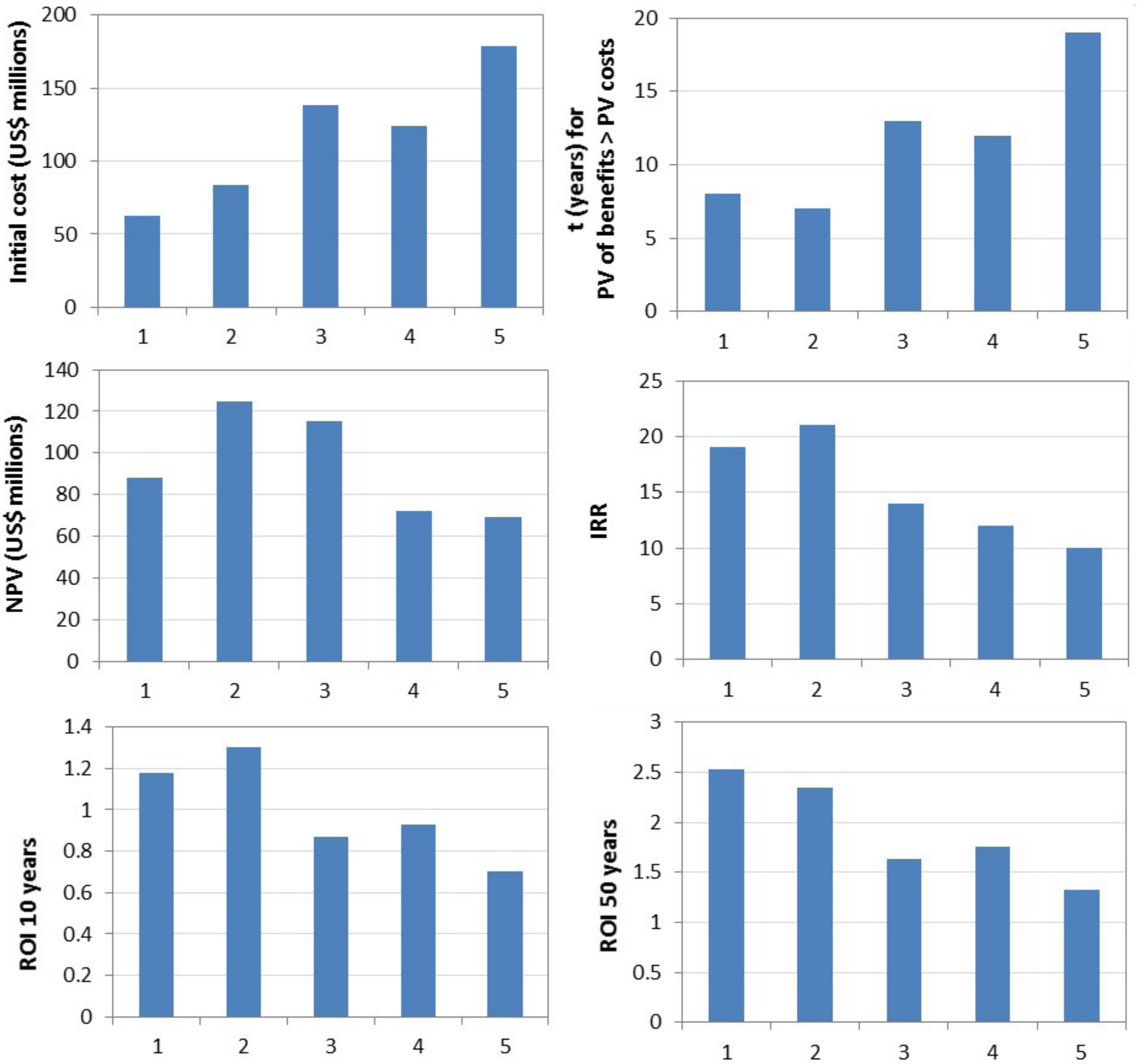
Results

All of the scenarios resulted in a significant impact on EAL associated with flooding in the flood prone areas of the lower Msimbazi catchment, resulting in average annual cost savings ranging from $10 million to $26 million, or from 21% to 54% of present EAL (ES Table 3).

Costs generally increased from Scenario 1 to 5 (ES Figure 3). Nevertheless, all the options considered had positive outcomes, with the time taken for the return on investment to exceed 1 ranging from 7 to 19 years.

Net present value was highest for Scenarios 2 and 3. However, return on investment (ROI) was highest for Scenarios 1 and 2. A similar pattern is observed for IRR, which appears to exceed hurdle rates in most cases.

The results suggest that the investment should initially be targeted at implementation of GUD measures in the catchment areas, and that if sufficient funds are available, these should be used to extend the investment to include resettlement from a setback zone as well (i.e. scenario 3). Factors such as the availability of financial resources, the desired time for ROI to surpass 1 (breakeven time), the impact on the environment (life cycle analysis of the adopted mitigation strategies) and society, should also be taken into account at a definitive design stage.



ES Figure 3 Graphical representation of scenario results

Summary and conclusions

In this study we investigated the potential feasibility of investing in green urban development interventions to alleviate flooding problems in Dar es Salaam by analysing a range of stormwater management scenarios that considered measures that either reduced exposure to flooding, reduced flood risk, or a combination of these. The three types of measures considered - implementation of restoration and rehabilitation measures in the catchment, storage basins, moving people away from flood prone areas – all led to decreases in the damage costs of flooding. Absolute benefits therefore increase as more measures are combined, but so do costs. Taken alone, catchment rehabilitation measures provided higher net benefit than moving people from the flood prone areas, and also yielded the highest rates of return. The addition of a storage basin added least value, but largely because opportunities for the location of such an intervention were too low down in the catchment to be particularly effective. The results suggest that investment should be secured for the implementation of a combination of rehabilitation measures in the catchment that are specifically designed to attenuate flows and improve drainage, including formal solid waste management and community-based river cleaning programs, reforestation in the upper catchment, the rehabilitation of river buffers in the middle catchment and the reconnection of floodplains in the lower reaches. This could be part of an even broader catchment-to-coast rehabilitation programme for the Msimbazi River system which also aims to address water quality problems and the need for green open space within the rapidly-growing city.

It is important to note that this analysis did not capture all the costs and benefits associated with the implementation of GUD interventions. On the positive side, these include the amenity benefits associated with the creation of green open space areas along the riparian zones as well as improvement in biodiversity. A green urban development path would offer a variety of opportunities for enhancing the livability of the city. On the negative side, it should be acknowledged that relocation of people away from the setback areas could generate psychological suffering and anxiety in the affected individuals that is difficult to quantify or compensate in monetary terms.

Whilst conventional conveyance measures were not considered during this study it is important to acknowledge that solving the flooding and water quality problems in Dar es Salaam will likely require a combination of conventional and green urban development measures. Within the Msimbazi catchment a number of conveyance measures have been designed as part of the Dar es Salaam Metropolitan Development Project. These include the lining of 8.5 km of the main drainage channel of the Sinza River and 5.4 km of secondary drainage sections along the Msimbazi River. These engineering solutions have been designed for a 1:25 year flood on the Msimbazi River and for a 1:50 flood on the Sinza River. The unit cost of this is estimated to be $1500 - 2500 per m, with a total cost of $29 million. This is similar to the cost of the main GUD intervention included in this study; the rehabilitation and enhancement of middle catchment riparian and floodplain areas which cover 488 ha along the Msimbazi, Sinza and Ubungo Rivers.

The role of catchment riparian and floodplain areas in biodiversity conservation must be emphasised as these areas are considered critical for maintaining ecological connectivity between terrestrial systems, rivers and estuaries. These areas also include opportunities for other beneficial uses, such as sports fields and parks, and are more likely to reduce the chances of informal resettlement of the floodplain. Community-based river cleaning programmes also provide important co-benefits including education, social awareness and community development as evidenced by the effective operation of the Mlalakua River Restoration Project in Dar es Salaam. However the success of such programmes depends on active support and diversified and resilient funding. These green urban development interventions, while designed to control flooding impacts, also contribute to water quality enhancement and present opportunities for generating amenity value, other ecosystem services, and community upliftment. Many of the investments required in the Msimbazi catchment do involve costly rehabilitation (catchment land cover and river-floodplain connection) and relocation of unplanned settlements from river margins, demonstrating that better historic protection of both catchment and floodplain areas would have been a far more efficient development path. This is important for the city to bear in mind as it prepares for rapid expansion, especially toward the south.

Due to the limited availability of data, this study by necessity utilized simple models and assumptions. While the results strongly suggest that catchment rehabilitation interventions would yield a positive outcome in economic terms, the figures presented here are preliminary and warrant further investigation and refinement. The results, do however, provide a useful step towards informing policies and contributing to Dar es Salaam's green urban development path. It is recommended that investment is made in the development of better hydrological data, through establishment of flow and additional rainfall gauges, as well as development of detailed spatial datasets on soils, land cover, the built environment and the city's drainage systems. Moving forward these datasets can then be used to construct a more definitive analysis.

ACRONYMS AND ABBREVIATIONS

AMC	Antecedent soil moisture condition
BOD	Biochemical oxygen demand
BMP	Best Management Practice
CCIAM	Climate Change Impacts Adaptation and Mitigation
CDF	Cumulative Distribution Function
CLS	Collapse Limit State
CLUVA	Climate Change and Urban Vulnerability in Africa
CVM	Curve Number Method
DEM	Digital Elevation Model
DLS	Damage Limit State
DMDP	Dar es Salaam Metropolitan Development Project
EAL	Expected Annual Loss
EMA	Environmental Management Act
FM	Formal Masonry
GDP	Gross Domestic Product
GIS	Geographic Information System
GUD	Green Urban Development
IDF	Intensity Duration Frequency
IM	Informal Masonry
IRR	Internal Rate of Return
IUWM	Integrated Urban Water Management
LCC	Lifecycle cost
LID	Low Impact Development
LIDAR	Light Detection and Ranging
LULC	Land Use Land Cover
MAR	Mean Annual Runoff
NEMC	National Environment Management Council
NMFA	Norwegian Ministry of Foreign Affairs
NTU	Nephelometric Turbitity Units
OSM	Open Street Map
PAP	Project Affected Persons
RAP	Resettlement Action Plan
RCF	Reinforced Concrete Frame
REDD	Reducing emissions from deforestation and forest degradation
ROI	Return on investment
SUDS	Sustainable Urban Development Systems
TEEB	The Economics of Ecosystems and Biodiversity
TIN	Total Inorganic Nitrogen
TMA	Tanzania Meteorological Agency
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorous
TSS	Total Suspended Solids
TZS	Tanzanian standard
UMT	Urban Morphology Type
WCST	Wildlife Conservation Society of Tanzania
WHO	World Health Organisation
WSUD	Water Sensitive Urban Design

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I. INTRODUCTION

Background

Urbanisation is taking place at an unprecedented rate throughout the world, with the rate of growth often outpacing plans and the capacity of city managers, particularly in developing countries. As a result, existing natural areas within cities that provide a range of benefits are becoming smaller and degraded, and problems such as flooding, air pollution and water pollution are becoming worse. This has led to negative impacts on health, income, productivity and quality of life, as well as stretching local and national government finances. These problems are likely to escalate with continued movement of the poor into cities.

Environmental problems are particularly acute in African cities, where the lack of sufficient regulation of urbanization leads to unplanned urban growth characterized by poor or non-existent construction standards (De Risi *et al*. 2013c), and by structures located in high-risk areas such as river banks and flood plains (Sakijege *et al*. 2014), which also increases the risks associated with natural events such as floods, leading to "natural disasters". It also decreases cities' resilience to climate change, under which the likelihood of extreme flooding events is expected to increase (Khan & Kelman 2012, Jalayer *et al*. 2013a). Developing countries already tend to be less resilient to natural disasters because of their fragile economies, poverty, lack of risk awareness, and lack of coping capacities in urban communities (De Risi *et al*. 2013a, 2013b, Jalayer *et al*. 2015).

African cities often lack the resources to deal with these problems. Solutions have traditionally involved costly engineering interventions applied in the developed world. However, several studies have suggested that investing in the maintenance or restoration of natural assets may not only offset much larger engineering costs, but bring multiple benefits that ultimately translate into cost savings and increased human wellbeing. Various types of natural areas exist within urban areas, which yield a range of benefits to different sectors of society.

The benefits of natural ecosystems, or "ecological infrastructure", and more broadly, of "green infrastructure" which also includes man-made ecosystems, are increasingly being recognised in the growing area of research and development regarding urban stormwater management systems. Great strides have been made in the design of sustainable mechanisms to deal with stormwater flows and the attendant pollution problems, and management and planning of cities is increasingly taking a holistic approach that includes the use and conservation of semi-natural and natural areas within cities as part of a green urban development (GUD) strategy. This aligns well with the concept of "green urban development", the essence of which is development that minimizes impacts on and/or enhances the value of the natural environment through incorporation of an optimal mix of different types of green and grey infrastructure (Figure 1.1), in conjunction with supporting non-structural interventions (laws, maintenance, etc.).

The conservation of natural systems and the services they provide is believed to form an important part of this strategy. However, one of the challenges of green urban development will be to find the right balance between ecological and green or grey engineered infrastructure. There is generally a paucity of understanding of both the ecological functioning and the value of the existing natural assets in African cities, or of the trade-offs involved in developments that replace or degrade these assets (e.g. Daily & Matson 2008).

Dar es Salaam, located on Africa's Indian Ocean Coast, has a range of ecosystem types within and around the city that could deliver important ecosystem services (Figure 1.2). Yet many of these have become severely degraded. The degradation of the city's forest and river systems is well known, and is believed to have contributed to the some of the multitude of environmental problems that the city now faces.

At the top of its list is the problem of flooding in and around the city centre, which frequently brings the city to a standstill, as well as causing infrastructural damages. Many factors have contributed to this problem, including unplanned settlements in both the catchment and floodplain areas, a lack of drainage and a lack of solid waste management. The impacts of flooding are also exacerbated by high levels of pollution in the rivers. In consultations that were held for this study, stakeholders in Dar es Salaam identified the centrally-located Msimbazi River as being among the most degraded ecosystems in the city and also the source of the most serious flooding problems.

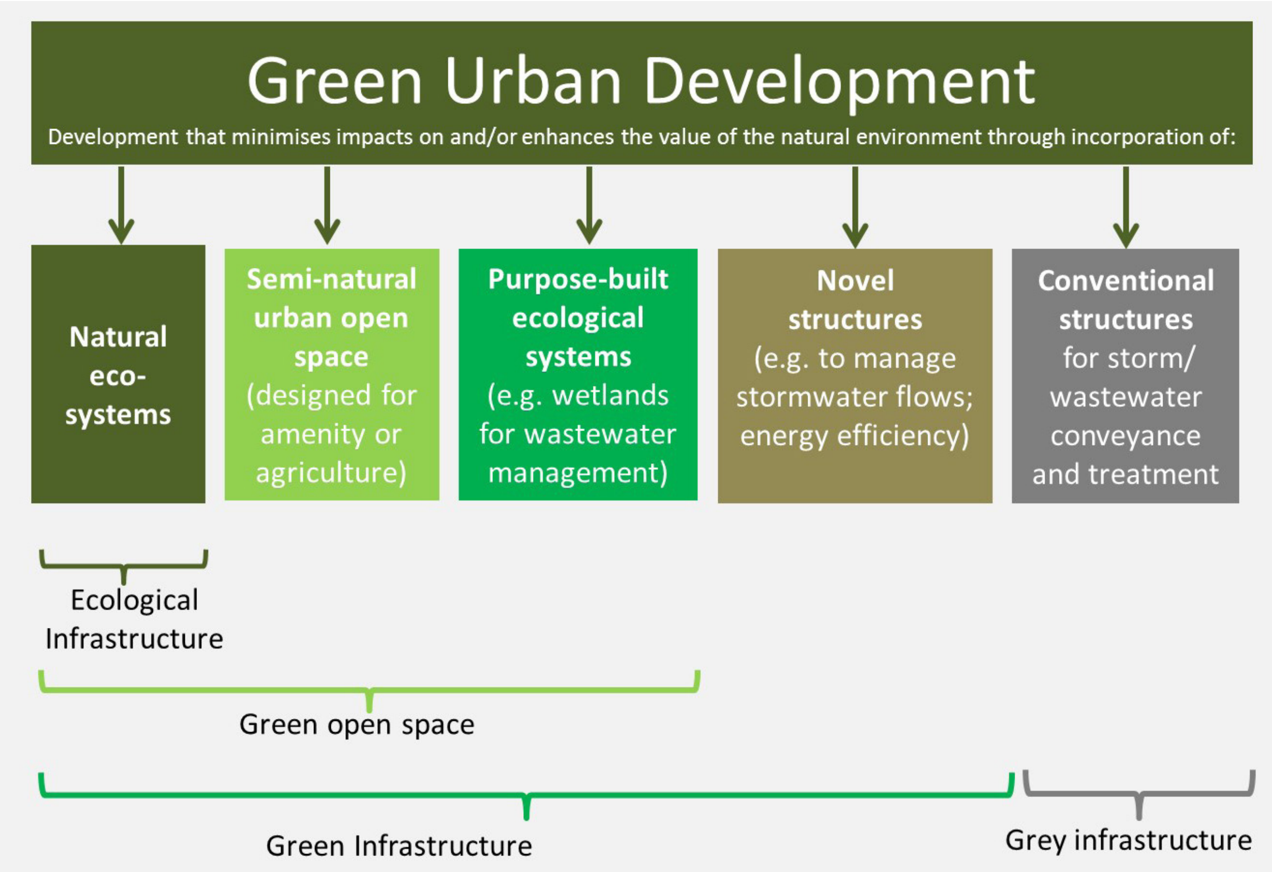

Figure 1.1 Schematic diagramme of the range of infrastructure required for Green Urban Development

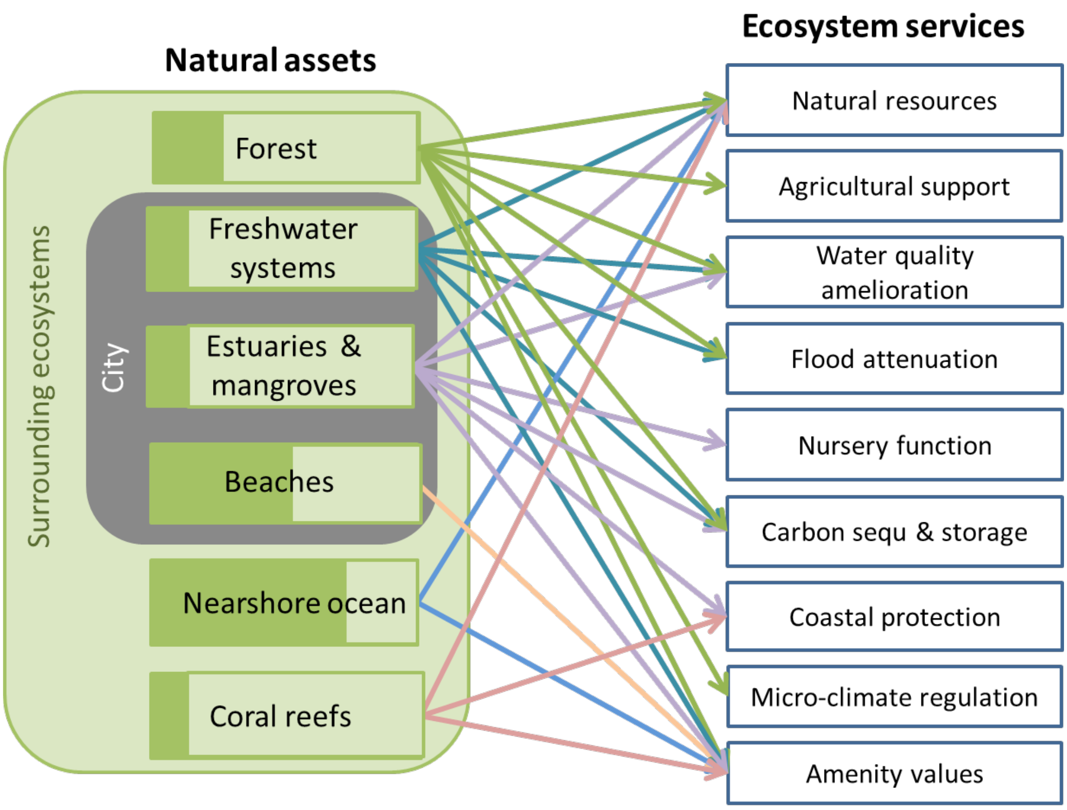

Figure 1.2 Rough sketch of the relationships between environmental assets, ecosystem services and their beneficiaries in Dar es Salaam. Bars provide a qualitative indication of the ecological condition of these ecosystems.

Source: Author

Study aims

The aim of the study was to explore the potential costs and benefits of undertaking a **green urban development approach** to addressing flooding problems in the Msimbazi River floodplain area of Dar es Salaam through a range of complementary measures, including ecological restoration.

The study aimed to provide a high level evaluation of measures to alleviate flood risk as a first step towards the development of more comprehensive plans that include the reduction of pollution loads into the system (notably improved sanitation systems and control of point source pollution), in order to realise the potential capacity of these interventions to also contribute to water quality enhancement and present further opportunities for generating amenity value and other ecosystem services.

1.1.1 Overall approach

The overall approach was to model current flooding and expected annual losses (EAL) in the Msimbazi catchment and to determine the potential change in flooding and EAL after implementation of a range of stormwater management scenarios involving different combinations of feasible measures. The scenarios were then compared in terms of their return on investment (ROI).

The study began with a review of all available information on the Msimbazi River system and its catchment and floodplain areas. The current state of the river system was assessed on the basis of a brief site visit, published and unpublished information including GIS data layers, and examination of Google Earth imagery.

A two-dimensional hydraulic model was set up using Flo2D software to model flood velocities and depths in the flood risk area and to estimate the expected annual losses in terms of structural damages, based on data on building locations, types, values and fragility. Design floods were generated from rainfall data using a hydrological model of the three sub-catchments that discharge into the flood risk area. The models were built using available data on the study area, which is generally poor in quality, necessitating some simplifying assumptions.

A review was carried out on stormwater management options, their efficacy in terms of various criteria, their cost-effectiveness and the necessary or suitable conditions for their implementation. Based on this, and available GIS data on land cover, slope and soils of the catchment, the long list of possible measures was reduced to a set of measures that had both a high feasibility of implementation in the study area and that would be complementary in terms of their effects on the flood risk area. The potential extent of their implementation was then estimated and mapped. Finally, a set of six scenarios was devised which included the full combination and various subsets of these measures.

The hydrology or hydraulic model parameters were adjusted, as appropriate, to simulate the effects of the different measures on the flood hydrograph[1] and/or the conveyance of flood water in the receiving area. The scenarios were compared in terms of their ROI, net present value and internal rate of return in order to identify the best solution to mitigate/avoid future flood catastrophes.

[1] A graph showing the rise and fall in water volume passing a particular point time during a flood event

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II. STUDY AREA

Dar es Salaam

Dar es Salaam, situated on the coast of Tanzania, is a city that has undergone rapid growth and urbanisation in the past few decades. The city has one of the highest population growth rates in Tanzania, which has been near or above 5% per annum for the past 30 years, compared to the national average of 3% (URT 2002, 2012). Estimates from the 2012 census place the city's' population at around 4.36 million with a density of 3.133 persons per km^2 (URT 2013).

The city is governed by three separate municipalities, Kinondoni in the north, Ilala in the centre and Temeke in the south. The rapid growth and expansion of the city has led to the proliferation of unplanned residential areas, especially on the outskirts of the city and along major roads. In addition there is consolidation in already developed areas leading to many houses being built in areas previously considered unsuitable, such as on floodplains and river banks. The result of this rapid expansion and consolidation is that unplanned developments now occupy over three quarters of the city (NEMC 2009, Hill & Linder 2010). While plans are in place to try and formalise the unplanned areas and provide some infrastructure and services, the municipalities have not been able to keep up with the growth of the city and, as a result, most residents still have poor sanitation, inadequate infrastructure and a lack of services (UN Habitat 2010). It should be noted that in Dar es Salaam, unlike many other African cities, the 'informal' structures that are built in unplanned areas are generally constructed using durable building materials and are therefore considered to be relatively permanent structures.

The coverage of storm water drains throughout Dar es Salaam is extremely limited and the majority of the drainage infrastructure, located mainly in the city centre, is currently in poor condition (Draft Dar es Salaam Masterplan 2012-2013). The current sewerage system in Dar es Salaam only services about 10% of the population, leaving 90% of the city relying on on-site sanitation (URT 2014b, TSCP). Even the sewage that does pass through the sewerage system is only partially treated before being discharged into rivers or the ocean. The system consists of 15 pumping stations and 8 independent waste stabilisation ponds that, at best, provide primary treatment of effluent, and a sea sewage outfall (AECOM 2015).

Up to 60% of the solid waste generated in Dar es Salaam remains uncollected with collection rates of 27%, 39% and 41% for Temeke, Ilala and Kinondoni respectively (AECOM 2015). The city of Dar es Salaam only has one operational dumpsite, Pugu Kinyamwezi which is located to the west of the city in a former sand quarry. Other dumpsites have all been shut down through either community protest or court order, due to poor planning and management (Kihampa 2013). The lack of dumpsites, along with the lack of access to all areas, inadequate finances and low priorities within municipalities, have contributed to the solid waste problem in Dar es Salaam.

Lacking proper infrastructure like sewerage systems or waste removal, unplanned areas are a large source of pollution within the city. While both raw effluent and solid waste can contribute to polluting waterways, solid waste can also lead to clogged drains and canals and exacerbate flooding as it hinders the drainage of water during storm events. Not only do these polluted waters pose a health risk to residents that come into contact with the water, but they also pose risks through contamination of clean water sources as well as contributing to the spread of diseases like malaria and lymphatic filarial.

Dar es Salaam has two rainy seasons, March-April-May and November-December. The mean rainfall intensity is highest in the March-April-May rainy season (average of approximately 50 mm in 24 hrs). The most intense single storm events between 1971 and 2009, however, were recorded during the November-December rainy season, reaching 150 mm in 24 hrs (TMA 2011). Up to a 6% increase in mean precipitation during the long rainy season is projected to occur within the next 100 years along Tanzanian coastline (Matari *et al*. 2008). While predictions for changes to overall rainfall in Tanzania are unclear, it is likely that it will result in great variability in rainfall which will likely lead to more frequent and intense droughts and floods (Watkiss *et al*. 2011).

There are four main rivers draining the city municipalities; the Mpiji, Kizinga and Mzinga and Msimbazi rivers. The Mpiji forms the northern boundary of Dar es Salaam, the Kizinga and Mzinga rivers flow into the large harbour south of the city centre, where as the Msimbazi flows through the heart of the city. During the rainy season, intense rainfall events often cause flooding in certain areas of the city. The Msimbazi river valley tends to flood frequently due to its relatively high-clay soil content compared with the well-drained coastal plain sands which characterise the Kazinga and Mzinga river basins (NEMC 2009). While the river floodplains would have flooded naturally after large storms, the increase in hardened surfaces in the catchment area such as roofs, pavement or compacted dirt in conjunction with the inadequate storm water system have exacerbated the flooding, effectively extending the active floodplain area. However it is not only the structures that have been built within the original floodplain area that are at risk, but also structures that have been built in areas that would have been safe from flooding before the level of flooding was increased as a result of increased runoff from the increasingly hardened catchment areas as Dar es Salaam has grown.

This study focuses on the Msimbazi River system, where the flooding problems have been greatest. The river system is described in more detail below.

The Msimbazi river system

2.0.1 Overview of the river system

The Msimbazi catchment is approximately 300 km^2 and extends across two city municipalities, the Kinondoni and Ilala councils, as well as extending west of Dar es Salaam city (Figure 2.1). The Msimbazi River stretches approximately 35 km from Kisarawe outside of the Dar es Salaam and flows into a mangrove estuary within the heart of the city before discharging into the Indian Ocean. It is joined by the Sinza and Ubungo tributaries prior to meeting the ocean.

The Msimbazi River was historically important as a source of water for Dar es Salaam residents, providing water for drinking, bathing, industry and agriculture (NEMC 2009). The river has, however, become progressively contaminated. Up to 55 tonnes of diffuse pollution from illegal solid waste and up to 450 tonnes from other sources enters the Msimbazi River each year (NEMC 2009). While this discourages use as drinking water especially along the main river, some poorer residents in some tributaries are still using the water for human consumption. The most common usage of water is extraction for agriculture.

Landuse within the Msimbazi catchment is divided amongst cultivated land, woodland/bushland and forest, with urban areas concentrated in the lower catchment area but encroaching up into the whole catchment (ILIR 2007, Figure 2.2). The Ubungo catchment has the highest proportion of cultivated land with some woodland/bushland and urban areas, whereas the Sinza is highly urbanised (ILIR 2007).

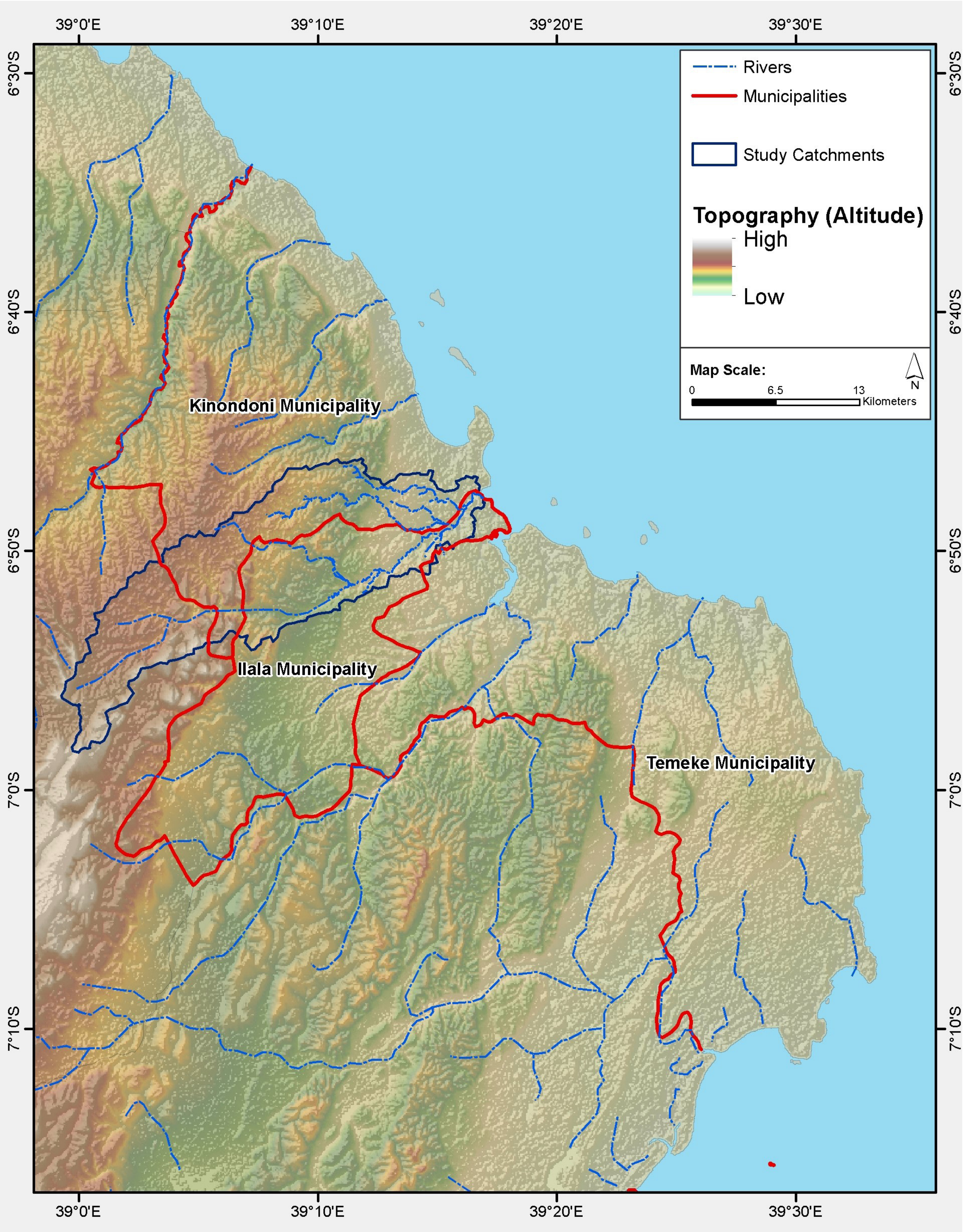

Figure 2.1 Location of the Msimbazi River catchment in relation to the three municipalities of Dar es Salaam, and showing the topographical landscape.

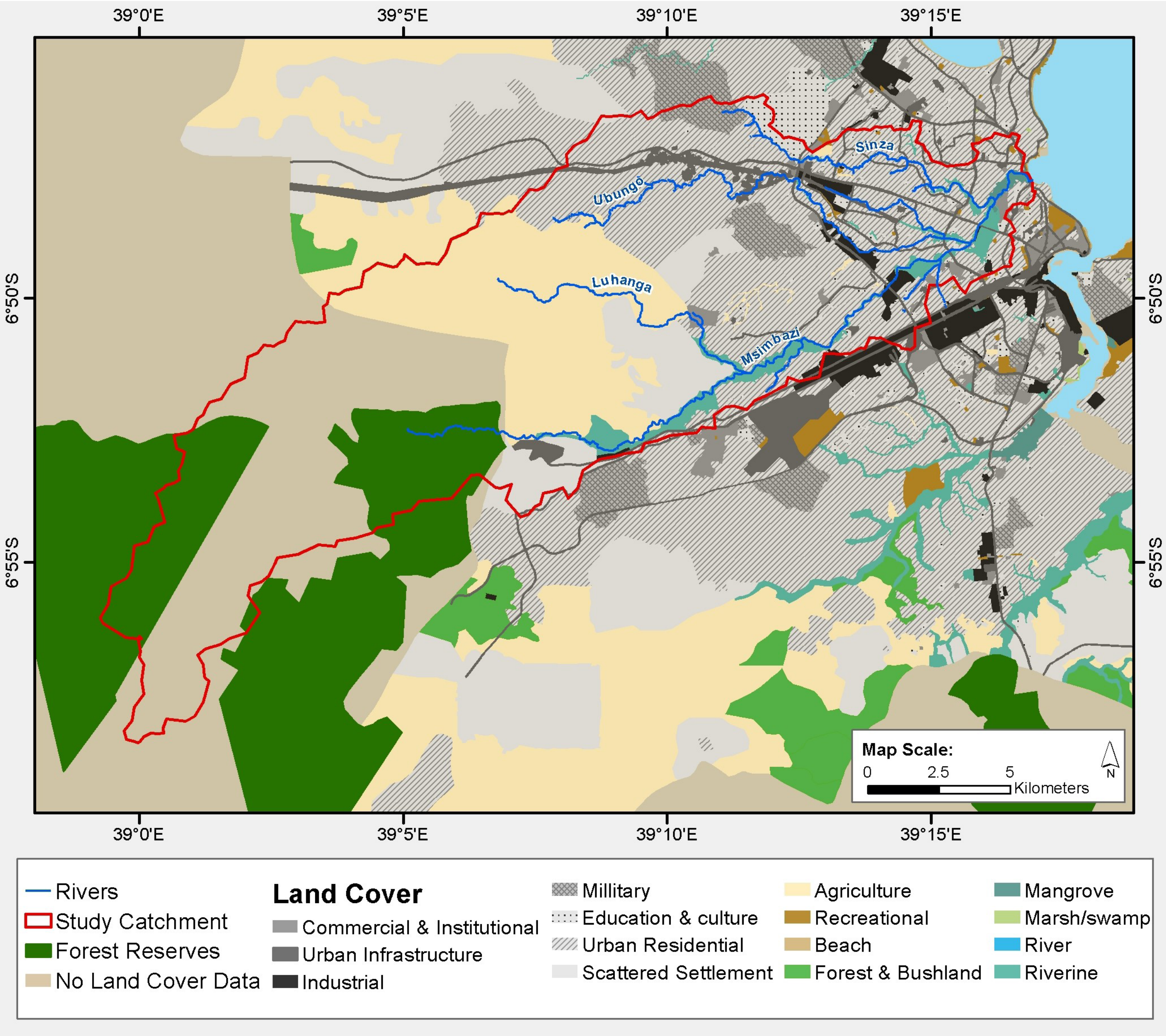

Figure 2.2 Land cover within the Dar es Salaam municipal areas in and around the Msimbazi catchment.

The headwaters of the Msimbazi River are situated in the Pugu Forest Reserve at the top of the catchment. This reserve, while somewhat conserved in comparison to the rest of the catchment, is still considered degraded (CCIAM 2011). The edge of the reserve has been heavily encroached by the surrounding small-scale agriculture and up to 1 km within the reserve is now completely converted. Additionally, from satellite imagery, it is evident that deforestation and thinning of the natural vegetation is also taking place over a large portion of the reserve. Only about 20% of the reserve is considered to be in good condition (CCIAM 2011).

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2.0.2 Condition of the riparian areas

As the Msimbazi flows east out of the Pugu Forest Reserve it crosses crop fields and agricultural land (Figure 2.3). South of the river in an old sand quarry, the city's sole working solid waste dump, Pugu Kinyamwezi dumpsite, can be found. Here the riparian vegetation has been heavily denuded and little remains. Farming and small settlements frequently extend right up to the river banks. As the river approaches the city, the density of settlements increases. Along this stretch there is some remaining riparian vegetation, although it is likely to be degraded.

Figure 2.3 Msimbazi River at the edge of the Pugu Forest Reserve (on left), flowing through agricultural land and scattered settlements showing Pugu Kinyamwezi dumpsite on the south bank. Location of the image is shown in Figure 2.4 (A).

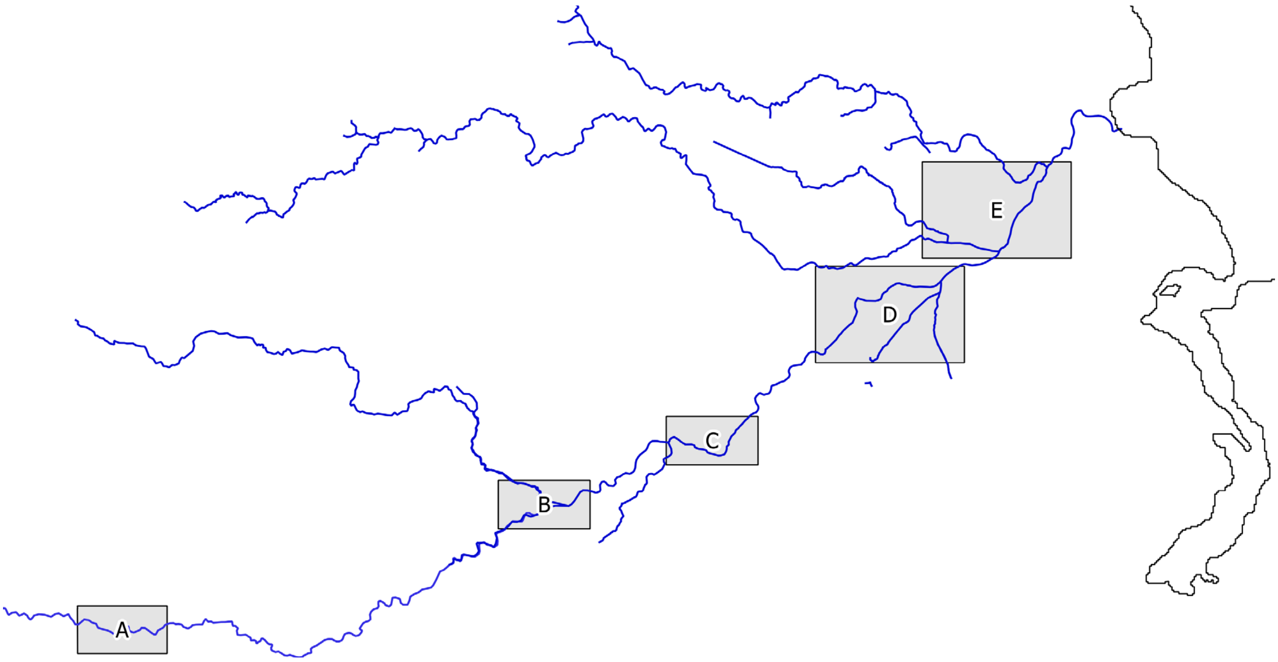

Figure 2.4 Locations of the Google Earth images shown in this section

Figure 2.5 Confluence of Msimbazi River and Luhanga tributary showing some riparian vegetation amongst scattered settlements. Location of the image is shown in Figure 2.4 (B).

At the confluence with a Luhanga tributary (Figure 2.5) there is still some remaining riparian vegetation, despite the increases in density of people. This tributary drains a large area of farmland to the north of the main Msimbazi channel. Below this, the river has an extensive floodplain area that is under dense unplanned settlement. Illegal sand mining in the middle catchment has caused severe degradation and destabilisation of the riparian zone.

Figure 2.6 Msimbazi River flowing through dense residential area and showing industrial areas at the bottom of the image and Vingunguti dumpsite along the banks in the right hand side. Location of the image is shown in Figure 2.4 (C).

The Msimbazi then passes some industrial areas and the old Vingunguti solid waste disposal site on its south bank (Figure 2.6). Adjacent this site the river has been straightened to allow expansion of the dumpsite. This immediate area also houses the Vingunguti Abattoir and mixed residential area. There is very little riparian vegetation along this stretch of the river and occasional scatted urban agriculture.

Figure 2.7 Industrial area surrounding Nelson Mandela Bridge and urban agriculture within the floodplain of the Msimbazi River. Location of the image is shown in Figure 2.4 (D).

Between the dumpsite and the Nelson Mandela Bridge (see bottom left hand corner of Figure 2.7), there are densely populated residential areas on both sides of the river, with occasional small patches of urban agriculture along the banks. At the bridge, there is a large industrial area backing directly onto the river (Figure 2.7). Beyond the industrial area the floodplain opens up into a wide area which is filled with agricultural fields on the south bank, and dense residential areas on the north bank.

Figure 2.8 Confluence of the Ubungo and Sinza Rivers showing large floodplain area and informal settlements. Location of the image is shown in Figure 2.4 (E).

Between the confluences with the Ubungo and Sinza Rivers, the Msimbazi passes through another wide floodplain area which is mainly covered with urban agriculture and scattered dwellings (Figure 2.8). The floodplain areas appear to have been disconnected from the river channel in this area by berms. The agricultural areas are surrounded by mainly mixed residential area. There are also small sections along the river that have been raised and converted to industrial areas.

The Ubungo tributary mainly courses through dense residential areas as well as some industrial areas. There are some tall trees and other riparian vegetation along the banks of this stream. There is limited urban agriculture except in a small floodplain near the confluence with the Msimbazi (Figure 2.8).

The Sinza River originates near the densely vegetated military base and the University of Dar es Salaam. As the Sinza approaches the Msimbazi it passes through formal residential areas with forested riparian buffers. Closer to the city centre, the houses become denser and the riparian vegetation disappears. Before the confluence with the Msimbazi, the river opens into a floodplain that is partially cultivated but also contains many informal dwellings.

2.0.3 Condition of the estuary and mangroves

Natural vegetation along the banks of the Msimbazi River and tributaries is mostly denuded as are natural floodplains and wetlands. Those that do remain are highly degraded and modified. At the Msimbazi estuary, there is still a large mangrove stand of approximately 0.5ha, which is dominated by Avicennia marina (Mremi & Machiwa 2003).

The mangrove system in the Msimbazi estuary serves as a filter for pollution before the river water is discharged into the Indian Ocean. The pollution from residential and industrial effluent as well as that from storm water has the potential to influence not only the health of this mangrove ecosystem, but also the coastal ecosystems including seagrass beds and coral reefs that are situated along the coast. These ecosystems provide important food, shelter and nurseries for a variety of different taxa including amongst others, commercially important fish species.

Examination of the pollution levels within the mangroves at the mouth of the Msimbazi has found high levels of heavy metals not only in the sediments, but also in mangrove roots and leaves as well as in fauna living amongst the mangroves including crustacean and gastropod species (De Wolf *et al*. 2001, Mremi & Machiwa 2003, Mrutu *et al*. 2013). The amount of these heavy metals that are bioavailable and thus can be transported up the food chain has not yet been determined. While some of the levels of heavy metals in the sediment amongst the mangroves are still lower than those reported in some European and American estuaries (Mrutu *et al*. 2013), the rate of increase has been quite rapid (De Wolf *et al*. 2001).

The clay content in the soils in the Msimbazi estuary play a large role in filtering these heavy metals out of the polluted river water. The clay content of the top layer ranged from 17-85%, making it potentially effective at retaining heavy metals, however the retention capability of the mangrove is exceeded by the amount of heavy metals being deposited (Mrutu *et al*. 2013). This indicates that pollution is still passing through the mangrove system and therefore can reach and have the potential to have negative effects on the coastal environments.

A few studies of the nearshore environment just off Dar es Salaam have also indeed showed that there is also heavy metal contamination in these environments (Mremi & Machiwa 2003, Mtanga and Machiwa 2007, Muzuka 2007). In addition, Daudi *et al*. (2012) found that the nutrient enrichment from the waters exiting from the Msimbazi River mouth was having negative impacts of a range of higher trophic levels species that inhabit seagrass beds.

2.0.4 Pollution and flooding

Pollution and flooding are both major problems in the Msimbazi River system, with pollution also exacerbating the impacts of flooding. Pollution comes from a number of different sources including industrial, residential and agricultural effluent, storm water, solid waste and wastewater (Table 2.1). As a result, the Msimbazi River is highly contaminated and pollutant levels exceed many standards for drinking, irrigation and contact with skin. The number of faecal coliform bacteria colony-forming units varied between 27 000 - 580 000 during the wet season and 37 000 - 117 000 during the dry season along the main Msimbazi River (Kassenga & Mbuligwe 2009). In the dry season the highest values were found near the Nelson Mandela Road Bridge, whereas in the wet season the highest values were encountered near the mouth of the river (Kassenga & Mbuligwe 2009). All measurements indicated that the water in the Msimbazi River was not fit for human consumption, and the values at the river mouth are over 1000 times the level that is safe for full contact (e.g. swimming).

Lead concentration in the water also exceeds WHO drinking standards (Mwegoha & Kihampa 2010). The level of lead ranged from 0.083-0.113mg/L, whereas the WHO drinking water standard is <0.01. The highest levels of contamination were found along the main Msimbazi River between the dumpsite and the Nelson Mandela Bridge, while the lowest concentrations were found further downstream between the confluences with the Ubungo and Sinza Rivers (Kassenga & Mbuligwe 2009).

Table 2.1 Point source and non-point source discharge entering the Msimbazi River

Category	Source	Description of effluent/discharge	Pollution concern
Industrial	Tanzania Breweries Ltd	Contains spent grain, yeast and dilute caustic soda	High BOD
	Friendship Textile Factory	Contains detergents, dyes, starch and chemicals	High pH and coloured effluent.
	Dar Brew	Contains spent grain and yeast	High BOD, TSS and low pH.
	Tanzania Dairies	Contains fats and waste milk	High BOD and high pH.
	Robbialac Paints	Contains waste paints	Traces of heavy metals.
	Ubungo Farm Implements	Hot water with traces of metals	Hot alkaline effluent.
	Ubungo Power Station	Contains fuel and lubricating oils	Diesel and oils.
	Diffuse industrial effluent discharge	Sewage from industrial premises discharged directly to stream or through groundwater seepage	High BOD, faecal coliforms, TN and TP.
Residential	Diffuse effluent discharge from on-site sanitation	Sewage from residential homes – flooded pit latrines, septic systems leaking into groundwater or open drains.	High BOD, faecal coliforms, TN and TP.
Agricultural	Diffuse effluent from farm land and animal grazing areas	Run-off contains organics or fertilizers from farms, gardens and grazing lands.	High BOD, TN and TP.
Other	Petroleum hydrocarbon storage and transportation facilities	Run-off contains oils/fuels due to inappropriate disposal of used oil and poor loading and off-loading procedures at depots.	Hydrocarbons in surface waters.
	Wastewater treatment plant	Sewage from three waste stabilisation pond systems.	High BOD, faecal coliforms, TN and TP.
	Institutional effluent e.g. hospitals	Wastewater from wards, theatres, laboratories, mortuary and laundry.	High BOD, COD and faecal coliforms.
	Vingunguti Abattoir	Wastewater passes through retention tank, but still contains blood, manure, urine and animal pieces.	Very high BOD and low DO.
	Vingunguti solid waste disposal	Leachates from solid waste disposal site.	Very high BOD
	Storm water drainage	Includes roadside run-off and contains oils and greases and some heavy metal traces.	Oils and heavy metals
	Diffuse effluent from areas without storm water drainage	In rains, on-site sanitation may flood and sewage carried with storm water into the river.	High BOD, faecal coliforms, TN and TP.

Source: NEMC 2009

Kassenga & Mbuligwe (2009) estimated the loads of pollution coming from different sources along the Msimbazi River (Table 2.2). The total pollution load was estimated to be between 93-503 tonnes per year, with the largest contributors coming from on-site sanitation systems and industrial areas without sewers. However, the pollution yield from these different sources may not necessarily correspond to the severity of the impact that they have on the population. Whilst illegal solid waste disposal has the lowest pollution yield (as shown in Table 2.2) this masks the high impact it potentially does have on the population when compared to other pollution sources.

During flood events, the river water has the potential to come into contact with a large number of people. In addition to the costs of rebuilding houses and repairing damage to infrastructure, there is an additional human health cost that is not often considered. The potential health effects associated with contact with this water during flood events are cause for concern. In addition to direct contact with river water during flood events, residents may also come into contact with pollutants through vegetables grown in soils contaminated by the river water. Studies examining heavy metals in the soil found highest concentrations in the top soil layers which then decreased with depth (Mwegoha & Kihampa 2010). While lead, chromium and cadmium levels in the soil were within Tanzanian standards (TZS 2003) permissible limits for soils, there is still potential for transfer of these heavy metals up the food chain (Mwegoha & Kihampa 2010). In the Msimbazi Valley there are high incidence rates of cholera, diarrhoea, intestinal worms, and gastroenteritis. For more detail and a map of the cholera prone areas of Dar es Salaam see the Environmental Profile (AECOM 2015).

Over recent years flooding in the Msimbazi Valley has intensified and the damages have increased due to the continuous influx of people choosing to settle on unplanned land that is prone to flooding (Figure 2.9). In fact, areas that were previously not prone to flooding are now at risk due to increases in amount of hardened surfaces in the catchment, construction of structures in drainage channels and solid waste blockages in pipes, culverts and channels (Figure 2.9). Bushesha & Mbura (2015) concluded that the main reasons for persistent floods in Dar es Salaam include inadequate enforcement of land policies and legislations, poor institutional capacity in enforcing land use planning, and inadequate infrastructure and services to support rapid urbanisation. Damages from floods in 2011, 2014 and 2015 were particularly severe.

Table 2.2 Estimated pollution loads from difference sources into the Msimbazi River

Pollution Source	Pollution estimate (t/yr)	
	Min	Max
On-site sanitation systems	20.32	101.57
Industrial areas without sewers	17.70	141.56
Informal sector premises	16.12	80.61
Storm water from undrained areas	8.57	42.83
Farm and animal grazing lands	19.75	80.57
Illegal solid waste disposal	11.17	55.86
Total Pollution Load	93.62	503.01

Source: Kassenga & Mbuligwe 2009

Figure 2.9 Flooding in the Msimbazi Valley causes significant damage and the dumping of solid waste blocks culverts, pipes and channels which further exacerbates flooding.

Source: Eric Schaechter UFZ, Resilient Cities: www.100resilientcities.org (top) and Dar Ramani Huria: ramanihuria.org (bottom)

III. MODELLING FLOOD RISK IN THE MSIMBAZI CATCHMENT

Overview

Flood risk assessment encompasses three phases: hazard, exposure and vulnerability assessment (Leader & Wallingford 2009; Jalayer *et al.* 2014). The hazard is generally assessed through physically-based hydraulic models, providing the flood depth and the velocity for each point within the study area, also accounting for the presence of buildings, infrastructure and soil characteristics (O'Brien *et al.* 1993; Aronica *et al.* 1998; Cobby *et al.* 2003; Fabio *et al.* 2010; Biscarini *et al.* 2013; Yang *et al.* 2015). These methods are generally computationally demanding, and they require significant amounts of data and parameters in order to describe the morphology and the surface characteristics of the flood basin (Bates & De Roo 2000; Bates *et al.* 2004; Di Baldassare *et al.* 2009). However, the required data and modeling capabilities are not always available in developing countries (Hagen & Lu 2011). Therefore reasonable simplifications in modeling hypotheses and assumptions are generally adopted and accepted. For flood risk assessment, simplified methodologies based on a basin's geomorphologic features can be used (De Risi *et al.* 2014; 2015). Such methodologies are less accurate since they rely only on the topography because of its important role in flood depth and propagation (i.e. extension; Gallant & Dowling 2003, Dodov & Foufoula-Georgiou 2006) and do not allow a straightforward probabilistic risk assessment. Therefore, in this study, only a physically-based method is adopted. Exposure assessments require identification of the elements at risk, including all the elements of human, built and natural environments at risk in the flooding area. These can be population, buildings, infrastructure, economic activities, ecosystems, etc. Finally, given the characterization of the built environment, vulnerability analysis can be carried out in order to quantify the adverse effects of flooding. A vulnerability analysis provides the fragility functions (Porter *et al.* 2007), representing the probability of reaching or exceeding predefined damage states, for a given level of intensity (i.e. flood depth or inundation velocity). According to the integration procedure proposed by De Risi *et al.* (2013a) the combination of hazard and vulnerability yields the mean annual rate of exceedance of a specific limit state. This rate can be further used to calculate the probability of exceedance in a given time window, by adopting a reasonable probability distribution describing the event occurrence (e.g. Poisson distribution). This probability can then be combined with the exposed asset value in order to quantify the flood risk in the predefined time window in terms of economic losses or in terms of number of casualties. Generally speaking, considering a time window of one year, the final result is expressed as the Expected Annual Loss (EAL).

Data requirements for flood risk assessment

Riverine flooding phenomena can be triggered by natural processes, such as heavy precipitation, or by the failure of man-made structures such as levees, dams, and drainage systems (in urban areas). The impact of flooding can be quantified in terms of depth, peak discharge, extent of area inundated, and volume of flows. Floods vary in size and scale, ranging from minor waterlogged fields or briefly-blocked roads to the total inundation and destruction of homes and other structures, involving casualties. Catastrophic flooding events take place with a certain regularity over long periods of time (in the order of one to hundreds of years). Therefore, one way to classify the recurrence characteristics of a flooding event is in terms of its return period (TR). In evaluating inland river floods, the basic hydrological unit in river systems is the drainage basin, or catchment (i.e. the area that drains to any defined point along the river network). After a dry spell, rainfall infiltrates into the upper layers of soil and rock and only a small amount of water runs off in the catchment; only some soils need to be a little wet to encourage infiltration. However, continuing rain may lead to saturation of the surface soil layers; and as a result, the volume of water will eventually exceed the amount that can be absorbed. At this point, surface runoff begins. One way to represent the proportion of total rainfall that is not infiltrated (i.e. is transformed to surface runoff) over a catchment is through the runoff coefficient.

Surface runoff usually starts as sheet flow in which water moves as a thin, continuous film over relatively smooth soil or rock surfaces and it is not concentrated into channels. As the volume of water increases, it forms tiny rills, then gullies, and then flows into small tributary streams. The triggering of a flooding event is determined by many factors, such as:

- the amount of prior rainfall, which determines the degree of soil saturation—referred to in this document as antecedent moisture condition;
- topography of the drainage basin;
- type of soil and land use; and
- intensity of rainfall.

Extended wet periods during any season can lead to saturated soil conditions. In such cases, additional rainfall will quickly run off into streams and rivers. At some point, the run-off volume is going to exceed the river channel capacity and lead to flooding. At times, very heavy rainfall is followed almost immediately by a large run-off volume, despite highly pervious and dry soil conditions. This condition is usually caused when large volumes of rainfall take place in a short interval of time. Such bursts of extreme rainfall can produce spatio-temporally localized and devastating flooding events known as flash floods.

It is particularly challenging to create a mathematical model of flooding due to its spatio-temporal complexity and multi-stage triggering process. As a consequence, quantified flood risk assessment demands a considerable amount of data and information. Hence, data acquisition plays a pivotal role in a quantified flood risk assessment framework. This Section discusses the basic concepts and data requirements for a quantified flood risk assessment procedure.

3.0.1 Historical rainfall data

Riverine flooding events are strictly connected to rainfall patterns. Therefore, rainfall time-series data are essential for estimation of total flood discharge. These data can be obtained as pluviometer records from governmental organizations or other sources and in many cases are available online (e.g., www.tutiempo.net and www.knmi.nl). Ideally the pluviometric data should be available as precipitation extremes (maxima) recorded over a range of time intervals. The rainfall maxima recorded for different intervals are used in order to construct the rainfall curve, also known as the Intensity-Duration-Frequency (IDF) curve. Historical rainfall data can also be used to evaluate the antecedent soil moisture condition. In hydrological modeling, antecedent moisture condition is usually described as the pre-storm soil moisture deficit. This latter has a significant effect on the amount of rainfall drained by the river network and finally on the flooding potential of a rainstorm.

In this study, historical rainfall data was obtained from the single existing meteorological station in the catchment, located in the Dar es Salaam International Airport at 55 m above sea level, 6°86’S and 39°20’E. A detailed description of these data is presented in De Paola *et al.* (2014).

3.0.2 Geomorphologic / biophysical data

Geomorphologic/biophysical spatial data (e.g., topographic maps, geology maps, land-use, etc.) are fundamental data requirements in various stages of flood risk assessment. These datasets are described in more detail below.

3.2.2.1 Topography/ digital elevation model (DEM)

Topography plays an important role in flood modeling, with a demonstrated macro-scale correlation in between terrain elevation and annual accumulated rainfall (Allamano *et al.* 2009). Moreover, topography plays a key role in surface runoff and catchment response time (i.e. the time between the peak rainfall and the peak flow discharge). Steeper catchments have higher runoff coefficients and faster response time, with mountain rivers flowing much faster than lowland rivers. The typical instrument used to describe the topography of a generic hydrological domain is a digital elevation model (DEM), a 3D digital representation of a terrain surface. The DEM is used herein for flood diffusion/propagation by employing a classic hydraulic routine.

In this study, three topographic datasets were collected: (i) a DEM of 30 m horizontal resolution, obtained from the U.S. National Aeronautics and Space Agency (NASA) SRTM project website (http://gdex.cr.usgs.gov/gdex/) (STRM Project; Figure 3.1); (ii) a contour map with 2 m vertical resolution covering only the central part of the city, acquired from the Dar es Salaam city council (Figure 3.2); (iii) ten LIDAR surveys for strategic areas in the city of Dar es Salaam, obtained from a previous research project (Climate Change and Urban Vulnerability in Africa; Figure 3.3). Using GIS techniques, a final DEM was constructed of the analysis domain, using the best available resolution data[1] (Figure 3.4).

[1] The three DEMs were combined in a Geographic Information System (GIS) using a classic mosaic operation. Such a tool, available in many professional GIS platforms, is based on the pixel of a pre-defined grid, stores detailed properties, metadata, and processing information in order to produce a new dataset containing the combination of the initial data. In this study, this technique was used both to have a global DEM for the catchment identification and to have a final DEM for the geographical domain (hereafter referred to as the analysis domain) in which the inundation analyses are carried out. For the definition of the analysis domain, a 2 x 2 m grid was constructed. The resampled data were obtained through a linear interpolation. For each node of the resampled lattice, the topographic elevation then was obtained selecting the most refined data among the available DEMs (i.e. in sequence 0.5 m, 2 m, and 30 m).

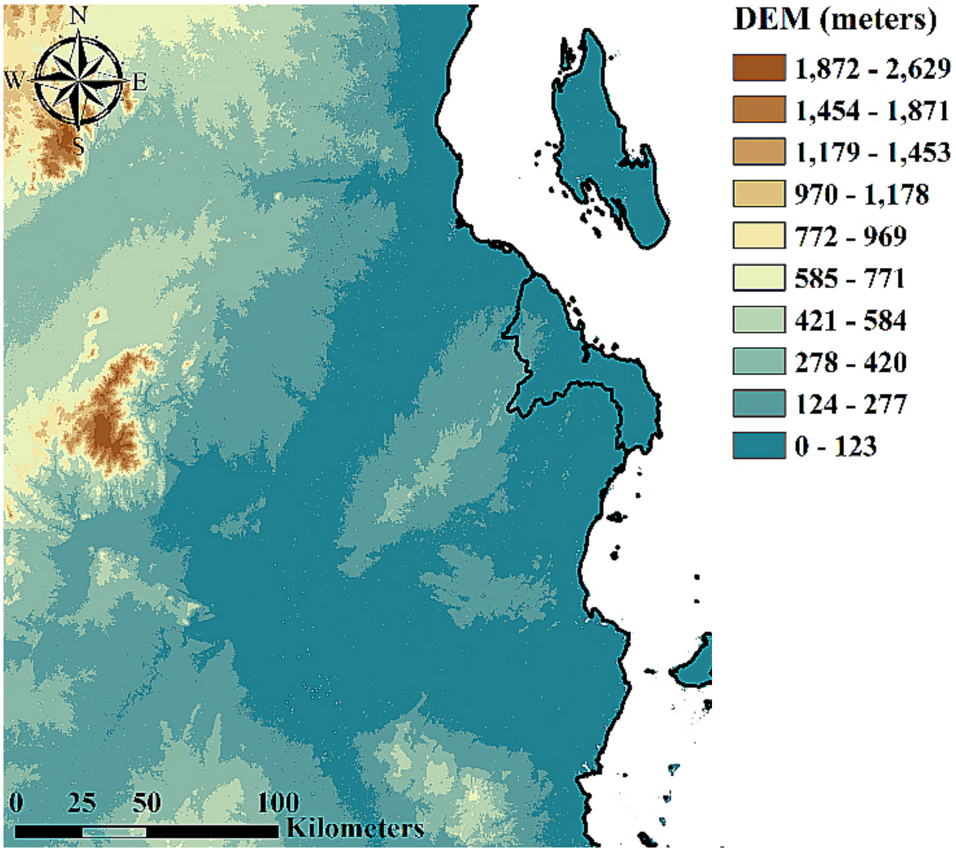

Figure 3.1 DEM NASA SRTM 1 arcsec (i.e. horizontal resolution 30 meters)

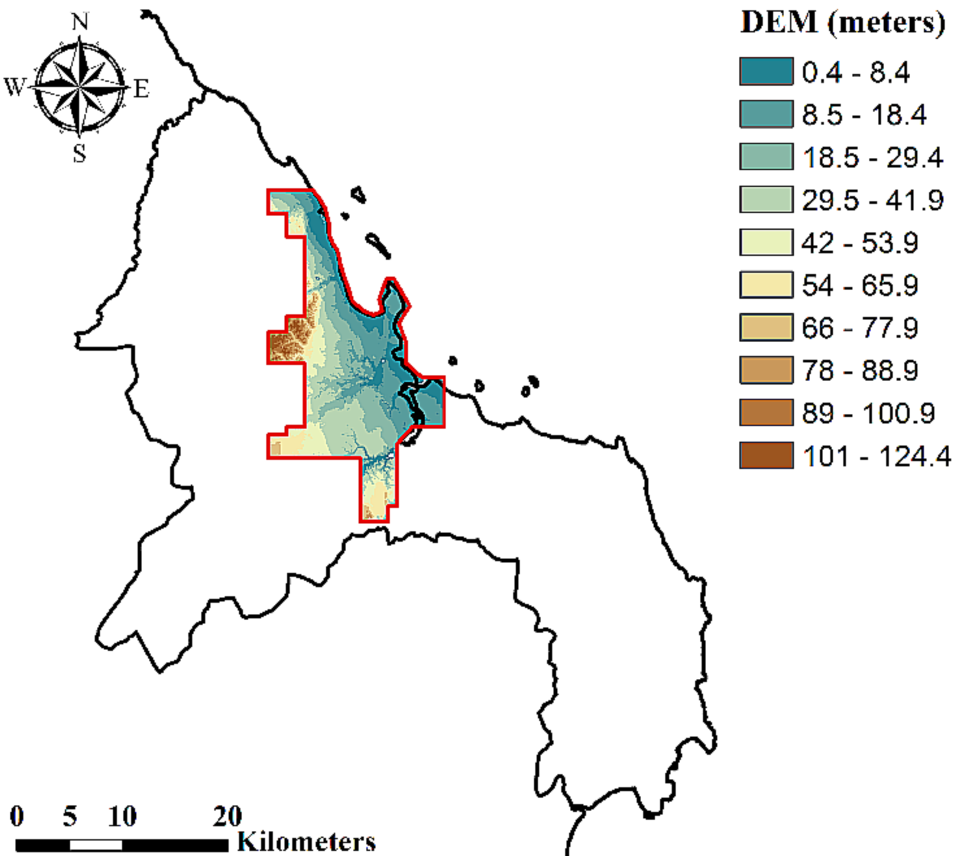

Figure 3.2 DEM acquired from the local city council (vertical and horizontal resolution of 2 meters)

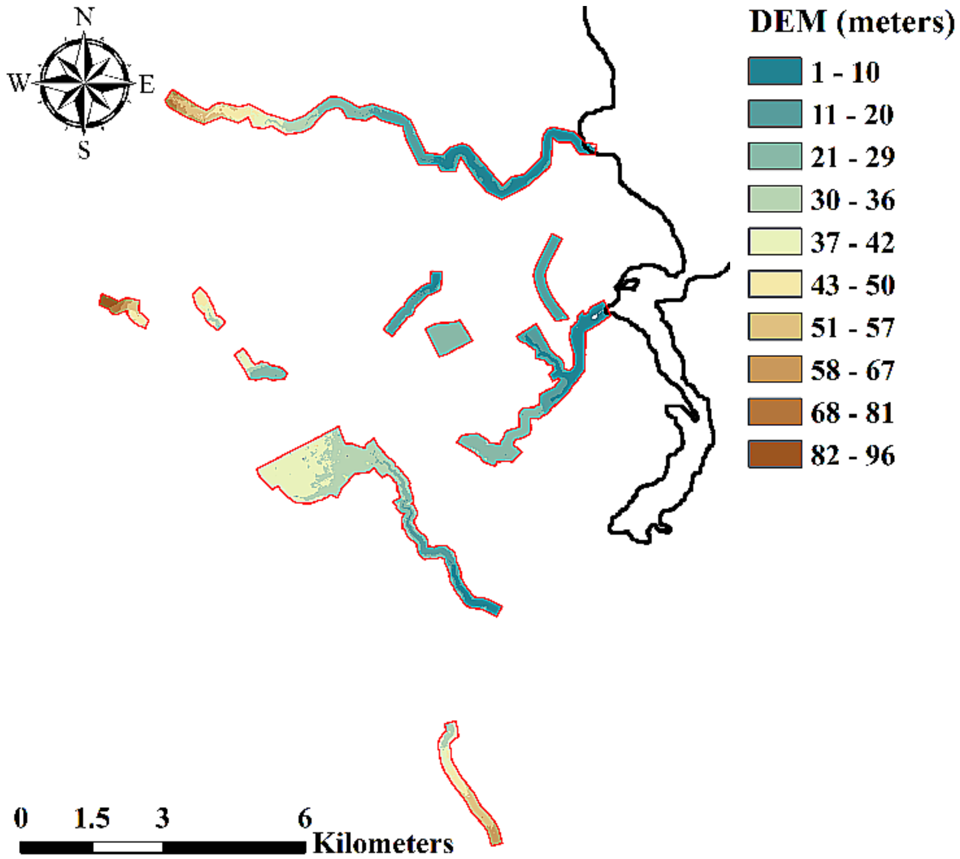

Figure 3.3 Lidar surveys (vertical resolution 0.5 meters, horizontal resolution 0.5 meters)

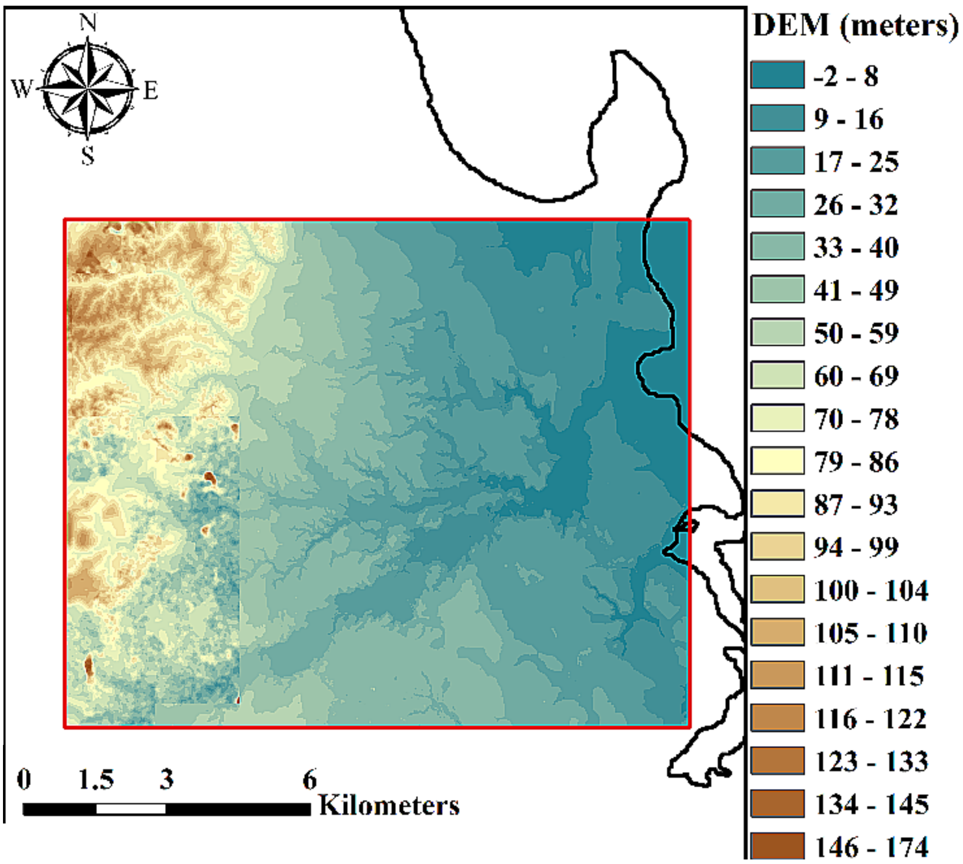

Figure 3.4 DEM for the analyses domain (horizontal resolution 2 meters)

Table 3.1 Percentage of utilization of the available DEMs.

DEM	Res.	Area of the analyses domain covered by DEM	Percentage of the analyses domain covered by DEM	Area of the analyses domain covered by the resampled DEM	Percentage of the analyses domain covered by the resampled DEM
1	30 m	1396 ha	100%	258 ha	18%
2	2 m	1135 ha	81%	1041 ha	75%
3	0.5 m	97 ha	7%	97 ha	7%

Table 3.1 lists the area of the analysis domain covered by each available DEM and the percentage of area used to build the resampled DEM.

3.2.2.2 Geological data

The underlying geology and dominant soil type of a catchment area are important factors in determining the quantity and proportion of the surface run-off. The water infiltration capacity of the soil depends on both the soil type (e.g., its grain size distribution and porosity) and the characteristics of the underlying water-bearing rock layers (e.g., porosity and thickness) also known as "groundwater aquifers." Large groundwater aquifers act as large reservoirs in that they release --over long periods of time-- the water infiltrated after a storm. Igneous rocks produced from lava or magma from the earth's lower crust (e.g. basalt and granite) have very low infiltration capacity unless they are heavily fractured. On the other hand, chalk and limestone have high infiltration capacity to the extent that they can prevent rivers from forming. Sandstone and shale are the analogs of sand and clay consolidated into rocks over millions of years through a process called lithification. Their infiltration capacity is usually low unless they are heavily fractured by subsequent geologic processes. A common and widely-used way to quantify the effect of soil type and stratification on the quantity of surface run-off is by means of the runoff coefficient that expresses the proportion of total rainfall that is drained by the river network. This coefficient reflects the runoff-relevant effects of the numerous possible combinations of soil types and underlying geology.

Generally the geological data are in form of GIS-based shape files or raster files with variable scale --between 1:1000 to 1:200000. In order to gain knowledge about subsoil stratigraphy, appropriate geological sections can be defined inside a geological spatial dataset. In this study, the source data were acquired from the Geological Survey of Tanzania's Geological and Mineral Information System (http://www.gmis-tanzania.com/). The map has a resolution 1:2M and represents the best data available for the country. This is the official map recognized by the Republic of Tanzania and it is in good accordance with the ISRIC – World Soil Information data (http://www.soilgrids.org/). Figure 3.5 presents the geology and Figure 3.6 shows the lithology of the study area. These show that the entire area of Dar es Salaam is characterized by the presence of Marine and Fluvio-Marine sandy-clayey sediments. These soils have moderate infiltration rates when thoroughly wetted and a moderate rate of water transmission.

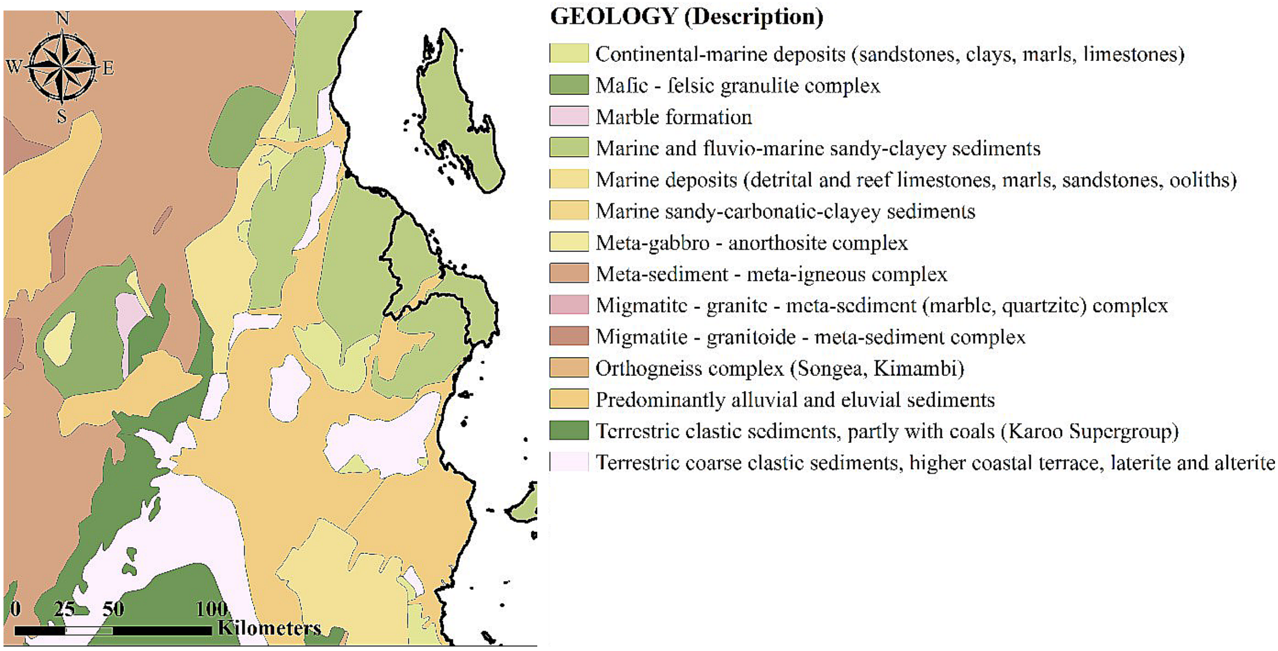

Figure 3.5 Geology: The description of soils

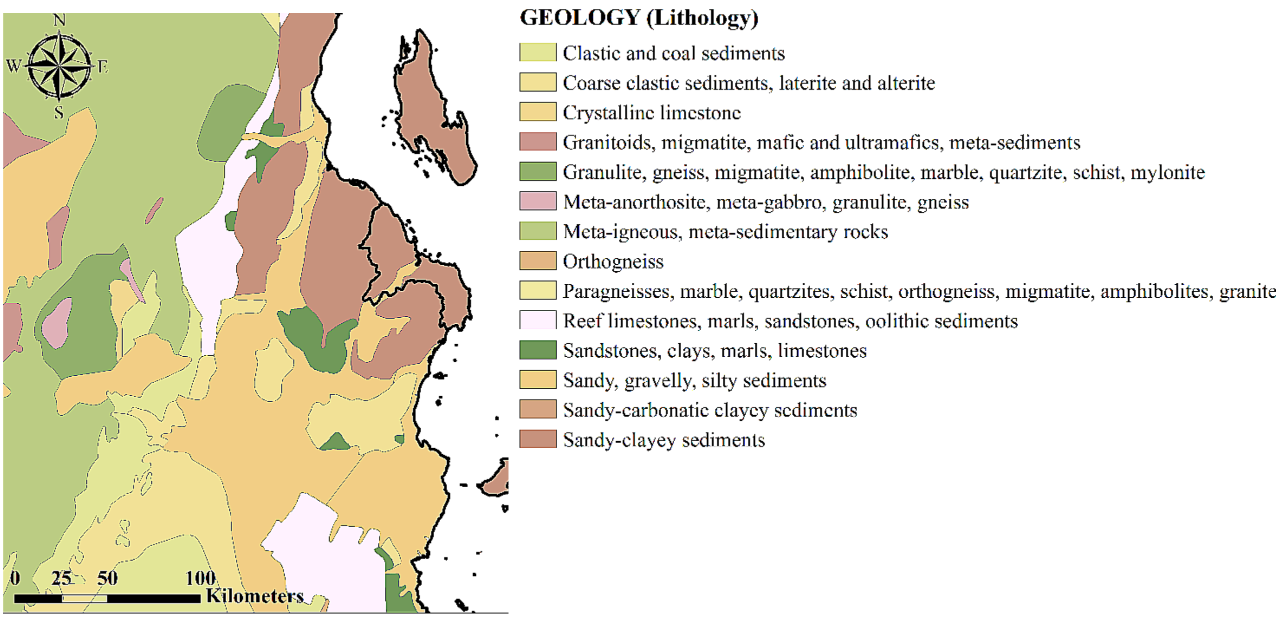

Figure 3.6 Lithology of the study area

3.0.3 Land use/land cover data

The runoff coefficient, catchment discharge and catchment response time all depend on land cover. In forested areas, tree roots increase the infiltration of water by channeling it deeply inside the soil layers down to the ground water. This effect is less pronounced in areas covered by shrubs and in pastures where the roots are much shallower. In urbanized areas, and in particular in large cities, the large percentage of paved areas may increase the runoff coefficient significantly. This is because smooth surfaces like asphalt and concrete generally have very low infiltration capacity. This leads to larger flood discharge and shorter response times in urban areas. The land-use geo-spatial datasets can be found in GIS-based formats such as shape files and raster files. The resolution of these maps may vary between 1:1000 to 1:100000.

In this study, two different sources were used to characterize land use in the study area: (i) a CGIAR coarse-resolution map (available at http://192.156.137.110/gis/search.asp?id=543) showing the land use for the entire Tanzania in 2002 (Figure 3.7), and (ii) a finer-resolution map of the city of Dar es Salaam (Figure 3.8) obtained from the Climate Change and Urban Vulnerability in Africa (CLUVA) project (www.cluva.eu). The latter is mapped as Urban Morphology Type (UMT), which is a powerful tool for the representation of the built and natural environment. UMTs (Pauleit and Duhme 2000; Gill *et al.* 2008) form the foundation of a classification scheme bringing together facets of urban form and function. UMTs have characteristic physical features (i.e. land cover) and are further differentiated on the basis of the human activities they accommodate (i.e., land uses). The procedure adopted to obtain UMT for the specific case of Dar es Salaam is described in Cavan *et al.* (2012).

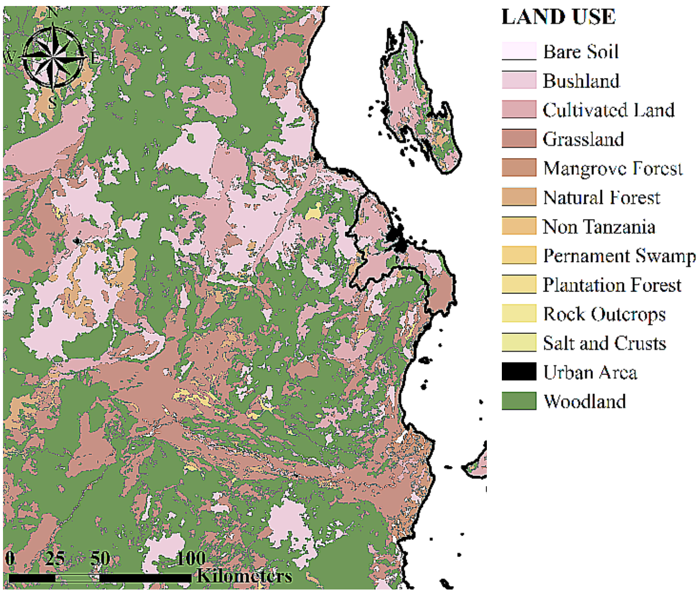

Figure 3.7 Land use for the larger Dar es Salaam region

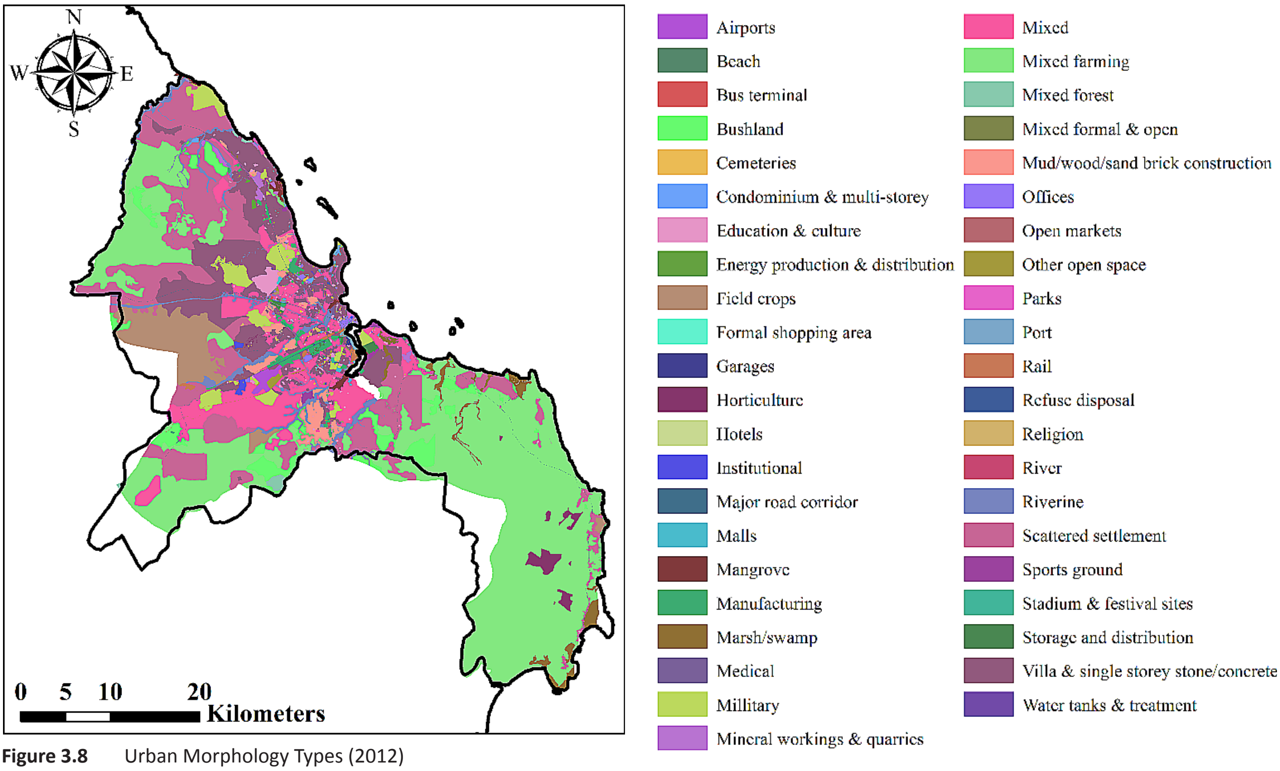

Figure 3.8 Urban Morphology Types (2012)

The use of two different resources for land use characterization was necessitated by the fact that the main catchment feeding the Msimbazi River extends beyond the limit of the more refined UMT map which is confined to the political borders of Dar es Salaam. Therefore, a mixed resource was created, with the less refined data being used for the area outside the city boundary.

While there is a high level of urbanization in the city centre, beyond these areas the study area contains areas of bushland, cultivated land, bare soil, forest and savannas. It is also worth noting that for a large part of the area identified as urbanized, the absence of road paving and the lack of proper drainage systems lead to low water run-off towards the main channels.

Flood hazard assessment

In this section, the methodology employed for the hazard assessment is described, with some of the technical detail in boxes. A schematic diagram of the procedure used for hazard modeling is illustrated in Figure 3.9. In summary, intensity-duration-frequency (IDF) curves, geologic and land-use information are used to characterize the hydrograph leading to the calculation of the discharge (Q) and the total water volume (i.e. the area under the hydrograph) for different return periods. This information, together with the topographic map of the zone of interest are used in a two-dimensional diffusion model in order to generate the maps of maximum water height and velocity for each node of a lattice covering the zone of interest for a given return period (the flood hazard map).

3.0.1 The rainfall curve

Rainfall curves or intensity-duration-frequency (IDF) curves are described for various return periods. Rainfall curves are normally used where there is a lack of sufficient flow data for direct probabilistic discharge modeling, in order to evaluate the peak discharge. The IDF curve presents the probability of a given rainfall intensity and duration expected to occur at a particular location.

The data adopted for constructing the IDF curves are those presented in Box 3.1, and the calibrated coefficients are those presented in De Paola *et al.* (2014) for the specific case of Dar es Salaam. The following generic procedure for constructing IDF curves was used.

The IDF curve characterizes an area's rainfall pattern. By analyzing past and projected rainfall events, statistics of the recurrence of rainfall extremes can be determined for various return periods (TR) (e.g. 5, 10, 30, 50, 100 and 300 years). The annual extremes are usually obtained as maximum rainfall over a one-year time period, as extreme rainfall height values hr (in mm) calculated over time window duration d. The rainfall curve, corresponding to a specific return period, is calculated by fitting a suitable probability model to the extreme rainfall data. Estimation of IDF curves is explained in more detail in Box 3.1.

The rainfall probability curves for Dar es Salaam based on historical data are shown in Figure 3.10.

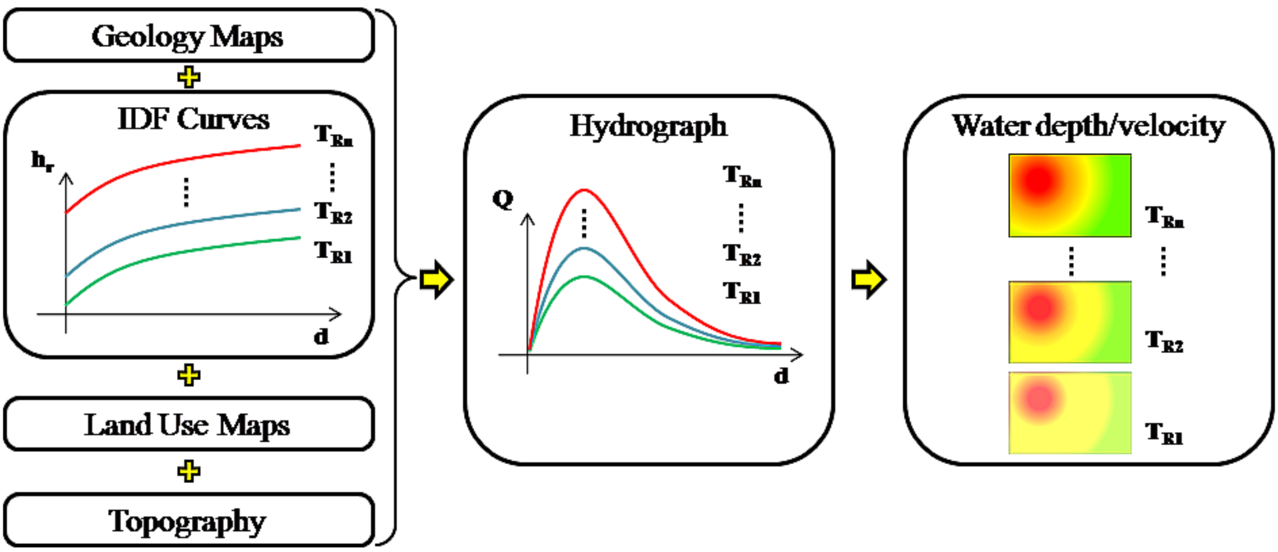

Figure 3.9 Hazard assessment procedure (h = rainfall height, d = duration, Q = discharge, and TR = return period; De Risi et al. 2013a)a

Box 3.1. Calculation of intensity-duration-frequency (IDF) curves

The IDF curves can be characterized by either two or three parameters, as shown in the following expressions:

$$h_r(d,T_R) = a(T_R)\cdot d^n \tag{3.1}$$

$$h_r(d,T_R) = \frac{a(T_R)\cdot d}{(b+d)^c} \tag{3.2}$$

data in which h_r is rainfall (mm), d is duration (hours), T_R is the return period and $a(T_R)$, b, c and n are the parameters that have to be estimated through a probabilistic approach. In the present study, the power-law curves expressed in (3.1) were used. Herein, a Gumbel probability distribution (part of the GEV family of distributions) has been employed, considering only the extreme events on a block fixed window (Maione & Mosiello 1993) to fit the extreme rainfall data:

$$P(h_r) = \exp\left\{-\exp\left[-(h_r-\mu)\backslash\sigma\right]\right\} \tag{3.3}$$

where $P(h_r)$ is a cumulative distribution function (CDF) for rainfall height h_r. The two parameters v and u are related to the real mean (μ) and to the real standard deviation (σ) through the following equations:

$$\sigma = \frac{u}{1.28} \tag{3.4}$$

$$\mu = v - 0.577\cdot\sigma = v - 0.45\cdot u \tag{3.5}$$

The inverse of the CDF (3.3) can be calculated by writing h_r in terms of $P(h_r)$ and duration d:

$$h_r(d,P) = \mu - \sigma\cdot\ln\left[-\ln(P)\right] \tag{3.6}$$

where $h_r(d,P)$ denotes the maximum annual flooding height calculated over a time window of duration d and exceeded with probability 1-P. Substituting (3.4) and (3.5) in (3.6), and introducing the coefficient of variation CV equal to u/v:

$$h_r(d,P) = v(d)\cdot\left\{1 - CV(d)\cdot\left[0.45 + \frac{1}{1.28}\cdot\ln\left[-\ln(P)\right]\right]\right\} \tag{3.7}$$

Since the probability P is related to the return period T_R, through $1\text{-}p=1/T_R$[3], h_r can also be expressed in terms of the return period:

$$h_r(d,T_R) = v(d)\cdot\left[1 + CV(d)\cdot K\right] \tag{3.8}$$

Where

$$K = -\left\{0.45 + \frac{1}{1.28}\cdot\ln\left[-\ln\left(1-\frac{1}{T_R}\right)\right]\right\} \tag{3.9}$$

$h_r(d,T_R)$ denotes the maximum annual flooding height calculated over a time window of duration d and exceeded with frequency $1/T_R$. The experimental evidence also shows that extreme precipitations have a physical property, known as scale invariance or self-similarity, so that the following relation holds:

$$h_r(T_R, sf\cdot d)\,/\,h_r(T_R,d) = (sf)^n \tag{3.10}$$

in which sf is a scale factor and n is a parameter function of the location. This scale invariance implies the statistical self-similarity between the probability distribution of $h_r(d)$ and $h_r(sf\cdot d)$. As a result of the statistical self-similarity, $v(d)=a_\mu\cdot d^n$, in which $v(d)$ is the parameter of Gumbel distribution. Substituting the expression for $v(d)$ in Eq. (3.8) one obtains the flood height as function of duration d and return period T_R:

Box 3.1. Calculation of intensity-duration-frequency (IDF) curves (continued)

$$h_r\left(d,T_R\right)=a_\mu\cdot d^n\cdot\left(1+CV_m\cdot K_T\right) \quad (3.11)$$

Taking into account the general expression (3.1), the above equation can be written as:

$$h_r\left(d,T_R\right)=a\left(T_R\right)\cdot d^n \quad (3.12)$$

Where $a(T_R)$ can be calculated as:

$$a\left(T_R\right)=a_\mu\cdot K_{T_R} \qquad K_{T_R}=\left(1+CV_m\cdot K\right) \quad (3.13)$$

where K_{TR} is generally known as the growing factor (as a function of T_R). CV_m denotes the mean CV over different durations *d*. Assuming that the coefficient of variation is quasi-invariable as a function of duration *d*, its mean value for the coefficient of variation denoted as CV_m can be evaluated by the following expression:

$$CV_m=\frac{1}{k}\cdot\sum_{i=1}^{k}CV_i \quad (3.14)$$

in which *k* is the considered duration. In this study we chose five durations, i.e. d=1, 3, 6, 12, and 24 hours. These are typically the five values adopted for the building of IDF curves in practice.

Based on eqs. (3.12) and (3.13) and using the results presented in De Paola *et al.* (2014):

$$h_r\left(d,T_R\right)=K_{T_R}\cdot 36.44\cdot d^{0.25} \quad (3.15)$$

The values of the growing factor K_{T_R} as a function of the return period T_R are: K_5=1.23, K_{10}=1.42, K_{30}=1.70, K_{50}=1.83, K_{100}=2.01, K_{300}=2.28;

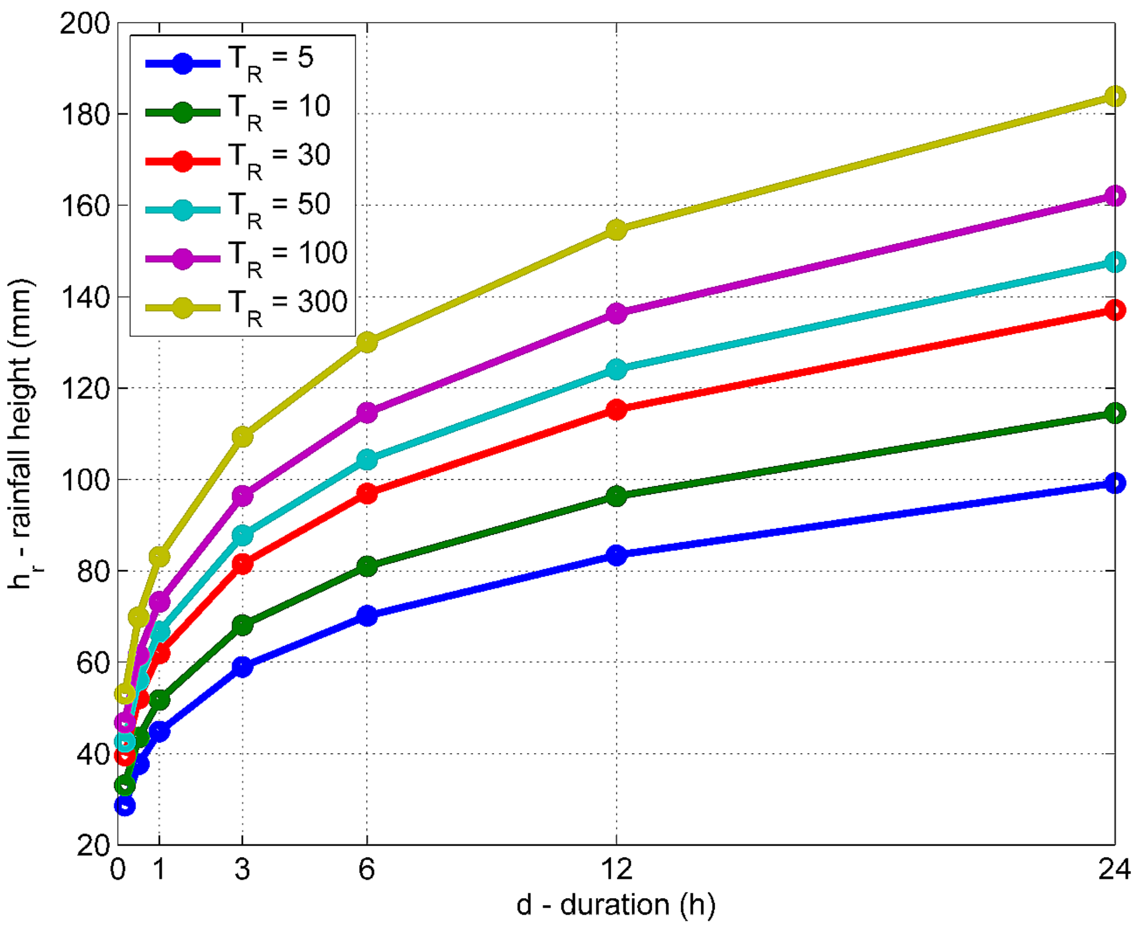

Figure 3.10 Rainfall Probability Curves for Dar es Salaam based on historical data

3.0.2 Hydrologic basin modelling

The aim of the hydrologic basin modelling is to produce a series of hydrographs (the discharge [volume/time] plotted against time), for different return-period flood events. A systematic description of the procedure is reported below.

3.3.2.1 Identification of catchments

Catchment area characterization, which is done based on the topography of the zone, is one of the first steps in hydrographic basin analysis. The catchment refers to the topographical area from which a watercourse, or a water course section, receives surface water from rainfall (and/or melting snow or ice). For the analysis domain within Dar es Salaam, the river representing the greatest threat is the Msimbazi River. Three catchments feed the Msimbazi (Figure 3.11):

1. The northern catchment (Catchment 3 in Figure 3.11) is drained by the Mto Ng'ombe water course that crosses the Kinondoni district, covering 9755 meters between the drainage outlets up to the junction with the Msimbazi. It crosses the Ubungo; Manzese; Tandale; Makumbusho; Ndugumbi; Magomeni and Upanga Magharibi sub-wards. In Upanga Magharibi sub-ward, the Mto Ng'ombe water course joins the Msimbazi River.

2. The central catchment (Catchment 2 in Figure 3.11) is drained by the Kibangu water course that crosses the Kinondoni and Ilala districts, covering 3363 meters from the drainage outlet up to the junction with the Msimbazi. It crosses the Kigongo (Kinondoni); and Mchikichini (Ilala) subwards. In the Mchikichini sub-ward, Kibangu water course joins the Msimbazi River.

3. The southern catchment (Catchment 1 in Figure 3.11) is drained by the Msimbazi River that crosses the entire Ilala district covering 12248 meters from the drainage outlet to the ocean. It crosses the Kipawa; Vingunguti; Buguruni sub wards (Ilala); and the Mchikichini; Jangwani; Upanga Magharibi and Upanga Mashariki sub wards (Kivukoni).

The drainage outlets (the black dots in Figure 3.11) in the analysis domain are upstream of the main built environment. The morphometric characteristics of the three catchments of these three points of flow are described in Table 3.2. The characteristics presented in Table 3.2 were used to calculate the concentration time TC for each catchment (see Box 3.2).

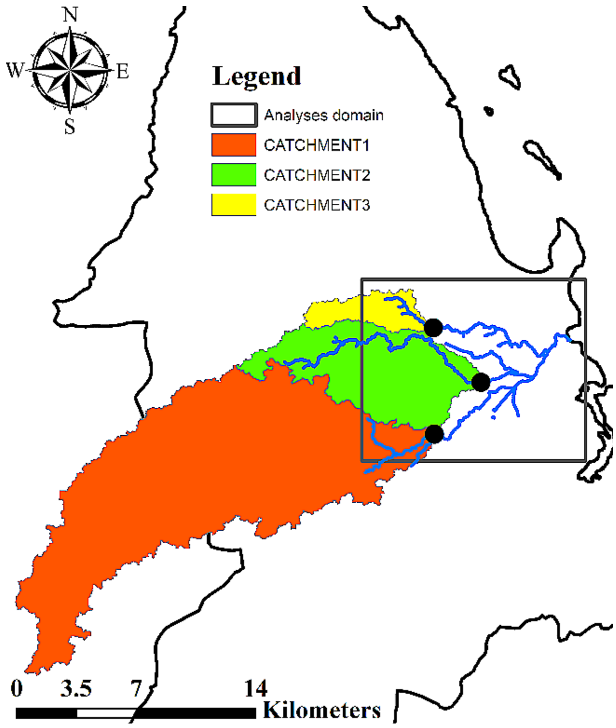

Figure 3.11 Catchments of the case study river

3.3.2.2 Estimation of the design flood hydrographs

Once the IDF curve has been characterized, a rainfall-runoff method must be applied in order to determine the hydrograph. The hydrograph refers to the flow discharge in the drainage outlet of the catchment as a function of time and constitutes the input for the hydraulic diffusion model (Figure 3.12). The area under the hydrograph is equal to the total discharge volume for the basin under study for a given rainfall event.

Different approaches can be used to estimate the peak flow for a specified return-period event (design peak flow), such as the Rational Method, the Curve Number Method or more complete approaches such as distributed models (e.g. TRibs, available at http://vivoni.asu.edu/tribs.html) or semi-distributed models (e.g. Hec-HMS, available at http://www.hec.usace.army.mil/software/hec-hms/). A detailed discussion about distributed and semi-distributed models is presented in El-Nasr et al. (2005). The more sophisticated the method, the more data is required for the calibration of the model's parameters. In developing countries, the choice of model is typically constrained by the absence of data. Therefore it is generally necessary to employ relatively simple tools.

Table 3.2 The characteristics of the Msimbazi River catchments

Characteristics		Msimbazi River		
		Catchment 1	Catchment 2	Catchment 3
A_b Drainage area	(km^2)	172.6	51.0	11.8
L_a Main channel length	(km)	25	15	7
Average catchment slope	(%)	12.3	8.5	9.0
Average channel slope	(%)	7.0	4.0	4.0
z_m Maximum height	(m.a.s.l.)	347	305	160
Average height	(m.a.s.l.)	145	83	103
z_0 Drainage outlet height	(m.a.s.l.)	12.8	16	50

Box 3.2. Concentration time and its estimation

Concentration time is the time taken for water to flow from the most remote point in a catchment to the catchment outlet. This parameter can be estimated through an empirical relationship. Several empirical relationships are available in the literature (Giandotti 1940; Kirpich 1940; Viparelli 1963, SCS 1975, among others). In this study, Giandotti's formula was used:

$$T_C = \frac{4 \cdot \sqrt{A_b} + 1.5 \cdot L_a}{0.8 \cdot \left(z_m - z_0 \right)} \quad (3.16)$$

This leads to concentration times of 9.79 hours, 7.80 hours, and 4.16 hours for the three catchments, respectively.

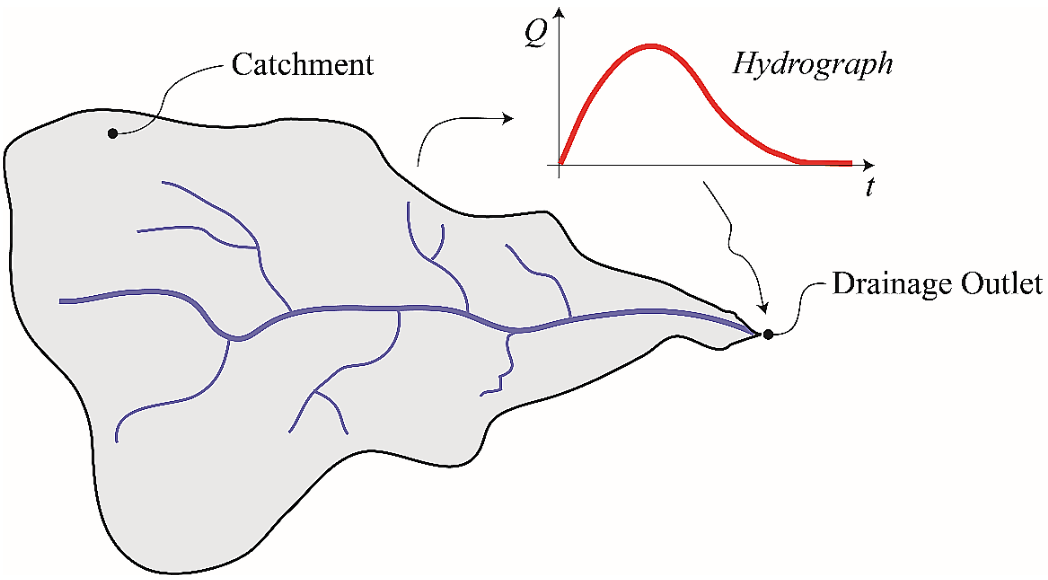

Figure 3.12 The schematic diagram of a hydrographic basin

For ungauged basins--where water runoff cannot be directly measured, such as is the case in Dar es Salaam, the classic Curve Number Method (CNM) (Mokus 1972; SCS 1972) is considered suitable for modeling the hydrograph for the following reasons:

- It is the simplest conceptual method for estimation of the direct runoff amount from a particular storm rainfall amount, and is well supported by empirical data,
- The method relies on only one parameter, the curve number (CN), which is a function of the major runoff producing watershed characteristics,
- It is fairly well documented for its inputs (soil, land use/treatment, surface condition, and antecedent moisture condition); and
- Its features are readily grasped, well established, and accepted not only in the US (i.e. the country for which the methodology was developed) but also other countries around the world.

However, the method has some limitations (Mokus 1972; SCS 1972):

- Rainfall is considered spatially uniform;
- It does not contain any expression for time and ignores the impact of rainfall intensity and its temporal distribution;
- There is a lack of clear guidance on how to vary antecedent moisture condition, especially for lower curve numbers and rainfall amount; and
- The method was originally developed for agricultural areas, and while it performs well also in other contexts, it performs poorly in forest areas.

Nevertheless, the method is considered acceptable for the examined case in Dar es Salaam. The Curve Number Method and assumptions for Dar es Salaam are explained in more detail in Box 3.3.

Box 3.3. Estimation of design flood hydrographs using the Curve Number Method

The Curve Number Method is based on two phenomena. The initial accumulation of rainfall represents interception, depression storage, and infiltration before the start of runoff and is called "initial abstraction". After this, some additional rainfall is lost, mainly in the form of infiltration; this is called "actual retention". With increasing rainfall, the actual retention also increases up to a maximum value that is the potential maximum retention. The fundamental CN relationship is:

$$P_{net} = \frac{\left(P - I_a\right)^2}{P - I_a + S} \quad (3.17)$$

Where P_{net} is the accumulated runoff depth (mm), P is the cumulative rainfall depth (mm), I_a is the initial abstraction (mm), or the amount of water before runoff, such as infiltration, depression storage and rainfall interception by vegetation, and S is the potential maximum soil moisture retention after runoff begins (mm). Assuming I_a equal to 0.2S, equation 3.17 can be rewritten as:

$$P_{net} = \frac{\left(P - 0.2 \cdot S\right)^2}{P + 0.8 \cdot S} \quad (3.18)$$

The runoff curve number, CN, is then related to potential maximum soil moisture retention, S, by the equation:

$$S = 254 \cdot \left(\frac{100}{CN} - 1\right) \quad (3.19)$$

As the potential maximum retention S can theoretically vary between zero and infinity, the Curve Number CN can range from one hundred to zero. Figure 3.13 shows the graphical solution, indicating values of runoff depth Q as a function of rainfall depth P for selected values of Curve Numbers. For paved areas, for example, S will be zero and CN will be 100; all rainfall will become runoff. For highly permeable, flat-lying soils, S will go to infinity and CN to zero; all rainfall will infiltrate and there will be no runoff. In drainage basins, the value will be somewhere in between.

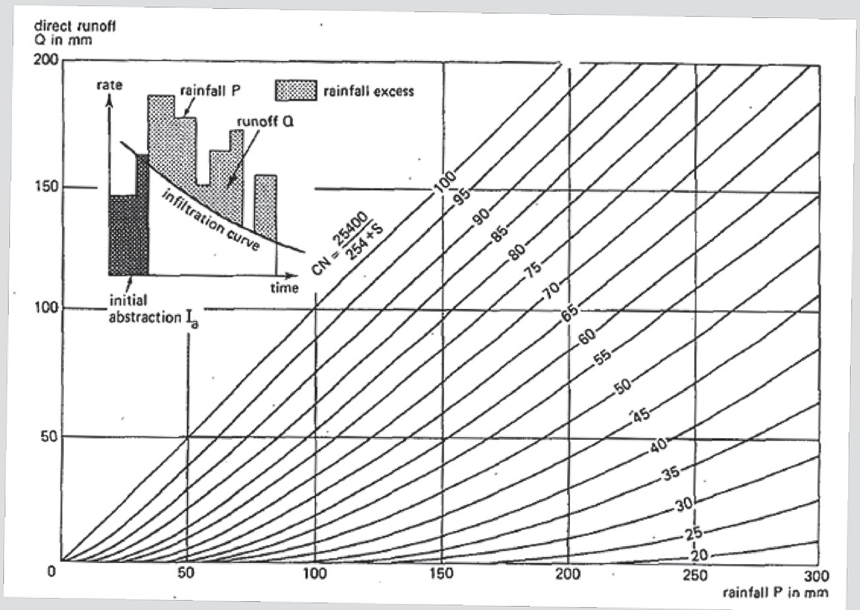

Figure 3.13. CN Method (SCS 1972)

The Curve Number is therefore a dimensionless parameter indicating the runoff response characteristic of a drainage basin. In the Curve Number Method, CN is related to land use, land treatment, hydrological

condition, and soil group. Soil properties greatly influence the amount of runoff. In the SCS method, these properties are represented by a hydrological parameter: the minimum rate of infiltration obtained for a bare soil after prolonged wetting. The influence of both the soil's surface condition (infiltration rate) and its horizon (transmission rate) are thereby included. This parameter, which indicates a soil's runoff potential, is the qualitative basis of the classification of all soils into four groups. The Hydrological Soil Groups are (SCS 1972):

Group A: Soils have high infiltration rates even when thoroughly wetted and a high rate of water transmission. Examples are deep, well to excessively drained sands or gravels.

Group B: Soils have moderate infiltration rates when thoroughly wetted and a moderate rate of water transmission. Examples are moderately deep to deep, moderately well to well drained soils with moderately fine to moderately coarse textures.

Group C: Soils have low infiltration rates when thoroughly wetted and a low rate of water transmission. Examples are soils with a layer that prevents the downward movement of water or soils of moderately fine to fine texture.

Group D: Soils have very low infiltration rates when thoroughly wetted and a very low rate of water transmission. Examples are clay soils with a high swelling potential, soils with a permanently high water-table, soils with a clay pan or clay layer at or near the surface, or shallow soils over nearly impervious material.

Table 3.3 presents the typical values of curve number for many typology of soil type. For the analyzed case study, according to the data presented in the Section 3.2.2, the Hydrologic Soil Group for Dar es Salaam is type B.

Table 3.3. Relationship between Soil typologies and Curve Number

Description of Land Use	Hydrologic Soil Group			
	A	B	C	D
Paved parking lots, roofs, driveways	98	98	98	98
Streets and Roads:				
Paved with curbs and storm sewers	98	98	98	98
Gravel	76	85	89	91
Dirt	72	82	87	89
Cultivated (Agricultural Crop) Land*:				
Without conservation treatment (no terraces)	72	81	88	91
With conservation treatment (terraces, contours)	62	71	78	81
Pasture or Range Land:				
Poor (<50% ground cover or heavily grazed)	68	79	86	89
Good (50-75% ground cover; not heavily grazed)	39	61	74	80
Meadow (grass, no grazing, mowed for hay)	30	58	71	78
Brush (good, >75% ground cover)	30	48	65	73
Woods and Forests:				
Poor (small trees/brush destroyed by over-grazing or burning)	45	66	77	83
Fair (grazing but not burned; some brush)	36	60	73	79
Good (no grazing; brush covers ground)	30	55	70	77
Open Spaces (lawns, parks, golf courses, cemeteries, etc.):				
Fair (grass covers 50-75% of area)	49	69	79	84
Good (grass covers >75% of area)	39	61	74	80
Commercial and Business Districts (85% impervious)	89	92	94	95
Industrial Districts (72% impervious)	81	88	91	93
Residential Areas:				
1/8 Acre lots, about 65% impervious	77	85	90	92
1/4 Acre lots, about 38% impervious	61	75	83	87
1/2 Acre lots, about 25% impervious	54	70	80	85
1 Acre lots, about 20% impervious	51	68	79	84

The Curve Number (CN) value depends also on the antecedent soil moisture condition (AMC) in the drainage catchment. AMC is the relative moisture of the pervious soil surfaces prior to the rainfall event in question and

reflects the level of soil moisture in a five day interval preceding the event. Antecedent moisture is considered to be low when there has been little preceding rainfall and high when there has been considerable preceding rainfall prior to the event in question. Determination of antecedent soil moisture content and classification into the antecedent moisture classes AMC I, AMC II and AMC III (Table 2), representing dry, average and wet conditions, is essential for the application of the curve number procedure described next. In particular, there are three classes of AMC, namely, AMC I: the soils in the catchment are practically dry; AMC II: average condition; and AMC III: the soils in the catchment are practically saturated from previous rainfall.

Table 3.4 shows the corresponding rainfall limits for each of the three AMC classes for each season according to SCS (1972).

Table 3.4. AMC according to the season and according to the 5-day antecedent rainfall height (mm)

AMC	Dormant Season	Growing Season	Average
I	< 13	< 36	< 23
II	13 - 28	36 – 53	23 - 40
III	> 28	> 53	> 40

Jalayer *et al.* (2013a) analyzed the AMC for the growing season in Dar es Salaam, using rainfall data from 1958-2010 (Figure 3.14a). Figure 3.14b presents the AMC frequency distribution for Dar es Salaam obtained in the aforementioned study.

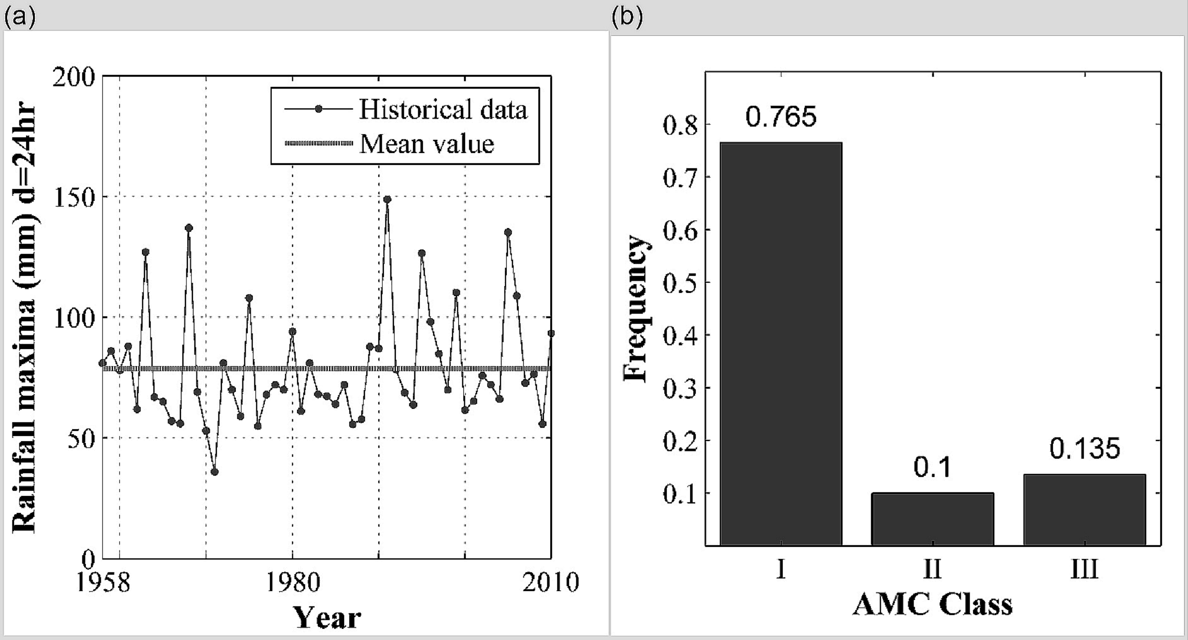

Figure 3.14. (a) Average daily rainfall during the Dar es Salaam growing season, 1958-2010, and (b) AMC frequency distribution during the Dar es Salaam growing season (Jalayer *et al.* 2013a) Dar es Salaam.

Jalayer *et al.*'s (2013a) analysis shows that AMC I (dry condition) is by far the most probable antecedent soil moisture condition during the growing season in Dar es Salaam, followed by AMC III and AMC II. Even so, in order to generate conservative estimates of intervention impacts, our analysis assumes that the AMC at the beginning of the modelled extreme rainfall events is the second most probable condition, AMC III.

The CN values corresponding to AMCI and AMCIII are related to the average condition of humidity (i.e. AMC II). Specifically, the CN values associated with AMCI and AMCIII conditions can be evaluated by the following expressions:

$$CN \quad (AMC \quad I) = \frac{4,2CN(AMC \quad II)}{10 - 0,058(AMC \quad II)} \tag{3.20}$$

Box 3.3. Estimation of design flood hydrographs using the Curve Number Method (continued)

$$CN(AMC \quad III) = \frac{23CN(AMC \quad II)}{10 - 0{,}13(AMC \quad II)} \tag{3.21}$$

With reference to the land use the three catchments exhibit different compositions of land typologies. Catchment 1 includes cultivated soil (25%, CN 81), woodland (25%, CN 55), bushland (30%, CN 66) and forest (20% CN 55). Catchment 2 covers cultivated soil (60%, CN 81), woodland (15%, CN 55), bushland (10%, CN 66) and urban area (15% CN 70). Finally, Catchment 3 covers cultivated soil (81%, CN 81), bushland (5%, CN 66) and urban area (15% CN 70). The weighted mean CN is 64.8 for Catchment 1, 74 for Catchment 2 and 78.6 for Catchment 3.

In the framework of the CNM, the characteristics of the discharge hydrograph are evaluated using a unit Mokus (Mokus 1972) hydrograph depicting the discharge Q as a function of time. A typical unit Mokus hydrograph is shown in Figure 3.15.

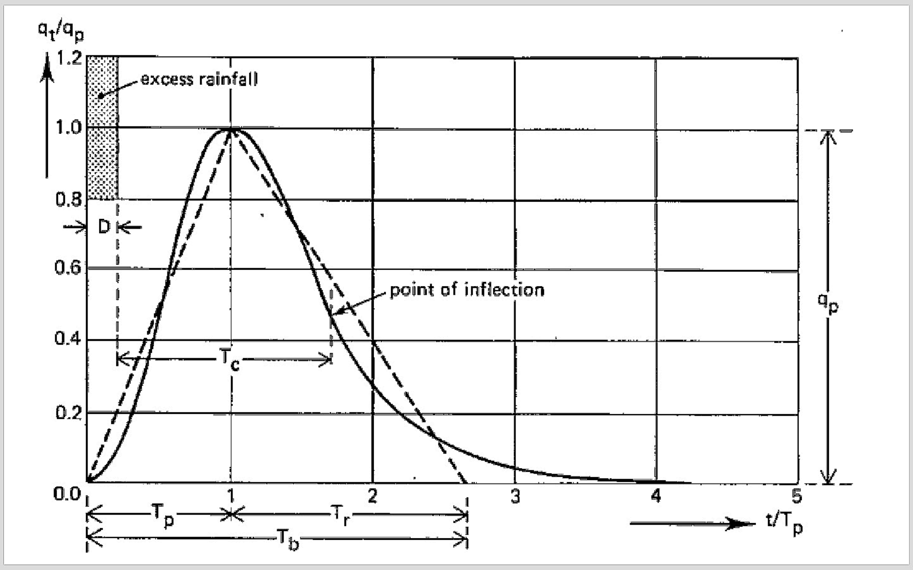

Figure 3.15. The Mokus Hydrogprah (SCS 1972)

In particular, for the evaluation of the hydrograph peak time t_p (in hours), the following formula is considered:

$$t_p = 0.5 \cdot D + t_l \tag{3.22}$$

where:

- *D* is the rainfall duration (in hours, equal to the concentration time evaluated from the Giandotti formula (Giandotti 1940)
- t_l is the catchment lag time (in hours), i.e. the time between the hydrograph centroid and the net rainfall centroid, equal to:

$$t_l = 0.342 \cdot \frac{L^{0.8}}{s^{0.5}} \cdot \left(\frac{100}{CN} - 9\right)^{0.7} \tag{3.23}$$

in which *L* is the length of the main channel (in kilometers) and *s* is the mean slope (as percentage). It can be noted that t_p measures the response time of the catchment; that is, time elapsing from the beginning of rainfall to the maximum discharge in the basin drainage outlet. Finally, $t_b = 2.67t_p$ (in hours) and $Q_p = 0.208VA / t_p$ is the peak flow in m^3/s. *A* is the catchment area in km^2 and V=P_{net} (mm) is the flood storage.

Figure 3.13 shows the hydrographs obtained for all three catchments analyzed, considering all the potential conditions in terms of AMCs and for all six return periods. The peak discharges increase passing from AMCI to AMCIII and the durations decrease passing from Catchment 1 to Catchment 3.

The characterization of the discharge hydrograph formed the basis for the identification of flood prone areas. In the next step, the flood discharge estimated by the hydrograph was propagated through the zone of interest in order to delineate the flood prone areas for various return periods.

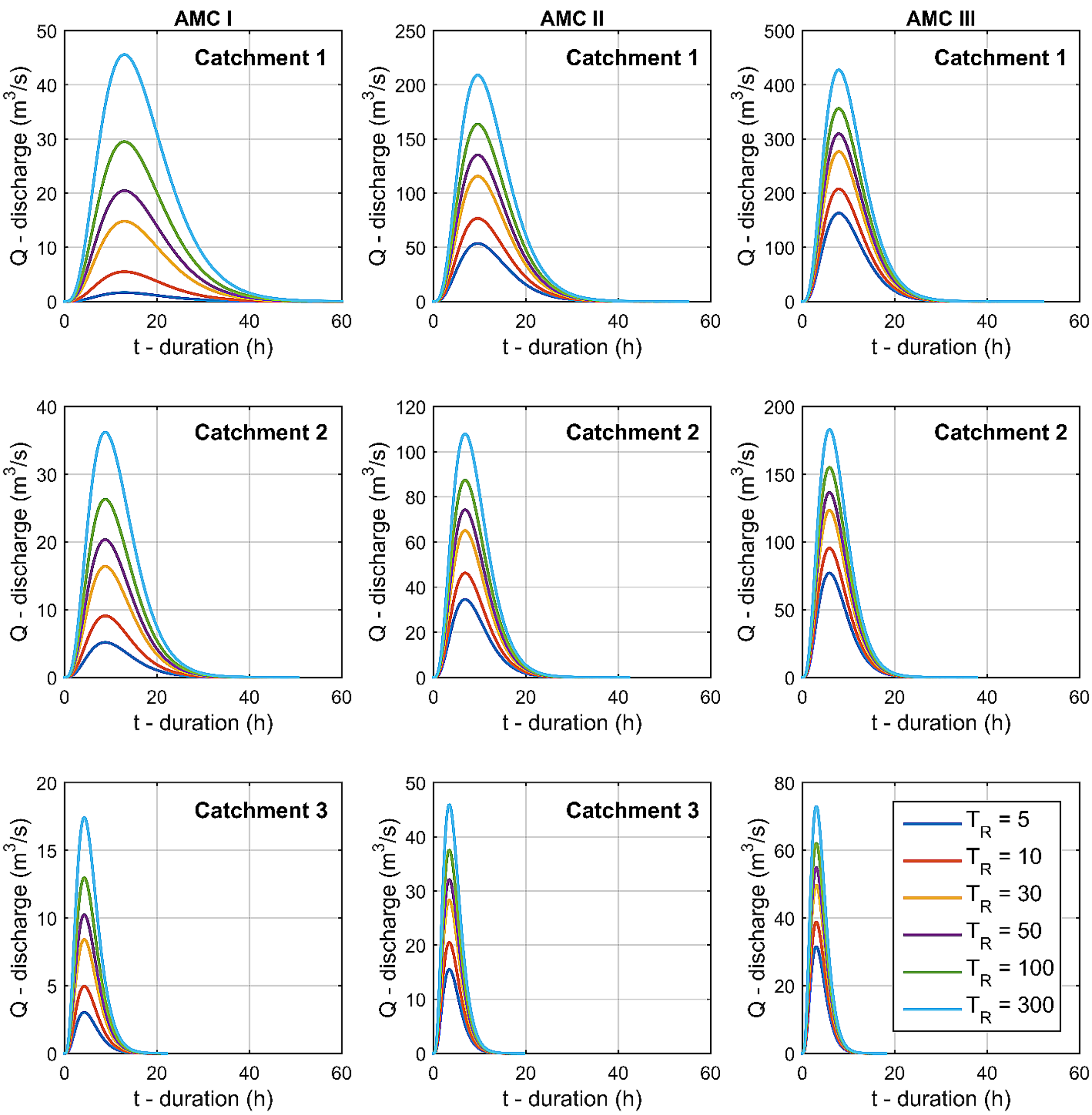

Figure 3.13 The hydrographs for the three catchments, for the three AMCs and for all the considered return periods. Note y-axis scales differ among panels

3.3.2.3 The two-dimensional propagation model

In this work, flood routing in two dimensions was accomplished through the numerical integration of the equations of motion and continuity (dynamic wave momentum equation) for the flow. This was accomplished by means of the commercial software FLO-2D (O'Brien *et al.* 1993, FLO-2D 2004) which is a flood volume conservation model based on general constitutive fluid equations of continuity and flood dynamics, i.e. shallow water equations or Saint-Venant equations. The flow is considered variable in space and in time, and the bottom friction is evaluated using Manning's formula. The Manning's coefficients were assigned to computational cells based on a literature review. Conservative estimates of 0.04 and 0.02 were assumed for natural and for urban areas, respectively. Drainage features not already incorporated in the DEM (e.g. the sewage system) were omitted due the lack of available data on these systems.

A two-dimensional flood simulation is based on a digital elevation model (DEM) overlaid with the surface grid, aerial photography and orthographic photos, detailed topographic maps and digitized mapping. Detailed cartography is needed in order to identify the surface attributes of the grid system; for example, streets, buildings, bridges, culverts or other flood routing or storage structures. The principal advantages in using a two-dimensional diffusion model is that it can be applied in special cases such as, unconfined or tributary flow, very flat topography and split flow.

In this study, the 2 m resolution DEM presented in Section 3.2.2 was adopted; a computational grid of 10 m resolution was defined within the single domain for the simulation code, returning an output having the same resolution of the initial DEM. Such hypothesis on the computational resolution allow reasonable computational time. The buildings in the area were treated in the simulations as obstacles to water accumulation/flow.

In order to optimize the computational time, the analysis domain was divided in five sub-domains. The first, second and third sub-domains were related to the three main water courses; the last two sub-domains are defined below the junctions of the previous main water courses. In each drainage outlet the related hydrograph was applied; in each junction a hydrograph was obtained as the sum of the flows from the upstream water courses. Figure 3.14 shows the five sub-domains considered and the junction points.

The simulation duration for each sub-domain is equal to the time necessary to exhaust the related hydrograph. The results of the hydraulic routine are presented in Appendix 1. The most important observations validating the reliability of the simulations are:

- Inundation depth and flow velocity values increased for increasing return period;
- Maximum depth and flow velocity were generally reached in proximity of intersections with infrastructure (e.g. road or railway embankments), especially where reductions of floodable section occurred;
- All the infrastructure features, well represented in the adopted DEM, created overflowing upstream; dam-effects can be observed first in correspondence of the railway embankment of the Nelson Mandela Expressway and then in correspondence of Morogoro road embankment.
- The final part of the Msimbazi River (i.e. near its mouth) had its flow well confined in the flood plain between the more external stems, even if the flow was very high for the contribution of the other two catchments.

A large part of the built environment in the case study area is affected by the flood events in all the analyzed sub-domains. More detailed descriptions of the exposure and of the affected assets are given in Section 3.4.

3.0.3 The hazard curves

Flooding hazard curves were associated with each building in the inundation area. Such curves represent the mean annual frequency of exceeding (equal to the inverse of return period for a homogenous Poisson process) a given flood height for a given point within the case-study area (e.g. one of the corner of a given building), based on the input grid data set described previously. This is done by a spatial interpolation between the point (e.g. the corner of the building) and the flood height values at the vertex of the lattice grid containing the point in question.

For each building, the interpolation with the hazard was repeated for all the building's corners. Then, only the maximum value of inundation depth was considered for each return period. Figure 3.15 below shows the schematic representations of the adopted procedure and the final output.

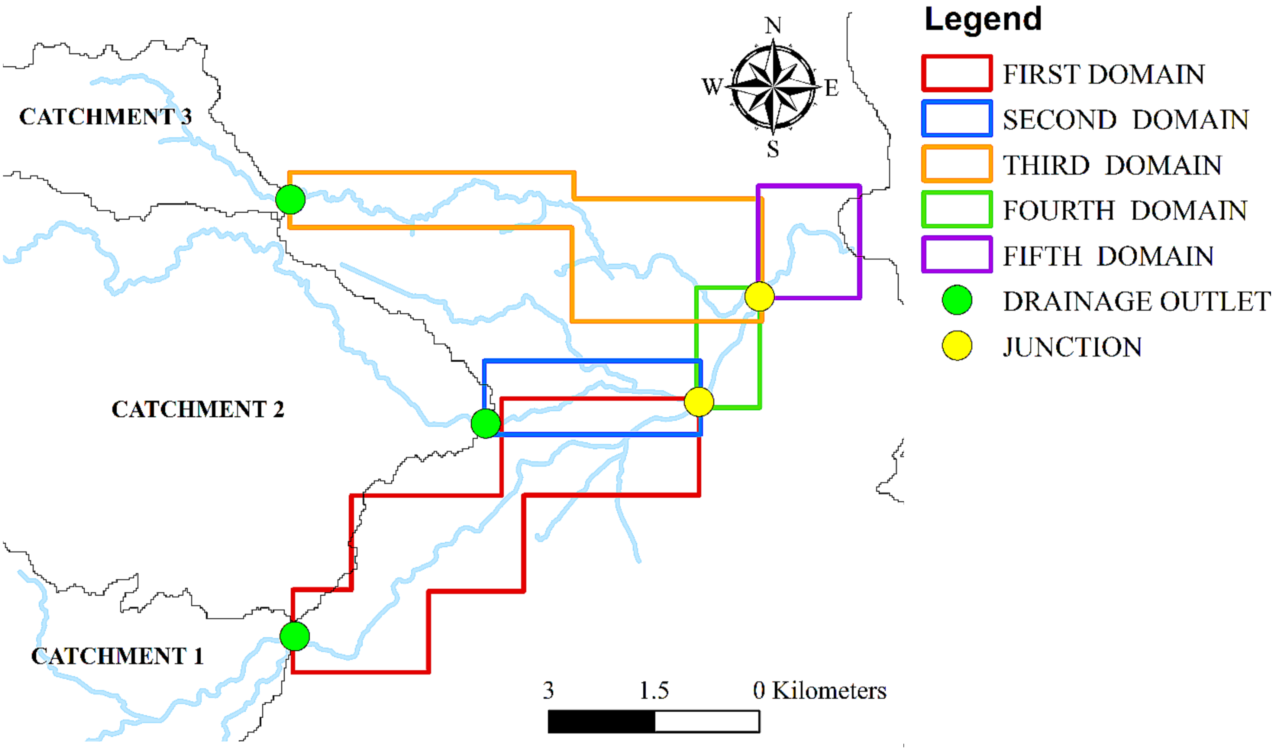

Figure 3.14 Analysis sub-domains

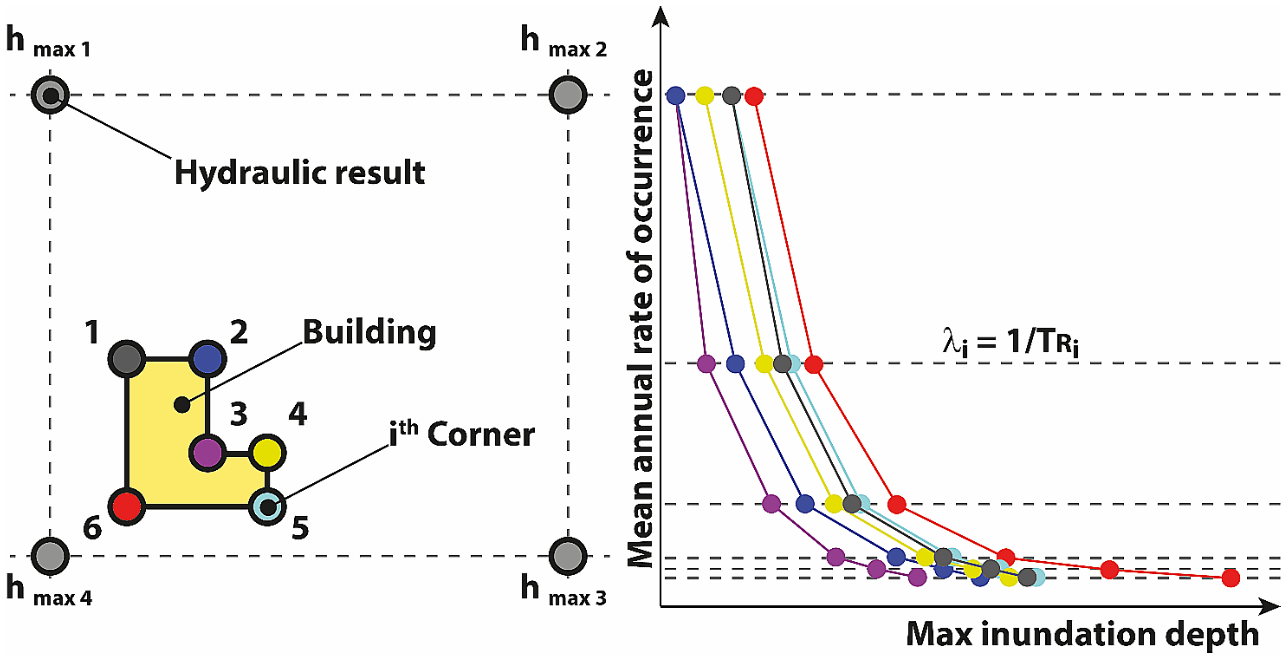

Figure 3.15 Schematic representation of the procedure and of the expected output in terms of flood hazard curves. In this example only the red hazard curve will be associated to the analyzed building.

The exposure and vulnerability models

The analysis domain and the sub-domains cover portions of all three municipalities in Dar es Salaam, as shown in Figure 3.16, and represent one of the most populated areas in the city. The analysis domain covers the sub-wards of Ilala, Kinondoni, and Temeke. The study area was chosen because it contains the low-lying densely populated areas that have experienced recurrent flood damages in the past, often annually or sub-annually.

According to the results presented in Section 3.2.3 and represented in Figure 3.8, it is also possible to observe that the analysis domain covers a big part of the city center in which residential areas and economic activities are concentrated. In this study, the buildings potentially subject to the flood hazard were investigated in detail, and were used as main elements of the exposed asset. Appendix 2 contains a literature survey and presents the estimation of the current building value in Dar es Salaam used in this analysis.

Building-by-building identification benefiting from Volunteered Geographic Information (VGI), in particular OpenStreetMap (OSM, www.openstreetmap.org), one form of big data, was used. Such a resource is often very useful in developing countries where there is a lack of data on exposed assets and it represents an alternative source for detailed spatial building information.

By intersecting the Urban Morphology Type map with the building footprints it was possible to identify the typology of each building. Figure 3.17 shows the buildings in the analysis domain; the total number of buildings is 209124; and the distribution of building footprints according to their typology. For the buildings falling in areas of mixed types, we used the additional details in the OpenStreetMap shapefiles.

The buildings at risk in the analysis domain were identified by intersecting the map of all buildings with the maximum extent of the baseline flood inundation. A total of 12,744 buildings fell within this area. Figure 3.18 (a) shows the footprints of the buildings at risk.

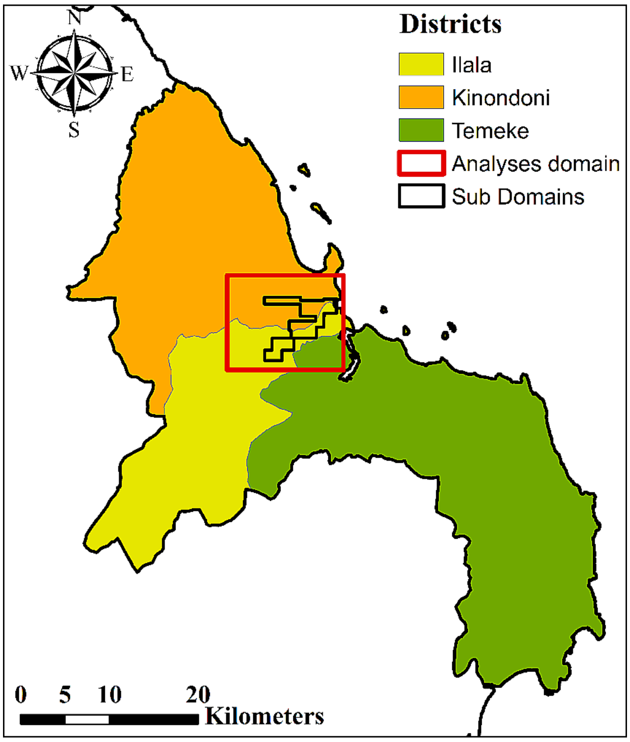

Figure 3.16 Geographical localization of the analyses domain.

The breakdown of the building characteristics based on available information is reported in Appendix 3. Sixty-two potential combinations of available characteristics were recognized. Such combinations led to the identification of three main structural types: informal masonry (IM), formal masonry (FM), and reinforced concrete frame (RCF). The sixty-two combinations of characteristics were also analyzed in order to estimate an average unit cost using the data reported in Appendix 2. The criteria adopted for identifying the structural typology and the unit cost is documented in Appendix 4. Figure 3.18 (b) shows the distribution of building structural typologies according to the adopted distinction criterion: 89.5% of the buildings analyzed were characterized as IM, 8.8% as FM, and 1.7% as RCF.

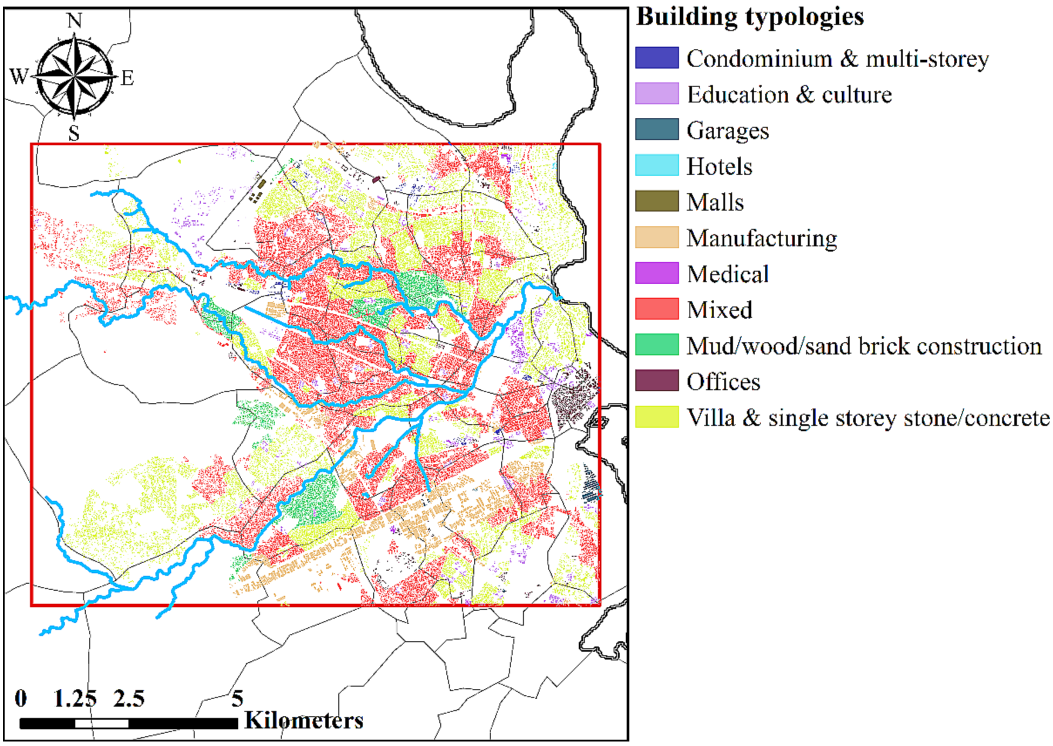

Figure 3.17 Building footprints in the analyses domain distinguished by typology

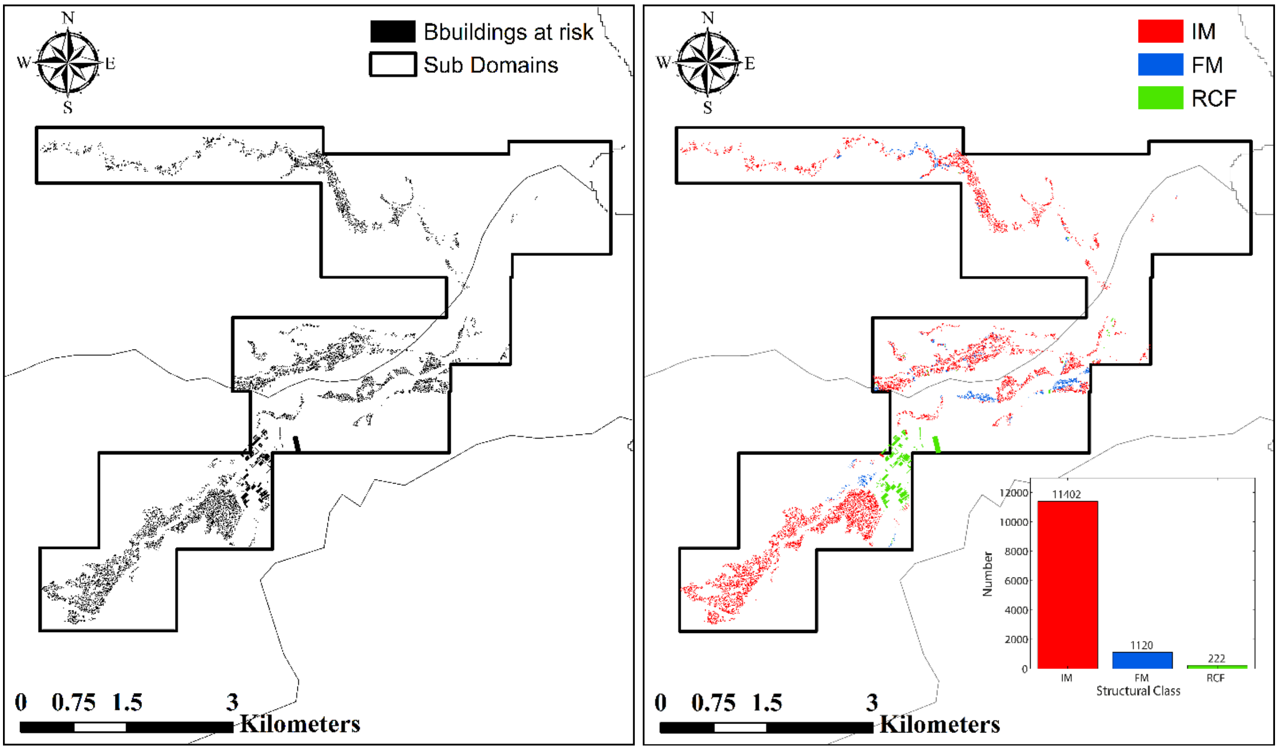

Figure 3.18 (a) Buildings at risk, and (b) buildings at risk distinguished by structural typology.

3.0.1 The vulnerability model

Once the main structural typologies were identified, it was necessary to assign a vulnerability model to each. According to Durra & Tingsanchali (2003) the damages caused by floods can be classified in two categories: qualitative and quantitative. The qualitative damages include human conditions like anxiety, mental suffering or the inconvenience associated the loss of possessions or with resettlement. On the other hand, the quantitative damages can be measured in economic terms in a more straightforward manner. The latter can be subdivided into indirect and direct damages. The indirect damages can be quantified --in economic terms -- as a function of downtime and its consequent disruption of economic and social activities. The direct damages are due to the interaction between the water flow and the physical system (i.e. structure, infrastructure, green space, etc.). In this study we focus on direct damages. It is important to note that while this represents the most appropriate economic approach to measuring the damages, it may overstate the damages to commercial or industrial businesses, as a result of higher unit costs, and understate the damages to residential unplanned dwellings that are owned with the most vulnerable in society.

The vulnerability of the structure was described using fragility functions. A fragility function evaluates the probability of reaching or exceeding specific damage states for a given hazard intensity (in this case inundation depth; Porter *et al.* 2007). Such relationships between hazard and potential damage play a vital role in quantifying damage and losses associated with flood events. In this study, the onset of damage was defined as the structure being 50% affected relative to the onset of collapse.

The fragility curves provide a visual and efficient way of representing the structural vulnerability. One of their characteristics is that they correspond to a specific structural limit state. Two limit states were considered in this study: a damage limit state (DLS); and the collapse limit state (CLS). The methods and assumptions for estimating the curves are described in Box 3.4. Figure 3.19 shows the fragility functions adopted in this study.

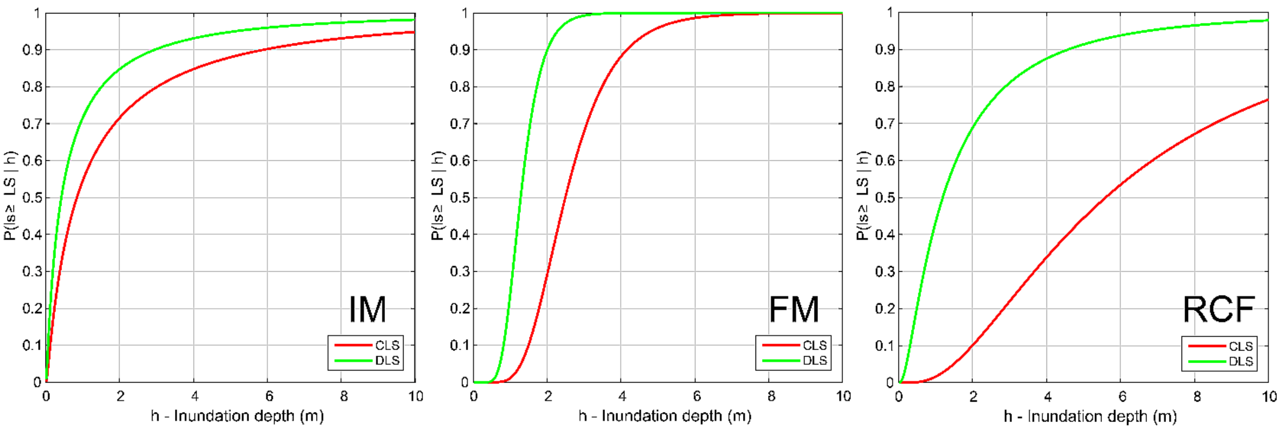

Figure 3.19 Fragility curves for the three considered structural typologies and two potential limit states

Many studies have been carried out on flood damage to different structures (Herath *et al.* 1999; Gissing and Blong, 2004; Scawthorn *et al.* 2006a; 2006b; Jonkman *et al.* 2008b; De Risi *et al.* 2012; Büchele *et al.* 2014). In this study, specific fragility models considered suitable for the case of Dar es Salaam were adopted. All the curves were modeled as a log-normal function:

$$P\left(ls \geq LS \mid h\right) = \Phi\left(\frac{\ln\left(h/\eta\right)}{\beta}\right) \tag{3.24}$$

having median η and logarithmic standard deviation β. $\Phi(\cdot)$ represents the normal CDF.

Jalayer *et al.* (2016) developed flooding collapse fragility functions for typical low-standard structures in Dar es Salaam. Such curves are suitable for describing the vulnerability of informal masonry buildings in the city. To obtain the damage fragility function, according to the results presented in De Risi (2013b), the median value corresponding to the collapse limit state is divided by two, and the logarithmic standard deviation is kept the same. Table 3.5 lists the statistics necessary to build the fragility function for IM structures.

Table 3.5. Statistics of fragility functions for informal masonry buildings.

LS	η	β
DLS	0.42 m	1.52
CLS	0.84 m	1.52

For the formal masonry structures, Reese *et al.* (2011) developed empirical fragility functions for residential masonry buildings with respect to the action induced by tsunamis. The use of tsunami fragility curves can be considered valid since the empirical fragility curves are obtained considering aggregated data for which the median velocity values are usually not so high, varying between 2 m/s and 5 m/s (Charvet *et al.* 2015), values that are comparable with the velocity values obtained with the current simulations in Dar es Salaam. In this work such curves are obtained for five different damage states; among those five damage states the two corresponding to the two limit states taken into account here are the curves associated to DS3 (i.e. DLS) and to DS5 (i.e. CLS), respectively. Table 3.6 lists the statistics necessary to build the fragility function for FM structures.

Table 3.6. Statistics of fragility functions for formal masonry buildings.

LS	η	β
DLS	1.28 m	0.35
CLS	2.49 m	0.50

Finally, for reinforced concrete frame structures, Supparsi *et al.* (2013) developed empirical fragility functions for RC buildings for the action induced by tsunamis. Herein the statistics related to 1 storey and 2 storeys are averaged. Among the six damage states taken into account, only the curves associated to DS3 (i.e. DLS) and DS5 (i.e. CLS), are considered. Table 3.7 reports the statistics necessary to build the fragility for RCF structures.

Table 3.7. Statistics of fragility functions for reinforced concrete buildings.

LS	η	β
DLS	1.20 m	0.79
CLS	5.60 m	0.81

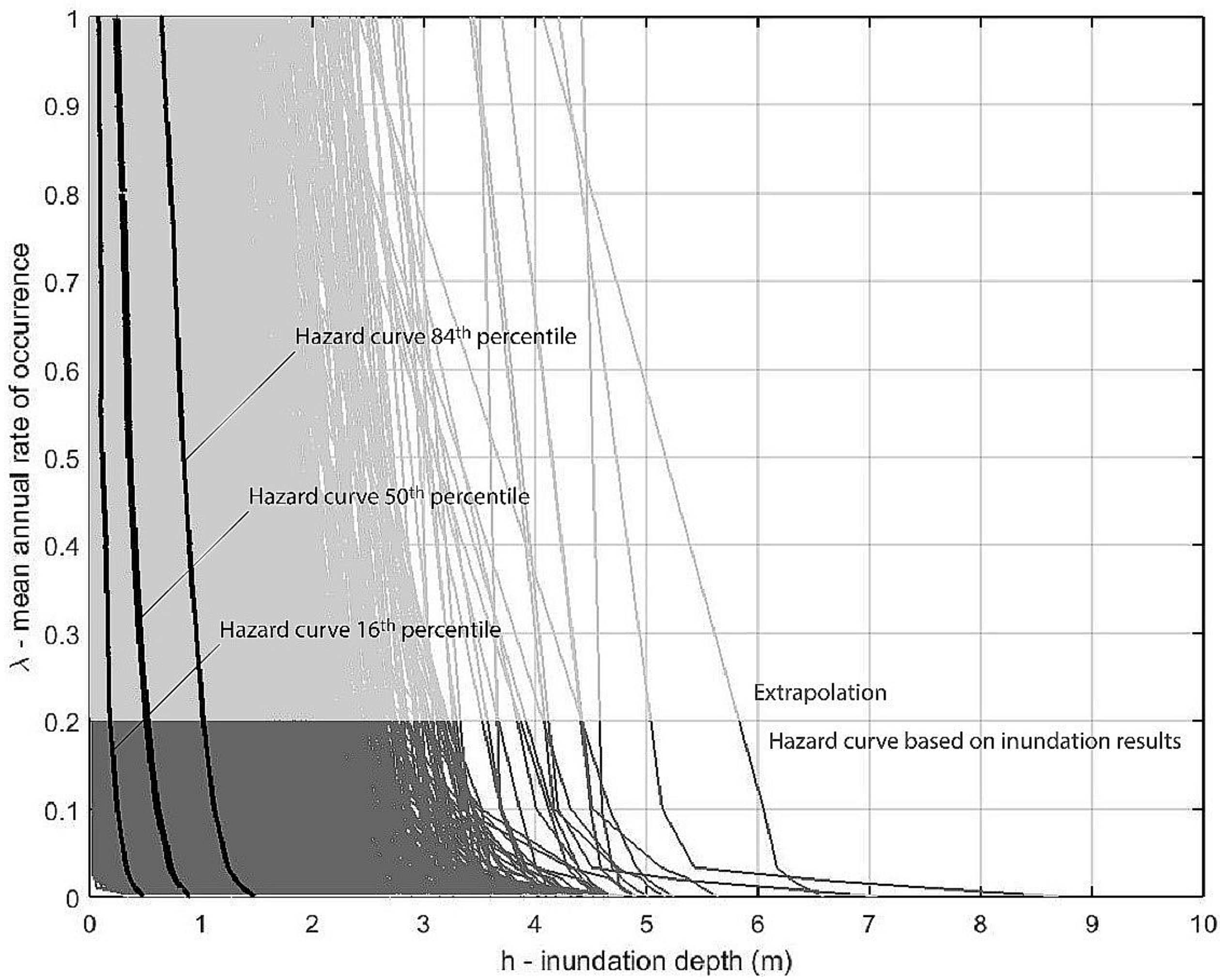

Figure 3.20 Hazard curves for the baseline scenario; λ values ≤ 0.2 based on inundation records; values ≥ 0.2 based on extrapolation

3.0.2 The hazard curves for the buildings at risk

For all the buildings at risk represented in Figure 3.20 (a) the procedure explained in Section 3.3.3 was applied to generate the respective flood hazard curves. Figure 3.23 shows the hazard curves for the 12 744 buildings at risk.

3.0.3 Risk assessment

In recent years, increasing attention has focused on riverine flood risk assessment. In fact, several publications discuss the consequences of flooding, such as loss of life (Jonkman *et al.* 2008a), economic losses (Pistrika & Tsakiris 2007, Pistrika 2010, Pistrika & Jonkman 2010) and damage to buildings (Smith 1994, Kang *et al.* 2005, Schwarz & Maiwald 2008, Chang *et al.* 2009). These research efforts have many aspects in common, such as a direct link between flood intensity and duration and the incurred damage, and that they are based on real damages observed in the aftermath of flooding events. On the other hand, many research efforts are starting to galvanize in the direction of proposing analytical models for flood hazard and vulnerability assessment taking into account the many sources of uncertainties. Nadal *et al.* (2010) propose a stochastic method for assessing the direct impact of flooding on buildings. A general methodological approach to flood risk assessment is embedded in the HAZUS procedures for risk assessment (Scawthorn *et al.* 2006a, 2006b). Apel *et al.* (2009) comprehensively assess the various scales of complexity and precision involved in flood risk assessment.

Here, following De Risi *et al.* (2013a), we summarize flood risk assessment using a single equation (Eq. 3.25), where λ_{LS} denotes the risk expressed as the mean annual rate of exceedance of a given limit state (LS). The limit state refers to a threshold (e.g. critical water height $h_{f,c}$) for a structure beyond which it no longer fulfills a specified functionality. $\lambda(h_f)$ denotes the mean annual rate of exceedance of a given flooding height hf at a given point in the considered area. $P(LS|h_f)$ denotes the flooding fragility for limit state *LS* expressed in terms of the probability of exceeding the limit state threshold.

$$\lambda_{LS} = \int_{h_f} P(LS \mid h_f) \cdot \left| d\lambda(h_f) \right| \cdot dh_f \quad (3.25)$$

The risk λ_{LS} is calculated in terms of the mean annual frequency of exceeding the limit state LS for each node of the lattice covering the zone of interest by integrating fragility P(LS|hf) and the (absolute value of) hazard increment |dλ(hf)| over all possible values of flooding height. The mean annual frequency of exceeding the limit state λ_{LS} is then transformed into the annual probability of exceeding the limit state assuming a homogenous Poisson process as a model for occurrence of limit-state-inducing events, according to Eq. 3.26.

$$P(LS) = 1 - \exp(-\lambda_{LS} \cdot t) \quad (3.26)$$

where *t* is the time in years. It should be noted that Eq. (6.1) manages to divide the flood risk assessment procedure into two main modules, namely, the hazard assessment module which leads to the calculation of the mean annual frequency $\lambda(h_f)$ of exceeding a given flooding height h_f, and the vulnerability assessment module used to calculate the flooding fragility curve in terms of the probability of exceeding a specified limit state $P(LS|h_f)$.

3.0.4 The expected annual losses (EAL)

From an economic perspective, the costs of flooding and other natural disasters can be broadly categorized into market versus non-market and direct versus indirect losses (Hallegatte & Przyluski 2010). Direct market losses are negative impacts of the disaster on goods and services commonly bought and sold and whose value therefore generally can be fairly accurately determined using readily-available, directly-observable price data (e.g. costs of infrastructure repair or medical treatment). Direct non-market losses are costs that are caused by the disaster but whose economic value cannot be readily quantified because they are not themselves traded on markets (e.g. suffering caused by injury or by death of family members or friends; loss of life; loss of amenity). While economic valuation of direct, non-market impacts is possible (e.g. the cost of suffering from specific health effects) and in many cases even fairly common (e.g. the value of a statistical life or of disability-adjusted life years), the resulting values often are contentious because they rely on indirect valuation approaches that utilize people's stated rather than observed preferences, or because many individuals are uncomfortable with assigning monetary values to these impacts.

Indirect losses are not caused by the disaster itself but rather by its secondary effects. For example, if flooding damages infrastructure (e.g. transportation or utility networks), it often causes business interruptions that continue far beyond the duration of the actual flooding itself. Likewise, because of economic linkages among businesses and economic sectors, flooding may cause indirect losses in the form of negative effects on economic activity outside of the immediate flood footprint.

Our analysis only considers direct market losses from flooding in the form of damages to buildings. The expected loss is calculated as the expected repair costs[4] (per building or per unit residential area), $E[R]$ as a function of the limit state probabilities and by defining the damage state i as the structural state between limit states i and i+1:

$$E[R] = \sum_{i=1}^{N_{LS}} \left[P(LS_i) - P(LS_{i+1}) \right] \cdot R_i \quad (3.27)$$

where N_{LS} is the number of limit states that are used in the problem in order to discretize the structural damage; R_i is the repair cost corresponding to damage state *i*; and $P(LS_{N_{LS}+1}) = 0$. In this study, we set the repair cost associated with the CLS to 100% of the value of the total exposed asset, and the repair costs associated with the DLS to 50% of that value. Moreover, in the case of collapse, a further cost of 10% of the entire asset is assumed for the dismantling of the collapsed building and removal of debris. The expected annual loss (EAL) then is obtained using probability terms in equation 3.27 calculated considering a time window of one year in equation 3.26. Computation of EAL is explained in more detail in Box 3.5.

Box 3.5. Expected annual loss

The EAL is obtained by the integration of the hazard curves, fragility curves, and asset value (Cornell & Krawinkler 2000). The integration considers all the possible values of inundation; there is not an inundation threshold that once is reached identifies one damage state or the other. Hazard (the flood hazard curves) and Vulnerability (the fragility curves) are combined together in order to obtain a value (namely the mean annual rate of occurrence of a given limit state) that is independent by a single scenario; instead, all potential scenario (inundation depths) are considered according to their probability of occurrence (the hazard) and their probability of creating a damage (the fragility).

Integrating the hazard curves and the fragility associated with the CLS, the mean annual rate of occurrence of collapse limit state is obtained. Integrating the hazard curves and the fragility associated to the DLS, the mean annual rate of damage limit state is obtained. To convert these two latter (dimensionless) numbers in economic terms, they are combined with the expected losses associated to their occurrence.

The mean annual loss associated with the occurrence of the collapse limit state is equal to the mean annual rate of occurrence of the collapse limit state multiplied by the 100% of the total asset value. The mean annual loss associated to the occurrence of the damage limit state is equal to the difference between the mean annual rate of occurrence of the damage limit state and the mean annual rate of occurrence of the collapse limit state, multiplied by the 50% of the total asset value. The difference between the two mean annual rates of occurrence is required to avoid double-counting the contribution due to the collapse. Finally, the EAL is obtained summing the mean annual loss associated with the occurrence of the collapse limit state and the mean annual expected loss associated with the occurrence of the damage limit state.

Figure 3.24 provides a graphical explanation of the described procedure for a single value of inundation depth. The final expected loss is obtained summing the terms obtained in figure for all the potential values of inundation depth.

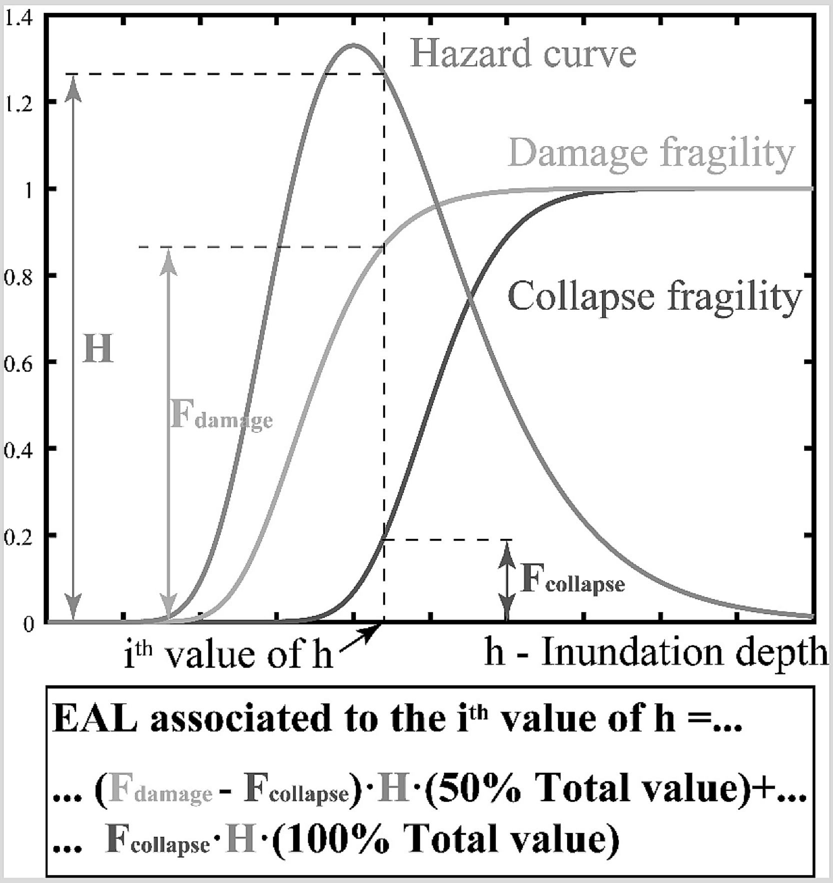

Figure 3.24. Schematic representation of the integration

The distinction on the asset values associated to the onset of the different limit states (i.e. 50% of the total asset associated to the onset of DLS and 100% of asset associated to the onset of CLS) is a well consolidated practice in literature in the field of risk assessment for the many natural hazards, such as flood (Scawthorn et al. 2006), earthquake (Goda & Hong 2008) and tsunami (De Risi et al. 2016).

IV. EVALUATION AND SELECTION OF POTENTIAL URBAN STORMWATER MANAGEMENT OPTIONS

Overview of stormwater management

Within urban areas, rain that falls onto impermeable surfaces such as streets, parking lots, pavements and roofs is unable to filtrate into the ground as it would normally do in undeveloped areas, leading to higher levels of surface runoff during storm events than would have happened naturally and creating flooding problems in downstream areas (Armitage *et al.* 2013). This problem is exacerbated by the fact that urban stormwater runoff generally contains litter, debris, and sediments which lead to blockages of the systems designed to convey water, and they also contain bacteria, heavy metals and nutrients, which means that floodwaters can become a pollution hazard. All of this can have negative impacts on property, urban infrastructure and natural habitats, as well as urban inhabitants. With an increase in urbanisation worldwide and the associated impact of increasing stormwater runoff on aquatic ecosystems, the management of urban drainage has become a critically important challenge (Fletcher *et al.* 2015).

Urban drainage management has changed significantly over the last few decades, from a conventional 'rapid disposal' approach to a more integrated and sustainable 'design with nature' approach (Fletcher *et al.* 2015). The early traditional attitudes towards urban drainage management focused on trying to dispose of stormwater in the fastest way possible with not much consideration for surrounding ecosystems or for downstream water quality impacts. In the 1980s and 1990s a new focus on urban stormwater runoff and water quality developed around the world, which concentrated on a more catchment-wide management and restoration approach to urban drainage as opposed to the standard end-of-catchment solution (Fletcher *et al.* 2015). This embodied a more holistic approach which treats stormwater runoff problems at source and minimises environmental degradation, while delivering environmental, economic and social benefits. This rapid development in the field of urban drainage saw a number of terms being used to define similar concepts (Fletcher *et al.* 2015). Terms such as **"Water Sensitive Urban Design"** (WSUD), **"Low Impact Development"** (LID), **"Sustainable Urban Drainage Systems"** (SUDS), **"Integrated Urban Water Management"** (IUWM) and **"Best Management Practices"** (BMPs) were first used by professionals in countries such as Australia, New Zealand, United States, England and Scotland to describe this new approach to urban drainage and are all essentially synonymous. **"Green infrastructure"** is another term commonly used in this context, and tends to refer to any environmentally-friendly stormwater management structures, natural and semi-natural systems used in stormwater management. Storm water management measures now tend to be designed to address both flooding and water quality problems, with many measures addressing both of these.

Types of stormwater management measures

Stormwater management measures are classified into structural and non-structural measures, with structural measures being further subdivided into passive and active measures (Figure 4.1; see Appendix 5 for details).

- Passive structural measures aim to convey water and protect areas from flooding. Examples are levees, increasing the channel capacity by clearing of debris or increasing its cross-section, and constructing hydraulic bypasses (waterways) to divert high flows.
- Active structural measures aim to modify the hydrograph (i.e. reduce flood peak and volume) and address water quality by retarding water movement, by increasing infiltration or storage in the catchment area (Topa *et al.* 2014). These can be referred to as "green" (sustainable/environmentally-friendly) engineering measures.
- Non-structural measures do not involve physical construction but use knowledge, practice or agreements to reduce risks and impacts through behavioral changes, in particular through policies and laws, public awareness raising, training and education (Kundzewicz 2002). These include flood warning systems, land use regulations such as development setbacks which identify where development can and cannot occur, or to what elevation structures should locate their lowest habitable floor to; flood proofing and retrofitting of buildings may increase the strength against flood actions; elevation of buildings may avoid completely the inundation. Flood insurance and relocations also belong to this typology of measures.

Passive structural measures for conveyance

- Drains, swales
- Modify river channel – widen/deepen/levees
- Hydraulic bypass

Active structural measures ("Green engineering")

Source controls

- Permeable pavement
- Infiltration trenches
- Sub-surface soakaways
- Green roofs
- Rainwater harvesting

Local controls

- Vegetated swales
- Filter strips
- Sand filters
- Bio-retention areas

Regional controls

- Detention basins
- Treatment wetlands

Non-structural interventions

- Policies, laws and enforcement (sanitation, effluents, litter)
- Solid waste management, river cleaning programmes
- Riparian buffers
- Catchment conservation areas

Figure 4.1 Different types of measures used in stormwater management. These measures are described in Appendix 5.
Source: This study

The active structures or "green" engineering measures tend to be grouped as either source, local or regional controls (Thampapillai & Musgrave 1985, Kundzewicz 2002, Armitage *et al.* 2013; Figure 4.1, see Appendix 5 for details):

- **Source controls** tend to be used to manage stormwater runoff as close to the source as possible, generally within the boundaries of the property such as green roofs, soakaways and permeable paving.
- **Local controls** are usually used to manage runoff as a second line of defence typically in public areas, along roadways and adjacent to parks such as filter strips and swales.
- **Regional controls** are used to manage runoff as the last line of defence and are generally large-scale interventions constructed on municipal land such as detention ponds and wetlands (Armitage *et al.* 2013).

Measures that retard flows generally also contribute towards improving water quality, and vegetated areas further contribute to water quality amelioration where flows are slow enough. The various structural measures are described in more detail in Appendix 5.

Relative performance of different measures

Generally a combination of these measures would be applied. There will be trade-offs among the interventions and finding the correct balance can be a complex task. The active structural measures, such as floodplain storage interventions will reduce the need for extensive passive measures such as levees or the widening of channels. However, active measures alone often will not be able to eliminate flooding problems completely and thus generally will need to be implemented in conjunction with some conveyance infrastructure. Generally, the 'softer' the intervention the less efficient it tends to be in terms of m^3 reduction per unit of space. However, the softer interventions tend to have greater benefits in terms of amenity and social value. Therefore it is necessary to develop a sound methodology for evaluating the interventions based on cost-effectiveness, efficiency in removing peak flows, reducing runoff volume and water quality amelioration, and providing amenity, conservation and social benefits. These are discussed in more detail on the following page.

When developing a proposed plan for managing stormwater it is important to link together the various interventions and the benefits that they provide with the greatest possible efficiency. That is, identify the combination of interventions for a specific project site that will achieve the outlined objective in the most cost-effective way, i.e. results are achieved at a lower cost compared to alternatives. This involves determining the cost effectiveness of different interventions, i.e. a cost per unit reduction of runoff volume (m^3) or cost per unit reduction in pollutant loads (kg), depending on what the proposed project is trying to achieve. Outside of cost-effectiveness, interventions need to be assessed in terms of any other benefits that they may provide, such as conservation value, amenity value or social benefits such as increased water supply. The interventions need to be realistic in terms of what is feasible and practical within the designated project area. While this study was focused on the flood amelioration aspect, it is worth considering the water quality impacts at the same time, since these go hand in hand, particularly if the required sanitation and sewage systems are in place.

Numerous studies have examined the relative ability of different interventions to reduce pollutant loads, flow volumes and attenuate peak flows during storm events, and their cost-effectiveness. Estimates for cost-effectiveness in terms of cost per unit runoff reduction ($\$/m^3$) and cost per unit reduction in pollutant loads ($/kg) were collated from a wide range of stormwater management literature. These estimates tend to be site specific based on local costs but nonetheless provide a clear indication of which interventions are generally more cost-effective in terms of their ability to reduce runoff and remove pollutants.

4.0.1 Average cost effectiveness in terms of peak flow and volume reduction

Cost-effectiveness in terms of runoff reduction ($\$/m^3$) is shown in Figure 4.2. These estimates are based on reviews and examples from the stormwater management literature (Joksimovic & Alam 2014, Liu *et al.* 2015, Jiang *et al.* 2015, Committee for Climate Change 2012, Xiao & McPherson 2002, McPherson *et al.* 1999). From the examples it is clear that green roofs and permeable pavements are the least cost-effective, even though they are efficient at reducing runoff, due to their higher capital and maintenance costs compared to other options. Soakaways and infiltration trenches are the most cost-effective of the structural engineering methods as they are cheaper to construct and maintain. Constructed wetlands, sand filters, bioretention areas, detention basins, filter strips and swales generally are all relatively cost-effective. They are however less efficient at trapping or attenuating peak flows after a large storm. Riparian buffers and catchment reforestation represent the most cost-effective option in that they do contribute significantly to rainwater infiltration, but they also do not trap or attenuate peak flows (which is not captured in the $\$/m^3$ assessment). The structural engineering options are more efficient in this regard.

4.0.2 Average cost effectiveness in terms of water quality amelioration

A number of interventions are designed to specifically control and improve the quality of stormwater runoff. Generally their performance is assessed based on their pollutant removal capabilities. Some interventions may be more efficient at removing suspended solids and hydrocarbons, whereas others may be particularly efficient at removing soluble nutrients such as phosphorus. Often this means that a number of interventions are required to achieve a specified outcome. The capacity for pollutant removal of different interventions is summarised in Table 4.1.

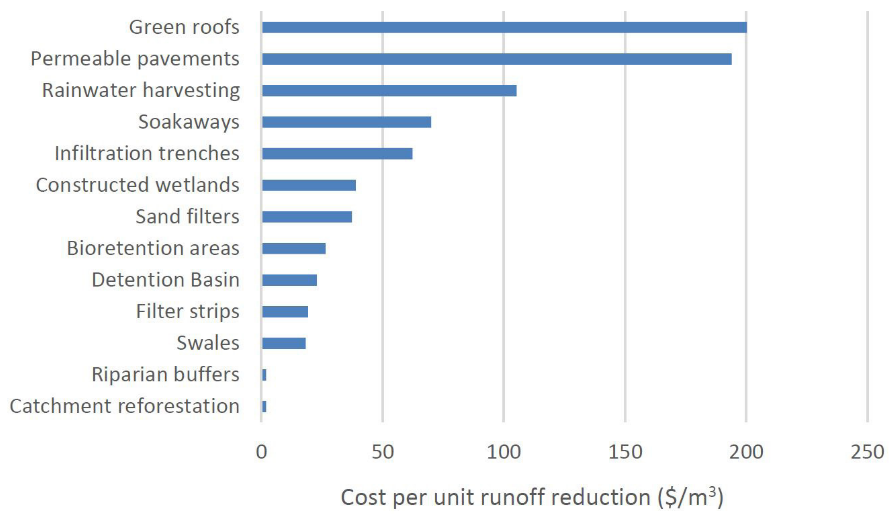

Figure 4.2 Comparison of cost per unit volume of runoff reduction for various stormwater management options, based on literature averages

Table 4.1 Measured pollutant removal capacities of selected stormwater management options and technologies

	Pollutant Removal (%)					
Option/Technology	TSS	Hydro-carbons	TP	TN	Faecal Coliforms	Heavy Metals
Source Controls						
Green roofs	60-95	-	-	-	-	60-90
Sand filters	80-90	50-80	50-80	25-40	40-50	50-80
Underground sand filters	75-90	-	30-60	30-50	40-70	40-80
Surface sand filters	80-90	-	50-60	30-40	-	-
Filter drains	50-85	30-70	-	-	-	50-80
Soakaways	70-80	-	60-80	25-60	60-90	60-90
Oil and grit separators	0-40	40-90	0-5	0-5	-	-
Modular geocellular structures	PS	PS	PS	PS	PS	PS
Stormwater collection and reuse	PS	PS	PS	PS	PS	PS
Local controls						
Bioretention areas	50-80	50-80	50-60	40-50	-	50-90
Filter strips	50-85	70-90	10-20	10-20	-	25-40
Infiltration trenches	70-80	-	60-80	25-60	60-90	60-90
Permeable pavements	60-95	70-90	50-80	65-80	-	60-95
Swales	60-90	70-90	25-80	30-90	-	40-90
Enhanced dry swales	70-90	70-90	30-80	50-90	-	80-90
Wet swales	60-80	70-90	25-35	30-40	-	40-70
Vegetated buffers*	50-85	70-90	10-20	10-20	-	25-40
Regional controls						
Constructed wetlands	80-90	50-80	30-40	30-60	50-70	50-60
Extended detention shallow wetland	60-70	-	30-40	50-60	-	-
Pocket wetland*	80-90	50-80	30-40	30-60	50-70	50-60
Submerged gravel wetland	80-90	-	60-70	55-60	-	85-90
Detention ponds*	45-90	30-60	20-70	20-60	50-70	40-90
Extended detention ponds	65-90	30-60	20-50	20-30	50-70	40-90
Infiltration basins	45-75	-	60-70	55-60	-	85-90
Retention ponds	75-90	30-60	30-50	30-50	50-70	50-80
*Estimated values based on similar stormwater technologies TSS – Total Suspended Soilds, TP = Total Phosphorous, TN = Total Nitrogen						

Source: Armitage *et al.* 2013

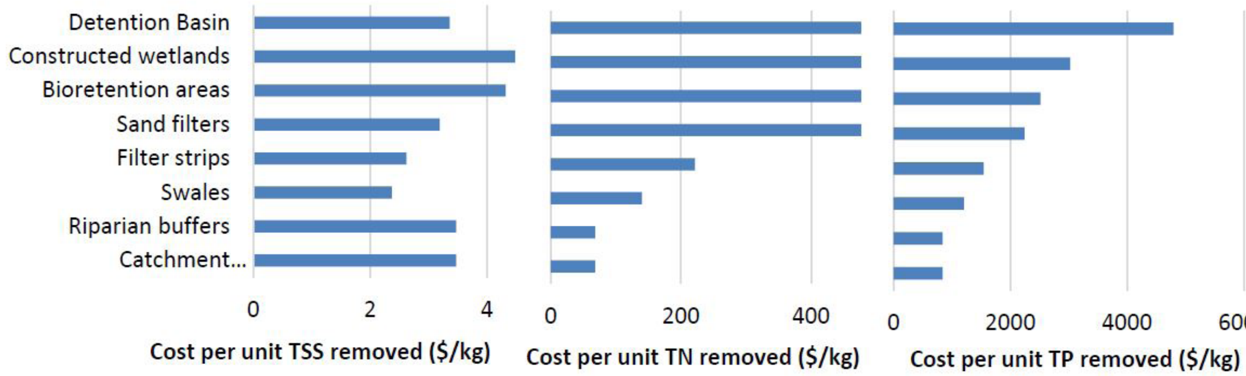

Figure 4.3 Comparison of cost per unit mass of pollutant/nutrient reduction for various stormwater management options

Detailed information provided in Armitage *et al.* (2013) (Table 4.1) was used to assess the water quality amelioration performance of the various interventions. These data as well as data from Centre for Watershed Protection (2013) were combined with cost data (see Appendix 6) to estimate relative cost-effectiveness for a selected range of interventions (Figure 4.3).

The most cost-effective options in terms of TSS removal are filter strips, swales and detention basins. Riparian buffers and catchment reforestation are also cost-effective options. In terms of TP and TN removal, riparian buffers and catchment reforestation are very cost-effective as are swales, filter strips and sand filters. Constructed wetlands and bioretention areas are less cost-effective for all three but they do have higher amenity values when compared to the other options.

4.0.3 Overall effectiveness, cost-effectiveness and potential co-benefits

The relative effectiveness of different interventions in terms of flood and water quality amelioration, their cost-effectiveness, and other potential benefits are summarised in qualitative terms in Table 4.2. This suggests that while conveyance measures are highly effective for reducing flood exposure/risk, they make little contribution to water quality amelioration, they vary in terms of cost-effectiveness and have relatively little in the way of co-benefits. Indeed, they are more likely to lead to negative externalities such as damage to aquatic ecosystems or acerbation of flooding further downstream. Of the conveyance measures, detention basins are potentially beneficial in terms of providing opportunities for amenity, such as sunken sports fields.

The “green” engineering measures are generally less efficient in flood protection, but are important for water quality. Effective flood protection will require these measures to be implemented in combination and/or at scale. Green engineering measures also vary in their cost-effectiveness and may not always compete with conveyance measures. They do however, also present much greater opportunities for delivering co-benefits, such as water supply and the provision of recreational areas. The latter is particularly the case for the vegetated options which have greater aesthetic appeal.

Table 4.2 Relative merits (indicated by number of "X") of different measures for stormwater and flood risk management, based on the literature. Measures considered in this study area are marked with an asterisk.

Option/ technology	Conveyance/ Reduction of exposure	Flood attenuation/ Reduction of flood risk	Water quality amelioration	Cost-effectiveness	Water supply	Amenity potential	Conservation value
Conveyance measures (lower catchment)							
Swales/drains*	XX			XX			
Channel enlargement/							
canalisation/levees	XXX			X			
Hydraulic bypass	XXX			X			
'Green' engineering measures (mid-upper catchment)							
Infiltration trenches		XXX	XXX	XXX	X		
Soakaways		XXX	XX	XX	X		
Permeable pavements		XXX	XXX	XX	X		
Rainwater harvesting		X	X	X	XXX		
Bio-retention areas		XX	XXX	XX		XX	
Sand filters		XX	XXX	XX			
Green roofs		XX	XXX	X		XX	
Filter strips		XX	XXX	XXX		X	
Vegetated swales		XX	XXX	XXX		X	
Constructed wetlands		XX	XXX	XX		XXX	X
Detention basins*		XXX	XX	XXX	X	XXX	
Non-structural measures							
Development setbacks*	X			XXX		XX	X
Conventional solid waste management	XX		X	XX		XX	X
River cleaning programmes*	X		X	XXX		XX	XX
Protection/restoration of catchment forests and wetlands*		XX	XXX	XXX	XX	XX	XXX
Protection/restoration of riparian areas, floodplains*	X	XX	XXX	XXX		XXX	XXX

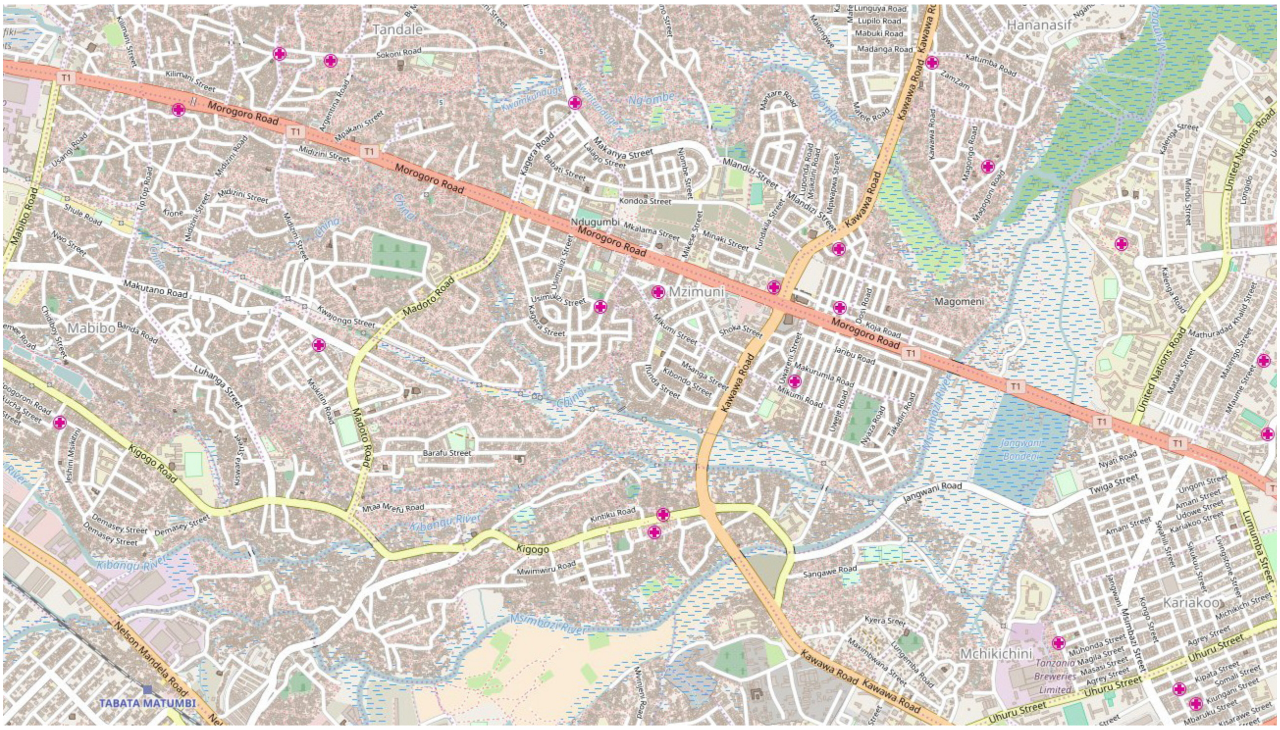

Figure 4.4 Heavy development around the lower floodplain areas of the Msimbazi River system in Dar es Salaam
Source: OpenStreetMap

The protection or restoration of natural systems in catchment areas contributes to the reduction and retardation of flows and to water quality amelioration. Within the flood prone areas, riparian buffers and functional floodplain areas reduce the exposure to flooding, and further contribute to water quality amelioration. In all cases, these areas have the potential to contribute significantly in terms of other co-benefits.

Selection of suitable measures for Dar es Salaam

This study sought to find a suitable set of measures that could be implemented in combination to address flooding problems in Dar es Salaam, while also contributing to a green urban development path for the city. As well as the relative merits discussed above, the limitations or requirements for the different interventions were taken into account, along with information on the catchment area, in order to determine the most suitable types of interventions to include in the analysis. Following this, the potential extent of each intervention was determined based on biophysical criteria.

An important consideration is that in the case of Dar es Salaam, not only has the expansion of the city resulted in increased stormwater runoff and reduced water quality coming from the catchment, but encroachment and reclamation of the floodplains in the lower catchment has also occurred (Figure 4.4). Thus the flow for any given rainfall event has increased, while the capacity of the floodplain to accommodate and convey this flow has been reduced. Both of these effects increase the exposure of people and infrastructure to flooding, so when they occur together they can create an enormous problem. In most developed country contexts the emphasis has been on amelioration of the effects of urbanisation in the catchment, for example by using measures to try and neutralise the effects of hardening on runoff volumes. But in the majority of developing country cities, not least in Africa, the lack of control over settlement patterns has led to much higher levels of encroachment of the original or natural floodplain areas, let alone the expanded floodplain area required as a result of increased runoff. This means that there might still need to be heavy reliance on conveyance measures in conjunction with green structural and non-structural measures, or that catchment measures might have to do more than neutralise the effects of catchment urbanisation, reducing storm flows to lower than natural levels. Both of these options may raise costs considerably. In addition, it should be noted that other characteristics of urbanisation in developing countries also affect the relative suitability of different measures compared to developed country cities.

This nature and pattern of development in both the catchment and flood receiving areas of Dar es Salaam severely constrains both the range of options that could be considered to offset flooding problems and their potential efficacy. An effective flood management scheme would need to offset the effects of floodplain infilling, channelization and canalisation in the lower floodplain area, as well as offsetting the impacts of urbanisation in the catchment area such as increased peak discharges and poor water quality. This means that whatever system is found to meet the combined objectives of improving water quality and addressing flooding will not be based on mimicking natural ecosystem function, but will of necessity require significant manipulation of flow regime in the upstream catchment and/or better conveyance from the flood prone areas. These limitations must be considered in planning remedial activities for Dar es Salaam, but should also be brought into the planning of any future urban expansion.

For this study, each intervention was assessed on its limitations and requirements as well as its suitability for application in the Msimbazi catchment in Dar es Salaam (Table 4.3). This study was carried out as a desktop study and as such the selection of suitable stormwater measures was based on available data, expert opinion and local and international literature. As a result of this, potential administrative issues surrounding the implementation of these interventions in Dar es Salaam have not been accounted for here and it is recognised that a more participatory approach may be needed to refine the selection or extent of application of GUD measures.

Conventional flood conveyance methods are not only expensive but would be difficult to establish in the study area because of the size of the floods that need to be contained. While dredging of the river channel may help to mitigate some flooding, it is not seen as a long term solution to the flooding problem in Dar es Salaam. Very few of the “green” engineering measures were considered feasible options for the study area. In some cases this was because of the low location in the catchment of the building structures they would be associated with, or because of the clayey nature of soils. Soakaways, or sub-surface infiltration beds, were considered for industrial and commercial areas where runoff from extensive roof surfaces could be collected and slowly infiltrated through soakaway pits. These are relatively cost-effective in terms of runoff reduction as well as in terms of their ability to remove suspended solids. The amount of roof runoff that could be captured by soakaways during a large stormwater event in Dar es Salaam could be significant. There are five large industrial areas in the catchment where soakaways could possibly be implemented and based on the size of these buildings it was estimated that collectively they could retain more than 30 000 m^3 of runoff in a 50mm rainfall event. However, the soil in the area where these industrial sites are located is predominantly clayey, making it unsuitable for implementation due to very poor infiltration rates associated with clay-type soils. The industrial areas are also located in the flood prone areas in the lower catchment, thus making these sites impractical and unsuitable for soakaways. There would also be little opportunity to implement measures such as green roofs in the catchment areas because of the fact that most of the buildings are informal structures.

Rainwater harvesting is something that could benefit households in the catchment area. However, apart from being fairly expensive to implement, it would have limited flood benefits in Dar es Salaam. The rainwater tanks would fill up quickly during a large storm event thereafter making them ineffective in trying to dampen the effects of increased runoff from the hardened surfaces. A much better option is to have large-capacity storage systems that release water, so that they are ready for the next high rainfall event. Indeed, of the green engineering options, detention basins were considered to have the most promise as an option to explore further.

Among the most feasible options were non-structural measures such as river cleaning programmes, solid waste management and the protection, restoration and/or enhancement of natural systems. River cleaning programmes and solid waste management are likely to be very worthwhile considering the immense problem created by solid waste and its contribution to flooding.

Table 4.3 Requirements for different stormwater management measures (apart from financial), and implications /suitability in Dar es Salaam

Option/ technology	Limitations/requirements for implementation	Potential for Dar es Salaam	Included in this study
Conveyance measures (lower catchment)			
Swales/Drains	-	**High** – enough space to implement in flood risk areas	Yes
Channel modification, Levees	Enough space to accommodate the engineering measures and straightening; potential damage to ecosystems; cost of resettlement is a potential limitation	**Low** – extremely large channel and/or high levees required to contain floods - unrealistic	
Hydraulic bypass	Enough space to accommodate the engineering measures; potential damage to ecosystems; cost of resettlement is a potential limitation	**Low** – requires drainage from catchment area; altering drainage path may only shift problem; negative impacts on lower river system	
'Green' engineering measures (mid-upper catchment)			
Permeable pavements	Not suitable in areas that experience heavy traffic	**Low-Med** – Paving is low priority at present.	
Infiltration trenches	Low gradient, permeable soils.	**Low** – clayey soils	
Soakaways	Would not be combined with other rooftop collection measures such as rainwater harvesting or green roofs. Needs to be in catchment area.	**Low** – clayey soils; suitable buildings mainly in lower areas	
Green roofs	Only on well-constructed, solid buildings, as very heavy	**Low** – most solid structures are low in the	
Rainwater harvesting	Requires adequate space between houses. Would not be combined with other rooftop collection measures	**High** – but mainly for water supply; limited flood benefit	
Vegetated swales	Not suitable for high pedestrian areas; hard to retrofit in developed urban areas	**Low** – high pedestrian activity	
Filter strips	Not suitable for high pedestrian areas	**Low** – high pedestrian activity	
Sand filters	Medium to low gradient.	**Medium** – but little flood benefit	
Bio-retention areas	Low gradient, permeable soils.	**Low** – clayey soils	
Detention basins	Large space requirements	**High** – space exists	Yes
Constructed wetlands	Large space requirements	**Medium** – but lower priority than restoration of existing wetlands/ floodplains	
Non-structural measures			
Conventional solid waste management	Good governance, traffic mobility	**Low –** many obstacles	
River cleaning programme	Good project management	**High –** high rate of unemployment	Yes
Protection/restoration of catchment forests and wetlands	Undeveloped, managed land; cost of resettlement is a potential limitation	**High –** large areas of degraded forest in upper catchment	Yes
Protection/restoration of riparian areas, floodplains	Undeveloped riparian land; restorable former/degraded wetland or floodplain areas; cost of resettlement is a potential limitation	**High –** supported by law; significant areas of floodplain have been 'cut off' or degraded in mid to lower catchment.	Yes

There are also substantial areas of degraded forest in the catchment that could be restored, and floodplains lower in the catchment have been artificially disconnected from the river, greatly reducing their potential benefits. Furthermore, there are a number of floodplain areas in the mid-lower catchment that could be enhanced to improve their water holding capacity at the same time as providing other benefits such as erosion control and provision of areas for agriculture and wetland that could also enhance water quality.

It interesting to note that the most feasible options are largely those to do with the protection or restoration of natural capital, rather than engineering measures, even though many of the latter would be "green" (environmentally friendly) options. The measures considered feasible and their potential design and extent of implementation in the study area are discussed in more detail below.

Conceptual design and costing of selected interventions

The extent and location of each intervention was estimated using Google Earth and GIS land cover maps in combination with the criteria and limitations described for the interventions to identify the most suitable areas within the catchment for implementing each specific stormwater management measure. The design of each and the extent is based on current land use in the catchment and identifying open space areas most suitable for implementing wetland and floodplain measures. The extent, design and location of each of the selected interventions is described below.

The costing of the selected interventions was based on a wide range of information sources collated from literature and various green urban development projects offered in other parts of the world. The estimated unit costs for the interventions and the sources of the information are outlined in Appendix 6. All costs were expressed in terms of 2015 US Dollars.

4.0.1 Swales

4.5.1.1 Design and function

Swales are useful in built-up, high density areas where flows can be conveyed via small channels. Swales can be constructed in the lower catchment, high residential, flood prone areas with the function of conveying rainfall and runoff out of these areas as quickly as possible. The residential areas identified are those situated immediately adjacent to the Msimbazi River in the lower inundation area at the confluence of the Sinza, the residential areas along the lower reaches of the Ubungo river north of where it joins the Msimbazi and the densely populated areas along the lower reaches of the Sinza River. The channels would probably need to be relatively small - around 1 x 1 m, as the residential areas are densely populated and space is limited. They would be graded and sized to convey up to a 1:5 year return interval flood, thus decreasing the frequency of flood damage/inconvenience in low-lying areas, which would remain vulnerable during larger events. The level of the base of the channels would need to be such that they were able to discharge above the 1:5 year flood level in the river – this could limit the areas in which this measure is applicable. That is, in low-lying areas, drainage may already be below the 1:5 year flood level

4.5.1.2 Extent and cost

It is estimated that in these residential flood-prone areas approximately 100 km of swales could be constructed adjacent to existing smaller roads and lanes. The cost is estimated to be $18 per linear metre of constructed swale. This equates to a total cost of $1.8 million. The primary maintenance objective for swales is to maintain the hydraulic and removal efficiency of the channel which involves litter and debris removal, and the maintenance of vegetation if the swales are vegetated.

4.0.2 Catchment reforestation

4.5.2.1 Effects of reforestation

A number of studies have shown that reforestation of catchment areas helps to significantly retain and slow down runoff, reducing downstream flooding (Oosterberg 1997, Bahremand 2006, Serrano-Muela *et al.* 2008, Taylor *et al.* 2008, Zheng *et al.* 2008, Olang & Furst 2011, Ouyang *et al.* 2013, Gageler *et al.* 2014). Reforestation helps to reduce peak flows through interception and storage of precipitation in the leafy canopy, by slowing down and storing runoff in the thick layer of organic matter on the ground (such as leaves and branches), and through increased infiltration as a result of improved soil structure (Gageler *et al.* 2014, Opperman 2014). In contrast, deforested or overgrazed areas within a catchment tend to be characterized by a limited or absent organic layer and compacted soils which encourage rapid surface runoff (Opperman 2014). Some of the findings from the literature are summarised below:

- Ouyang *et al.* (2013) determined the impacts of reforestation on runoff attenuation and sediment load reduction in the Lower Yazoo River Watershed (LYRW) within the Lower Mississippi River Alluvial Valley (LMRAV) and found that conversion of agricultural land into forests attenuated runoff and reduced sediment load significantly. A two-fold increase in forest land area resulted in approximately a two-fold reduction in annual runoff volume and sediment load mass, and on average, over a 10-year simulation, the

specific runoff attenuation and sediment load reduction were, respectively, 250 m^3/ha/y and 4.02 metric ton/ha/y.

- Gageler *et al.* (2014) compared remnant riparian rainforest, pasture and reforestation plantings aged 2–20 years in an Australian subtropical catchment to determine the extent to which reforestation restores key soil properties. They found that Infiltration rates were significantly lower in pasture than remnant riparian rainforest, and that within reforestation plantings, infiltration rates increased up to 60-fold with time post reforestation.

- Olang & Furst (2011) investigated the impacts of historical land cover changes on the hydrologic response in the Nyando River Basin, Kenya using hydrologic models. They found significant and varying increases in the runoff peak discharges and volumes within the basin as a result of deforestation. In the upstream sub-catchments where there were higher rates of deforestation, increases between 30 and 47% were observed in the peak discharge; whereas in the entire basin, the flood peak discharges and volumes increased by at least 16 and 10% respectively during the study period.

- Bahremand (2006) investigated and assessed the impacts of land use changes (particularly reforestation) on floods by means of distributed modelling and GIS in the Hornad River Basin in Slovakia. Their results showed that 50% reforestation decreased the peak discharge by 12% and total runoff by 4.5%. A 23% reforestation scenario decreased peak discharge by 5.2% and a 38% reforestation scenario decreased peak discharge by 9.1%. The time to peak of the simulated hydrograph of the reforestation scenario was 9 hours longer than for the present landuse.

- Taylor *et al.* 2008 investigated the impacts of land use change on flood risk, through an assessment of the infiltration characteristics of soils in the upper Waikato, New Zealand under both forest and agriculture. Infiltration measurements in this study were similar to literature values for a wide range of soil textures. Infiltration under grazed pasture was an order of magnitude less than that under forest for all sites, and infiltration rates were significantly greater in the forest sites (671 ± 335 mm.h-1) than in agricultural sites (47 ± 39 mm.h-1).

- Zheng *et al.* 2008 estimated the long-term influences of regenerating forest cover on soil and water loss from degraded land, the runoff and soil loss in the context of different forest restoration approaches over a four-year period (2000–2003) in a hilly red soil region in Southern China. Their results indicated that forest restoration decreased surface runoff by 63.0–88.1% and soil erosion by 75.5–97.1% compared to the control. They found that vegetation structure and plant life forms were the main factors reducing surface runoff and the movement of sediments.

Catchment reforestation and riparian revegetation should be seen as a catchment scale tool that can have a significant beneficial effect on flooding in lowland areas (Rutherford *et al.* 2006). At the catchment scale the effect of land use change, for example reforestation, will have a more substantial effect on the depth and duration of flooding (i.e. the amount of water in a flood event), whereas the effect of riparian vegetation is to alter the timing of the delivery of the flood (Rutherford *et al.* 2006).

5.4.2.2 Potential extent in the study area

The headwaters of the Msimbazi River are located in the Pugu Forest Reserve at the top of the catchment. The Reserve is heavily degraded. The edges of the forest reserve have been encroached by local communities who have cleared vast tracts of forest for subsistence agriculture. Satellite imagery has shown that degradation of the natural vegetation and deforestation is not only taking place at the edge but occurs in large areas of the Reserve. The loss of biodiversity and ecosystem services such as soil retention and flow regulation could have serious impacts not only for people living in the immediate area but also for those living downstream of the forested reserve. In the short term people are receiving immediate benefits from forests in the form of timber, charcoal making, cultivation, and grazing. However, over the long term the impacts are extensive such as increased soil erosion and loss of soil fertility, siltation of rivers, increases in flood events, reduced water availability, and severe fuel wood shortages (IUCN, WWF 2002). A concern in Tanzania is the overpricing of conventional energy sources via high taxation which makes fuelwood a very attractive source of energy, resulting in significant degradation of woodlands and forests (IUCN, WWF 2002). With only 20% (400 ha of a total 2180 ha) of the Pugu Forest considered to be in reasonably good condition, there is potential for significant reforestation initiatives within the Reserve.

Using Google Earth it was possible to identify the degraded areas of the forest reserve that could be restored and rehabilitated. In the most northern section of the reserve, a total area of 776 ha was identified for potential forest restoration (see Figure 4.5). The areas around the edge of the forest reserve have been completely transformed into agricultural fields and present a further but potentially far more costly option.

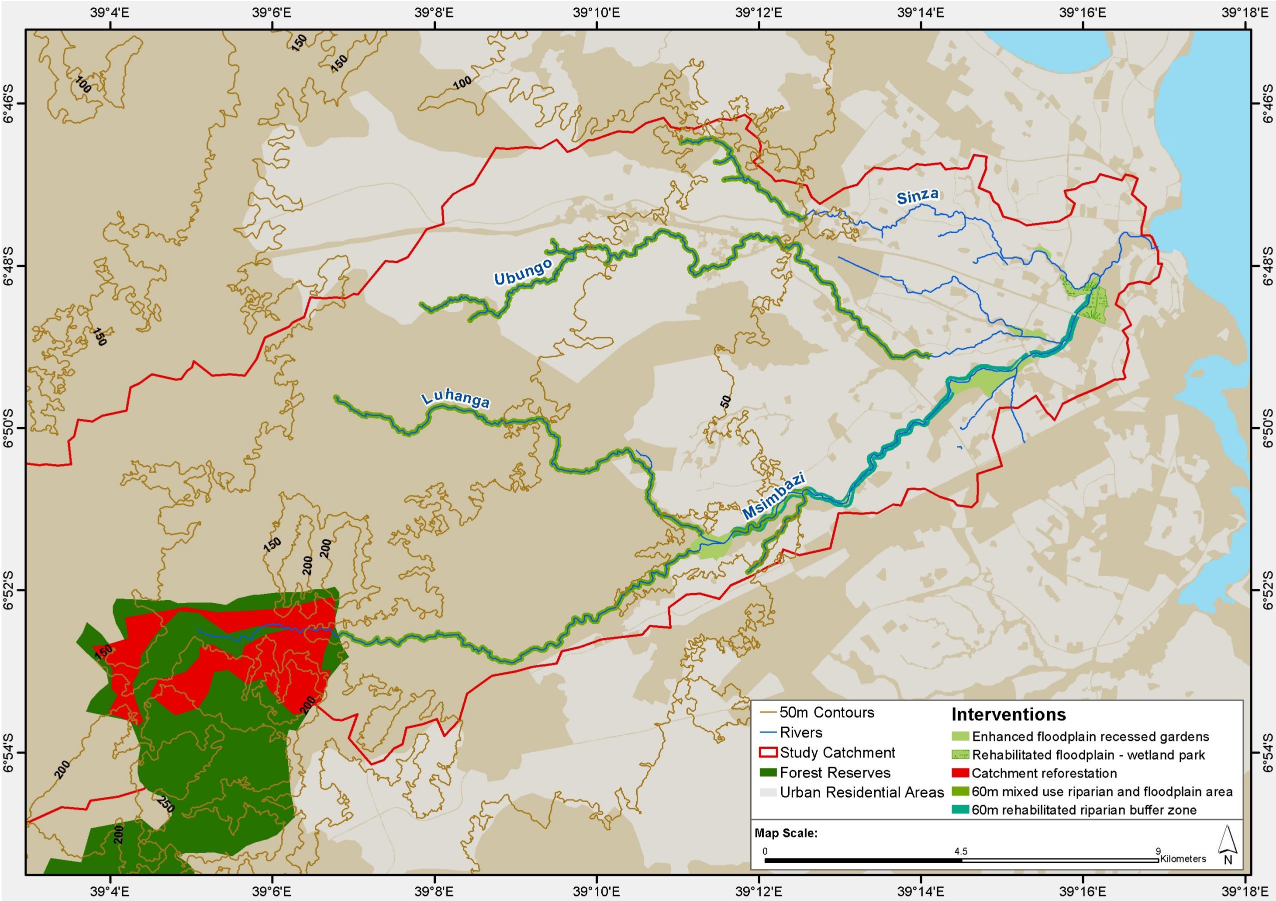

Figure 4.5 Map showing proposed location of "green" interventions within the Msimbazi River catchment

4.5.2.3 Methods and costs

Reforestation projects involve soil conservation and direct seeding and planting of indigenous tree species. The projects also need to go hand in hand with initiatives to prevent further deforestation. Soil conservation is a necessary part of the restoration process because deforestation can cause large scale erosion and loss of nutrients. Techniques for improved soil conservation include terracing in steeper areas to prevent erosion and to manipulate the flow of water by slowing it down, and to re-establish vegetation cover by using indigenous trees and shrubs. Therefore the following actions are required as part of the restoration initiative:

- Terracing to stabilise steep slopes
- Direct seeding and planting of indigenous seedlings
- Protection and raising of seedlings
- Measures to prevent further encroachment and deforestation

Ideally, the forest restoration process should involve recruitment and training of local people at the district and community level. An example of such an initiative is from the Upper Tana River Basin in Kenya where local women's groups are engaged and involved in protecting and raising tree seedlings to rehabilitate two degraded forest areas (TNC 2015).

Based on the Upper Tana River watershed project in Kenya and projects in Costa Rica and the Philippines (FAO 2011, TNC 2015), it is estimated that basic reforestation would cost in the region of US$1090 per hectare. This includes labour and material used for reforesting degraded areas but does not include the long term monitoring or maintenance costs, or the costs involved in developing strategies and policies to prevent further encroachment into the forested area.

While the primary restoration activities (soil conservation, planting and raising of seedlings) are relatively straightforward, the process required to pave the way for these activities, such as relocating people from the forest, and the implementation of successful measures to prevent further encroachment and deforestation present far more of a challenge. It is anticipated that for reforestation of the Pugu Forest Reserve to be successful, the resettlement of households out of the reserve may also be necessary and going forward this should be investigated.

In 2011 a “reducing emissions from deforestation and forest degradation” (REDD) project entitled “Piloting REDD in the Pugu-Kazimzumbwi Forest Reserves” was initiated by the Wildlife Conservation Society of Tanzania (WCST) and the Norwegian Ministry of Foreign Affairs (NMFA). Funding amounting to US$3.9 million to implement the four year project was provided by the NMFA. The main aims of the project were to reduce CO2 emissions by reducing deforestation and forest degradation as well as supporting community livelihoods (Deloitte 2012). However, in 2012 concerns around the mismanagement of the project and the misuse of funds were raised. Conflicts arose between local communities in the study area, government departments and project staff. As a result, the NMFA stopped all funding and the project ended. It is important that lessons learnt during this process are used to facilitate new initiatives so that the complete loss of Pugu Forest Reserve can be prevented.

However, it is clear from previous attempts at reforestation that the situation in Pugu Forest Reserve is complicated and will require a dedicated and focused approach to curbing deforestation. Informal land tenure within the reserve is a big concern and has damaged government credibility (Deloitte 2012). A successful reforestation measure will require dialogue between all stakeholders and will require focused government management and enforcement to address deforestation. Forest borders and village boundaries need to be re-established and enforced. The only way to prevent the complete loss of the Pugu Forest is to actively control, manage and enforce forest boundaries and the use of natural resources by local communities. Alternative livelihood projects (located well away from the forest), and awareness programs could be used to encourage communities to move away from harvesting forest products. This involves additional costs on top of monitoring and enforcement.

4.0.3 Rehabilitation and enhancement of middle catchment riparian and floodplain areas

4.5.3.1 Design and function

There are a variety of ways that the riparian and associated floodplain areas of the catchment could be treated. A common model is to use a development setback to create a riparian buffer. Riparian buffer areas would have different effects in different parts of the catchment. In the flood prone areas, this would mainly have the effect of reducing the number of buildings and people at risk. Further up the catchment, this could help to reduce flow velocities and improve water quality. Riparian buffer zones along waterways intercept sediments, nutrients, pesticides and litter in unchannelled surface runoff, thereby reducing the amount of pollutants entering rivers and streams. They also provide habitat and linear wildlife corridors through the landscape – increasingly important functions as adjacent areas are sterilised by urban or agricultural development. Assuming appropriate vegetation types, riparian buffers can also be important for reducing surface erosion and providing river bank stabilisation, both by reducing the velocity of overbank runoff from adjacent areas and by anchoring the soil and reducing near-bank velocities of water in the channel, through increased channel roughness.

The main shortcoming of riparian buffers is that they do not do much in terms of increasing the storage capacity of the catchment. In the catchment above the flood-prone area, more is required to reduce run-off to natural or lower levels. Therefore, it is suggested that the concept of riparian buffers is extended to the creation of enhanced floodplain areas that are designed in such a way as to store and retard flood flows. This entails a combination of riparian zone rehabilitation and floodplain enhancement measures that are primarily designed to retard flows but which can easily include opportunities for beneficial uses, including (variously) sports fields, agricultural lots and parks as well as active riparian buffer zones/conservation corridors. These beneficial uses of the floodplain might raise initial costs, but are more likely to reduce opportunities for informal resettlement of the floodplain.

The concept is best applicable along river reaches where the channel gradient is low (1: 1000 or flatter) but because it involves substantial manipulation of degraded floodplains, it would lend itself to attenuation of runoff into steeper-gradient watercourses, even if attenuation of instream flow through overtopping is less likely. The measures should not be considered where natural habitats of conservation value remain (e.g. in the forested zone in the upper catchment) or where river slopes are steep.

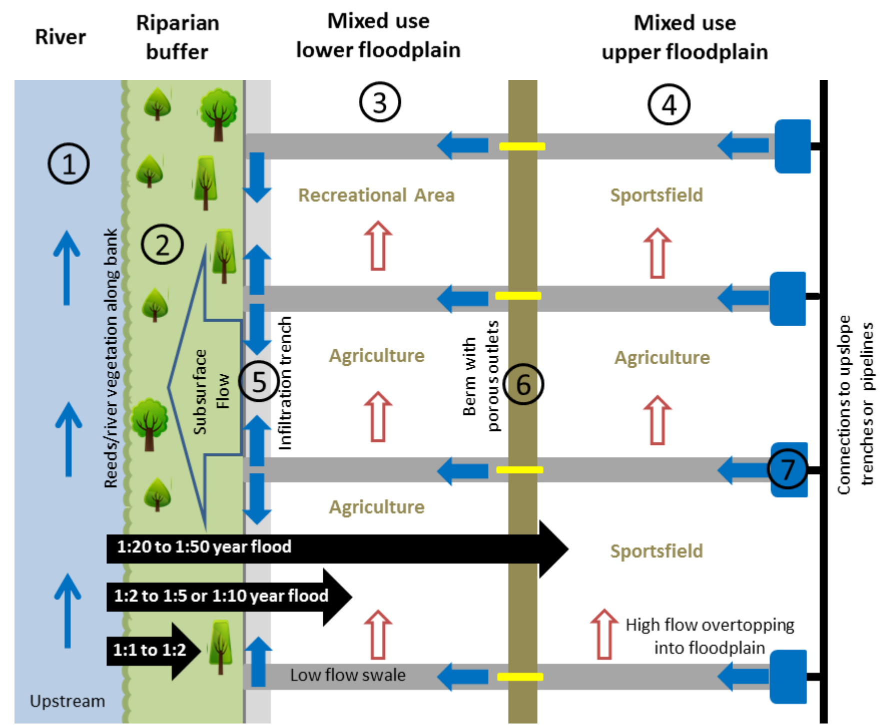

Figure 4.6 Conceptual plan of mixed use Enhanced Riparian and Floodplain areas. See text for description of zone treatment

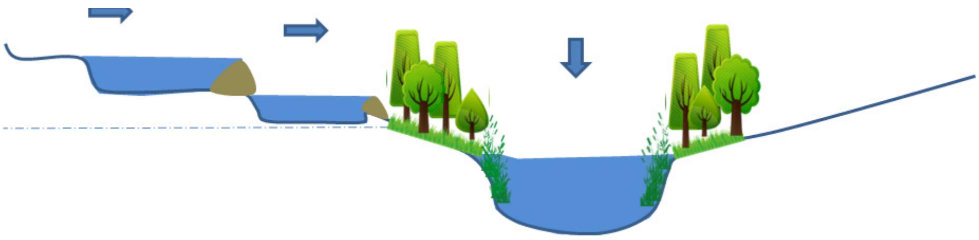

Figure 4.7 Rough cross-section sketch of concept

This approach, shown in rough concept in Figure 4.6 and Figure 4.7, would involve the creation of riparian buffer areas flanked by a series of bermed lower and upper floodplain areas running alongside the riparian area that have means for slow drainage system back into the river system after flooding. The lower floodplain areas would flood more often, whereas the upper areas would capture larger floods. Both the floodplains and berms could be designed for a variety of agricultural or recreational uses. The entire width is envisaged to be 60m on either side of the river, with a river buffer of 15 m on each side, and the combined upper and lower floodplains being at least 45 m wide. Ideally this should become wider with distance downstream through the catchment, but space is at a premium in the study area. The 60m buffer is already written into law, though not yet enforced.

The components, to be mirrored on both sides of all river channels, are described in more detail as follows:

1. **The river banks:** these would, where required, be graded (slopes flatter than 1:4 would probably be appropriate) and stabilised with appropriate (and preferably locally indigenous) riverine vegetation including reeds and sedges that will play a role in preventing bank erosion as a result of root penetration and stabilising effects as well as of increasing hydraulic roughness in the channel itself.

2. **The riparian buffer:** this area would extend a minimum of 15 m wide along minor streams and up to 30 m wide along major streams, and it is assumed that these areas would contain within year floods and possibly up to at least the 1:2 year river floods. It would be designed, so as to include plantings of trees, sedges, shrubs and other types that are locally indigenous/area appropriate, with the following primary functions: soil surface stabilisation,

prevention of erosion from sheet flows, provision of ecological habitat and faunal linkages to upstream and downstream areas. Note that provision of a rehabilitated riparian corridor along at least one side of any channel is considered important.

3. **Lower floodplain:** For rivers that are not steeply sloped (see above), this area should accommodate river floods at least up to the 1:5 year flood, and ideally up to the 1:10 year flood line. For rivers that are steeper, these areas can be narrower, and should instead be designed to detain surface runoff from the surrounding catchment - this area and the upper floodplain should together allow attenuation of (ideally) the peak discharge of up to the 1: 50 year return interval storm. It can be designed as a mixed use area, with seasonal crops included, on the understanding that periodic (less frequent than 1: 2 years) wet season flooding is likely. Planting of an extended riparian buffer along the lower part of this system could be envisaged – however it is noted that in some situations, densely planted riverine areas are viewed with concern by local communities from a security perspective, and this issue should be checked locally;

4. **Upper floodplain:** this area should accommodate less frequent floods than those of the lower floodplain. The two could be separated by a berm that would allow water levels and detention time in the upper floodplain to be controlled; the berm should be equipped with pipes or porous areas (e.g. stone packing) to allow slow downslope drainage of floodwaters into the adjacent lower floodplain and thence into the riparian buffer zone. The flood attenuation capacity of the upper floodplain could be increased if it included a shallow basin – significant earthworks would in any case be associated with the establishment of both floodplains. The passage of runoff from the adjacent catchment into the upper and lower floodplains could be further controlled and detention capacity enhanced by using porous berms to separate “compartments” that are arranged longitudinally down the river/floodplain corridor. Various uses that could be carried out in these “compartments” include agriculture, grazing, sports fields – active, planned establishment of specified uses in all such corridors would reduce the likelihood of their being resettled on in the future.

5. **Longitudinal swales:** these would manage the spread of flows from areas upslope of the riparian corridor, and allow its dissipation as sheet flow into the riparian areas, allowing functions such as sediment trapping, prevention of concentrated flows and associated erosion, and nutrient uptake both within the swale and with diffuse passage across the buffer. Ideally, the swale should be designed as an infiltration trench that allows water to seep out of multiple porous areas in the trench, potentially created by stone or gravel packing. The swale would also serve as a final litter collection zone;

6. **Lateral swales (towards the river):** these should be designed for water quality improvement, and sized to convey small storms (< 1-year return intervals) across the floodplains and into the infiltration trench (5 in Figure 4.6). Larger volumes of runoff should overtop into the adjacent upper floodplain, and pass as overland flow into the lower floodplain. Channelling of runoff into the lateral swales should be via stilling ponds (7 in Figure 4.6), in which litter and sediment can collect, providing zones for concentrated litter collection activities.

Important assumptions of this concept include the following:

- It is assumed that river channels and their riparian zones, flood plains and abutting terrestrial areas to a distance of 60m to 100m on either side of the channel (or as wide as the scheme extends) are already so degraded that the significant disturbance and long-term changes in utilisation and management will have no negative biodiversity or other ecological effects. This is an important point and requires thorough ground-truthing and verification prior to any consideration of implementation of this concept;

- Setting of the width of the intervention at 60m on either side of the river is based on legislated setback widths rather than any hydrologically defendable data. If the concept is considered further, it would be necessary for their detailed design to evaluate their effect on flood lines, so that the width of adjacent areas, as well as berm and terrace heights can be designed to accommodate the 1:5, 1:10 and 1: 50 year (or higher if required) flood return intervals as required.

4.5.3.2 Extent and costs of rehabilitation work

This measure has been costed for application for a band of 60m either side of all rivers in the study area above the flood prone area and below Pugu Forest. This amounts to 270 ha in the Msimbazi River subcatchment, 110 ha in the Ubungo subcatchment, and 8 ha in the Sinza subcatchment, a total of 488 ha. The intervention is expected to be very effective as it could detain almost 5 million m^3 of runoff in the middle-upper catchment areas. Aside from the flood mitigating benefits and the ecological benefits associated with this intervention, space for multi-use areas such as agriculture, parks and sports fields all contribute to improving quality of life in the urban environment.

The plan involves a river rehabilitation component for the area up to about 20 m from the channel, and earthworks to create a modified floodplain. In the Msimbazi catchment there are extensive sections of river between Pugu Forest and the confluence of the Sinza that are severely degraded, with eroded banks, and the riparian vegetation either completely removed or in poor condition. Costs of rehabilitation of riparian buffer areas vary greatly depending on specific site conditions and the level of degradation. If rehabilitation only includes seeding and planting then the costs involved are relatively low per hectare. However, these areas would require some landscaping or earth grading as well as seedling protection, which can increase the costs significantly. Based on projects carried out elsewhere, restoration of the riparian zone, including seeding and planting, is expected to cost approximately $2376 per ha (Appendix 6), or just under $400 000 in total. This estimate is based on the fact that the riparian buffer includes riparian zone rehabilitation and floodplain enhancement measures and was based on the assumption of approximately one third of the riparian buffer zone requiring rehabilitation. The main cost component is that of excavation and earthworks to create the berms and swales to control water in the rest of the buffer zone. The extent of earthworks required is dependent on factors such as slope. In some areas it may be possible to create the stormwater damming effect simply through creation of berms, whereas in other areas some degree of excavation may be required. Assuming that the latter is minimal, the overall cost of earthworks would be estimated to be in the order of $10.5 million. If all holding areas were to be excavated, it would be closer to $44.5 million. The overall cost of the works is therefore in the region of $11 – 45 million, with a mid-point estimate of $28 million. Further work is required to refine this estimate.

4.5.3.3 Potential resettlement costs

In addition, there is a potential cost of resettlement. In Dar es Salaam the areas up to 60 m on either side of all river channels are known as River Reserves and are protected areas in which no development is allowed (Environmental Management Act of 2004). However, the River Reserve areas have not been demarcated or enforced and as a result have become encroached by unplanned settlement, with densities increasing downstream. During December 2015 a significant number of demolitions (over 700 houses) took place within the River Reserve areas in the lower catchment. However, the process was stopped pending the use of proper procedures. Therefore, unless government acts to enforce this law, people who have moved into these areas might need to be resettled in order to execute the project.

The resettlement of affected households requires a structured, participatory approach following international best practices related to displacement and resettlement of people. This may entail significant compensation costs. World Bank-funded projects in Tanzania would estimate compensation costs on the basis of:

1. Replacement cost of dwellings and other structures;
2. Replacement cost of land (the market value plus transactional and other costs involved in acquiring new land);
3. Replacement cost of productive assets such as enterprises, water supply facilities, etc.;
4. Projected production losses from land, crops and trees; and
5. A disturbance compensation which is a specified percentage of the total of the above costs.

Important note: This study does not provide a formal estimate of these costs, but provides a preliminary estimate in order to obtain a ball-park estimate of the potential additional costs of the project, if all households currently within the project area had to be moved with compensation. It is very important to note that compensation payments under these circumstances are likely to be counterproductive, as they might encourage rent-seeking behaviour in this and other such reserve areas in the future. This could raise the costs of the whole exercise. Further work is required to determine what role the Government might play and what compensation would be necessary and appropriate.

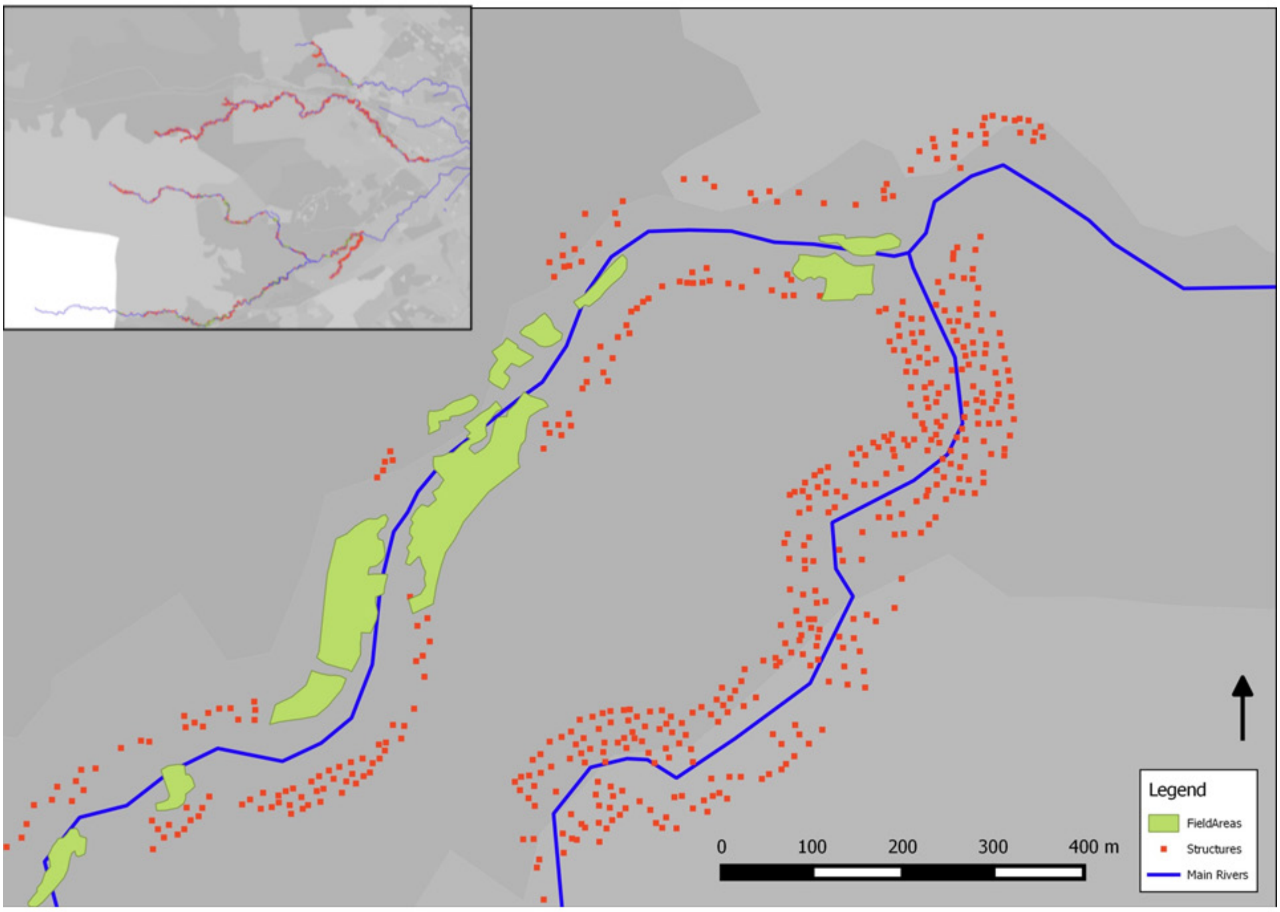

Figure 4.8 Digitised map showing the dwellings and agricultural fields in the setback zones of the middle to upper catchment areas of the Msimbazi, Sinza and Ubungo sub-catchments.

Replacement cost of dwellings

The affected houses within the 60m riverine buffer reserve areas were identified and counted by digitizing dwellings from the latest Google Earth satellite imagery for the middle to upper sections of the three sub-catchments where the rehabilitation initiatives are proposed (Figure 4.8).

A total of 4813 residential dwellings were identified for potential resettlement. The majority of these fell within the Ubungo and Msimbazi sub-catchments. Replacement costs for living structures was based on costs obtained from the literature for informal residential dwellings ($120 per m2, Appendix 2), and using an average house size of 70 m2 (based on a sample of actual dwelling areas in the study area from open street maps). The cost for replacing 4813 dwellings was therefore estimated to be $40.4 million.

Market value of land

In Mozambique, owners of agricultural land were compensated for labour invested in land improvements (clearing, tilling, and grubbing) as a proxy for land value (Mozambique LNG 2015). This follows an approach used by the World Bank that recognises the farmer's investment in land, without being a payment for the land itself, which remains vested in the State (Mozambique LNG 2015). The compensation amount includes the costs associated with bush clearing, annual clearing, tillage, maintenance and the provision for land investment and disturbance. A labour and agricultural disturbance rate of $1600 per ha was applied (Mozambique LNG 2015). Based on Google Earth imagery, the extent of the large agricultural fields within the 60 m buffer was estimated to be 32.3 ha, with most of these fields being located in the Msimbazi sub-catchment (Figure 4.8). Applying this value to the 32.3 ha of agricultural land, the total replacement cost for lost agricultural land is estimated to be approximately $51 830. It is likely, however, that many or most of the identified fields within the Riparian Reserve could be incorporated into the design described above. Where this is the case, compensation would not be necessary.

Losses of productive assets and projected production

Many of the affected households are likely to have gardens and at fruit trees at their homesteads, or along the river. The main types of trees planted in Dar es Salaam include coconut, mango, cashew, papaya and avocado. The main crops tend to be leafy green vegetables such as spinach, sweet potato leaves, pumpkin leaves and cowpea leaves, as well as other vegetables such as eggplant, okra and tomato. Accurate estimation of the numbers and extent of these was beyond the scope of this study, but a ball-park estimate of the potential compensation costs is derived from other Resettlement Action Plans (RAPs) in the area. A RAP provides an agreed plan for the resettlement and compensation of Project Affected Persons (PAPs) and aims to ensure that land acquisition is undertaken as per specific standards.

It was estimated that 18% of affected households had productive trees. Based on the findings of Jacobi (1997) that 15-20% of all houses in two unplanned areas of Dar es Salaam had vegetable gardens and/or fruit/nut trees, we used an estimate of 18%, which translates to 866 households. Average compensation per producer household was obtained from the Kinondoni Municipality RAP developed for the Surface Water Drainage System Subproject under the Dar es Salaam Metropolitan Development Project (DMDP) (PMO-RALG 2014a). The values taken from the RAP were inflated to 2015 prices and converted to US Dollars. The RAP included a summary of the total number of affected households, and total compensation costs for the loss of trees/crops. Compensation for crops is determined as the average value over the previous year, corrected for inflation and the compensation for trees is based on the type, age and productive value of affected trees plus 10% premium (PMO-RALG 2014a). The average compensation cost for the loss of these was $167 per household. Applying these values to our sample of affected households, the total compensation cost for loss of trees and crops is estimated to be around $145073.

Disturbance allowance

The disturbance allowance provides support for households during the resettlement process, and is calculated as a percentage of the total of the above costs. The percentage was taken from the Surface Water Drainage Systems (SWDS) Project Resettlement Action Plan, which was specified as 8%. This was applied to the calculated resettlement costs and added to the overall total cost. The disturbance allowance was estimated to be $3.2 million.

Total

Above the flood prone area in the middle to upper catchment the resettlement costs are estimated to be approximately $44 million (Table 4.4). Going forward, these preliminary estimates would need to be properly validated.

4.0.4 Rehabilitation and enhancement of lower floodplain areas

Increased stormwater runoff has resulted in increased flow into the rivers. These rivers therefore need larger-than-predevelopment floodplain areas to enhance the storage and capacity of the floodplain to dampen flooding events. Enhancing the floodplain areas involves deepening the floodplain area to increase storage capabilities. In certain areas, benefits of increasing the floodplain can be added through the establishment of agricultural areas, which is already the case in some sections along the river. In other areas along the river system it involves the removal of berms and re-establishing connections with adjacent areas to allow the river to overtop its banks into its floodplain more frequently. Restoring the natural hydrological connectivity of the system will have numerous ecological benefits. By deepening the floodplain areas in the lower

Table 4.4 Total estimated resettlement costs for the lower catchment and middle to upper catchment areas

Items	Msimbazi	Ubungo	Sinza	Total
Number of households	1939	2580	294	4813
Compensation Cost				
Loss of dwellings	16 287 600	21 672 000	2 469 600	40 429 200
Loss of productive trees/crops	58 445	77 766	8 862	145 073
Loss of agricultural land*	46 992	2 638	2 200	51 830
Sub-Total				40 626 103
Disturbance allowance (8%)				3 250 088
Total				43 876 191

*As explained in the text only some of this will actually be lost, as it can be incorporated into the floodplain buffer design.

catchment there is the opportunity to develop a wetland park to provide an important inner city recreational green open space area that could provide numerous benefits. Activities such as fish farming could also be considered for such areas, assuming that water quality was adequate and that the ponds were designed to include areas of permanent water.

4.5.4.1 Enhanced floodplain-recessed gardens in middle-lower catchment

Enhanced floodplains with recessed gardens in the middle-lower catchment would be a local scale approach to attenuate flood peaks in urban and peri-urban areas where households have market gardens situated along the river channel within the floodplain. The main aim of the recessed gardens is to increase the water storage capacity of the floodplain but still maintain functionality for crop production during non-flood periods. Currently the market gardens are grown in the floodplain and are constantly flooded during high rainfall events with not much storage of excess water. By excavating and thus deepening the floodplain area adjacent to the channel the storage capacity of the area is significantly increased, reducing flows downstream. Households would still be able to grow crops within these areas outside of the main flooding season. These areas have the potential to retain a significant amount of runoff during peak flows and will also contribute to the removal of sediments and nutrients through infiltration, although this function is expected to be relatively small. The vegetated floodplain is much the same as a vegetated channel in terms of nutrient and sediment removal.

The cost of deepening the floodplain areas for recessed gardens will include excavation costs and possibly some top soiling and grassing costs. Market gardens will provide vegetation cover during non peak-flow periods. There are three main areas on the Msimbazi River, two on the Ubungo River and two on the Sinza River that have been identified as possible locations for recessed gardens. The enhanced floodplain-recessed gardens in the mid-lower catchment will cover an estimated area of 47 ha, costing approximately $5.4 million (Table 4.5). Stormwater retention was calculated by assuming a depth of one metre for the floodplain recessed gardens.

It is expected that the recessed gardens will be relatively cost-effective in that the capital costs associated with the intervention are relatively low. The interventions can cover a very large area making the overall cost outlay rather high. However, the intervention, especially in terms of runoff retention is extremely cost effective. The intervention is not very cost-effective in terms of soluble nutrient removal.

Table 4.5 The estimated extent of enhanced floodplain-recessed gardens, estimated total cost of the intervention and the estimated total amount of runoff retained

Identified areas	Potential extent of intervention (ha)	Estimated total cost (US$)	Total stormwater runoff retained (m^3)
Msimbazi 1	26.63	2 796 150	266 300
Msimbazi 2	1.93	202 650	19 300
Msimbazi 3	5.58	585 900	55 800
Ubungo 1	5.34	560 700	53 400
Ubungo 2	4.43	465 150	44 300
Sinza 1	3.14	329 700	31 400
Sinza 2	4.00	420 000	40 000
Total	47.05	5 360 250	510 500

4.5.4.2 Rehabilitated floodplain / wetland park areas in lower catchment

Rehabilitation of floodplain wetland areas can also be incorporated with extended detention ponds to allow for storage and treatment of a greater volume of stormwater runoff than in a simple shallow wetland. These are known as "extended detention shallow wetlands" which are able to store most of the stormwater volume above the relatively shallow marshy depths within the macrophyte zone (Armitage *et al.* 2013). Restoration of wetlands and construction of the extended detention basin would require excavation and earthworks to develop a detention area that is dug out and can aid in regulating flow and attenuating flood peaks to an extent in combination with the functioning of the restored wetland.

In Dar es Salaam there is an area in the lower catchment that has been identified as a possible location for the development of an extended detention wetland. The area is frequently flooded during high rainfall events. Some informal houses have been constructed on this floodplain area and would therefore need to be relocated if the wetland were to be constructed here. These informal homes are regularly flooded. It is envisioned that the detention wetland will regulate and attenuate flood peaks, will remove pollutants and sediments from the water and will provide amenity value to the surrounding urban landscape. The shallow detention wetland will cover an area of just under 15 ha, with an estimated total construction cost of just over $3 million (Table 4.6). This intervention will detain approximately 298 000 m^3 of runoff, based on a depth of two metres.

4.0.5 Community-based river cleaning programme

One approach to keeping rivers clear of litter and debris and maintaining a healthy river system is to involve communities that live alongside rivers and streams. Community involvement projects can have multi-sectoral impacts as they generate employment opportunities, provide awareness, safeguard communities and provide city-wide services such as functioning river systems that are clean and clear of litter. Sections of rivers or streams are maintained by cooperatives which are responsible for removing alien vegetation, rubble and any solid waste blocking the free flow of water down the stream or river. They are also responsible for maintaining the grass and other vegetation along the banks of the waterway. The cooperatives generally consist of members of the community that are unemployed and vulnerable and the project focuses on raising awareness and generating employment.

Community based river cleaning projects have shown to be successful and sustainable. For example the Mlalakua River Restoration Project initiated in 2012 has been successful in raising awareness in communities and in cleaning the Mlalakua River in Kinondoni Municipal Area in Dar es Salaam (see Appendix 5). The Sihlanzimvelo Stream Cleaning Project initiated in 2011 with the aim of maintaining and cleaning approximately 490 km of watercourses throughout the eThekwini Municipality in Durban has been successful too (see Appendix 5). Most of the rivers and streams included in the Sihlanzimvelo project are located in the poorer, more densely populated suburbs of Durban. Both of these projects focus on cleaning rivers of litter and alien vegetation, provide employment opportunities for community members and educate communities on the benefits provided by clean and safe environments. A project such as this could be initiated in the Msimbazi catchment where the rivers and streams are constantly blocked with litter and debris. The significant amounts of rubbish that end up in the rivers and streams exacerbate the flooding problems in the city, causing widespread damage. By generating employment opportunities and providing education and awareness to communities, a project such as Sihlanzimvelo or Mlalakua, could have significant positive impacts in the Msimbazi catchment. Based on the programme in Durban and the Mlalakua Project in Dar es Salaam, it is expected that the cost of setting up and running such as programme would be in the region of $1 million in year one and thereafter would cost around $250 000 per annum.

4.0.6 Summary

Construction costs and maintenance costs were estimated using examples from the stormwater management literature and from examples of projects where similar measures have been applied elsewhere in the world. These estimates were used to develop an average cost for each intervention based on the knowledge of the extent of restoration or the extent of each intervention required in Dar es Salaam. These estimates and their sources can be found in Appendix 6. Annual maintenance costs were calculated based on estimates from the literature described as a percentage of overall construction costs. The total initial investment cost of these interventions is estimated to be approximately $40 million (without resettlement) and annual maintenance costs were estimated to be in the order of $1.6 million (Table 4.7). Around 40% of the total investment cost is for the mixed-use enhanced riparian and floodplain areas, which cover almost 500 ha and detain 5 million m^3 of runoff. Relocation costs were estimated to be in the order of $44 million. Total costs associated with the selected GUD interventions and associated resettlement activities was therefore estimated to be $84 million.

Table 4.6 Estimated extent and total cost of the extended shallow wetland and the total stormwater runoff expected to be retained

Intervention	Extent (ha)	Estimated total cost (US$)	Total stormwater runoff retained (m^3)
Floodplain reconnection and extended detention shallow wetland	15	3 129 000	298 000

Table 4.7 Summary of the extent and costs of the selected GUD interventions in the middle to upper Msimbazi catchment and the resettlement costs involved in relocating households from these areas

Identified areas	Extent (ha)	Initial /construction cost (US$)	Annual maintenance cost (US$)
Swales to improve drainage in flood prone areas	10	1 800 000	108 000
Catchment reforestation in Pugu Forest Reserve	776	845 000	17 000
Mixed use enhanced riparian and floodplain areas (~1m deep)	488	28 000 000	1 036 000
Rehabilitated floodplain and wetland park (~2m deep)	15	3 130 000	94 000
Enhanced floodplain-recessed gardens (~1m deep)	51	5 360 000	107 000
Community-based river cleaning project	-	1 000 000	250 000
Total without resettlement costs	1340	40 135 000	1 612 000
Relocation with compensation		44 000 000	
Total with maximum resettlement costs		84 135 000	1 612 000

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V. SCENARIOS ANALYSIS

Scenarios

Five combinations of stormwater management measures were included in the analysis:

1. Riparian setbacks in the flood prone area;
2. Green urban development measures (GUD);
3. GUD measures + riparian setbacks in the flood prone area;
4. GUD measures + additional detention basin(s); and
5. GUD measures + detention basin(s) + riparian setbacks in the flood prone area.

The scenarios are a combination of interventions that either reduce exposure to flooding, reduce flood risk, or a combination of both (Table 5.1). By removing people from flood prone areas within riparian setback buffers the number of people and structures exposed to flooding is reduced. By implementing GUD and additional storage interventions the flood hydrograph is lowered and flood risk is reduced. The cost of each intervention includes the potential costs associated with resettlement. Resettlement costs are described in detail in Appendix 4 for the riparian buffer zone in the flood prone areas and in Section 4.5.3.3 for the GUD interventions in the catchment area.

In the engineering design process, different stages at increasing level of detail can be defined: research, conceptualization, feasibility assessment, establishing design requirements, preliminary design, detailed design, construction/production planning and construction/production (Ertas & Jones 1992). The feasibility study stage narrows the scope of the project in order to identify the best scenarios. The scenarios conceptualized herein are then implemented in the preliminary design, returning the general framework to build the project on (Dym et al. 2009).

Hydrologic modelling assumptions

Given the amount and the quality of available data, and the large scale of application of the mitigation strategies, the analyses results discussed in the following are developed at the level of a preliminary design. In such a framework, several simplifications are made regarding the implementation of the mitigation strategies in the hydrologic/hydraulic model.

5.0.1 Riparian setback in lower floodplain

This intervention would not have a measurable effect on the storm hydrograph. However, it involves the resettlement of households from a defined development setback zone along the rivers, and therefore changes the number of buildings exposed to flooding.

Table 5.1 Scenarios 1-5 and their estimated costs

		Reduce exposure →	
		No interventions in flood prone areas	People and structures removed from 60m buffer in flood prone areas
Reduce flood risk ↓	No interventions in catchment		**Scenario 1** $62.6 million
	GUD interventions in catchment1	**Scenario 2** $84 million	**Scenario 3** $138.5 million[2]
	GUD with additional storage	**Scenario 4** $124 million	**Scenario 5** $178.5 million

[1] GUD: (a) restoration of forests in upper catchment, (b) rehabilitated and enhanced riparian and floodplain areas in middle catchment, (d) river cleaning in middle catchment, (c) floodplain rehabilitation in lower catchment, (e) swales in flood prone areas.

[2] This is less than the sum of 1 and 2 since the number of buildings at risk in the buffer is reduced, and so a reduced number of structures have to be relocated

5.0.2 Combined GUD interventions

In our analysis, the effect of the GUD measures on flood flows (the hydrograph) was simulated in the hydrological model through a change in the AMC. This approach is not new in the literature; for example, Jalayer et al. (2013) modelled the increase of urbanization (i.e. the increased impermeability of the soil due to the variation of land-use) in a lumped manner by increasing the AMC class. In this study, the same approach was followed but in the opposite direction: the hydrograph associated with the new scenario is obtained varying the AMC, from AMC III to AMCII. A more detailed explanation on this point is provided through the statistical analyses presented in section 3. Given the results presented in Figure 5.1, it would have been justified to use AMC I. However, using AMC II is more conservative (in engineering terms, i.e. the potential damage is increased) and therefore more appropriate for risk assessment purposes. The resultant changes are shown in Figure 3.16. For a 1:10-year flood, modelled reductions in the flood peak ranged from about 45% in sub-catchment 3 to about 60% in sub-catchment 1.

All the beneficial effects induced by this combination of interventions were lumped together and expressed as a change of the input hydrograph, based on the assumption that the set of GUD interventions (Scenario 2) has the equivalent effect of an improved capacity of the soil to infiltrate the storm water as would be achieved if the AMC was changed from AMCIII to AMCII, or if the soil hydrologic class was changed from soil B to Soil A which has a similar effect (Figure 5.1). Such variations are consistent with what has been observed in the literature; in fact, increasing the soil permeability, the peak reduction varies from 40% (Drake, 2014; Klingner, 2014) up to 90% (De Paola et al. 2013; 2015; Kowalik and Walega 2015; Aceves and Fuamba 2016). In this study, the extent of GUD interventions was estimated to meet this level of reduction in the hydrograph for a 1:10 return interval flood.

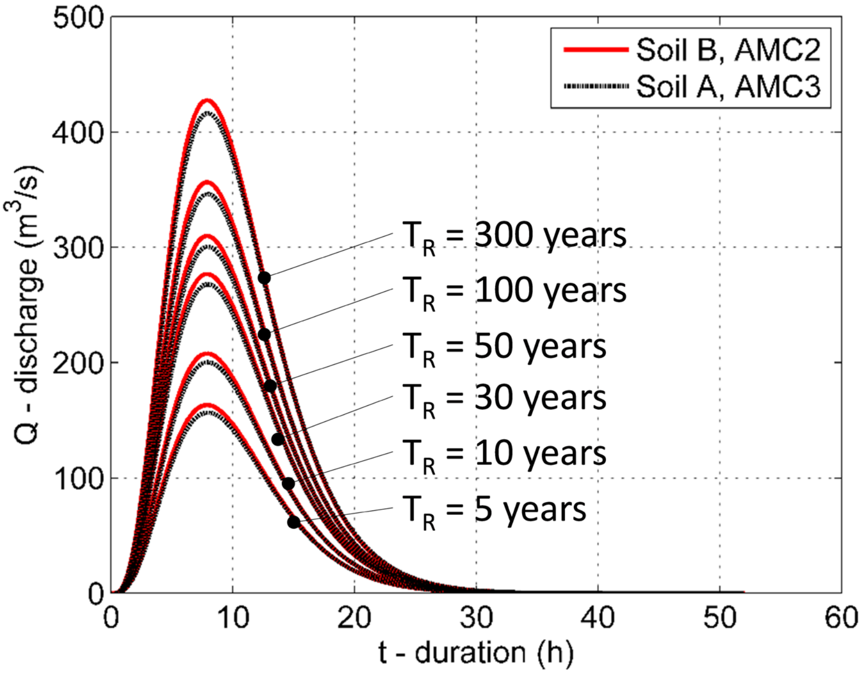

Figure 5.1 Two different ways to implement the mitigation strategies in the input hydrograph for different return periods

5.0.3 Additional storage in Scenarios 4 and 5

In the lower part of the main Msimbazi River, there is a floodplain area that has no construction on it. This area was identified as a potential area for the creation of an in-line floodplain storage area. The effect of the storage basin was modelled according to the procedure described above. With an area of 50 ha and a design depth of 6 m, the maximum volume that such storage can absorb is 3 million cubic meters.

The detention basin was modeled as a physical separation of the discharge between the storage and the urban area. There are two possible methods to implement such measures in the inundation code. The first is to implement it as a floodable area that can be reached by the flow through some hydraulic links. Such modeling requires a detailed description of all the design detail and generally cannot be implemented in a preliminary analysis. The second approach involves removing the discharge that is accumulated in the floodplain storage from the flow. This method is facilitated by the design equation presented below.

The continuity equation for a flow is:

$$\frac{dW}{dt} = q_{in} - q_{out} \qquad (5.1)$$

where W is the volume of the storage, qin and qout the incoming hydrograph and the outflow hydrograph respectively. Let is S the total surface of the floodplain storage and h is the water depth inside the storage; then W can be expressed as below:

$$W = S \cdot h \qquad (5.2)$$

The outflow hydrograph can be expressed through the outlet formula

$$q_{out} = \mu \cdot \sigma \cdot \sqrt{2 \cdot g \cdot h} \qquad (5.3)$$

where is the discharge coefficient (generally assumed equal to 0.61, Daugherty and Franzini, 1965); is the outlet area, that is variable with the return period considered in order to fill up the entire capacity of the storage; g is the gravity acceleration (i.e. 9.81 m/s2).

Deriving h from 5.3 and substituting it in 7.1 a new expression of the total flood volume is obtained:

$$W = k \cdot q_{out}^2 \qquad (5.4)$$

where k is the storage constant of the floodplain storage and is equal to:

$$k = \frac{S}{2 \cdot g \cdot \mu^2 \cdot \sigma^2} \qquad (5.5)$$

Substituting 5.4 in 5.1 it is possible to obtain the differential equation of the on line floodplain storage which indicates the relation between inflow and outflow:

$$2 \cdot k \cdot q_{out} \cdot \frac{dq_{out}}{dt} = q_{in} - q_{out} \qquad (5.6)$$

This equation is generally solved by means of finite differences schemes. Knowing the initial hydrograph, the previous equation allows one to evaluate the outflow hydrograph to consider for the two-dimensional propagation.

5.0.4 Caveats

All the presented hypotheses are valid at a preliminary design phase for two main reasons: (a) not all the mitigation strategies are defined and spatially allocated in a definitive manner (e.g. the application of swales in the urban area); (b) the full implementation of the mitigation strategies that can be obtained with a more sophisticated procedure requires more refined data (necessary to calibrate all the involved coefficients) and a more detailed knowledge of the territory and of the hydrographic characteristics (that can be acquired only through bespoke surveys). Therefore such an “aggregate” effect can still be considered informative in a context of lack/absence of detailed information. Moreover, the limitations due to the lack of more spatially refined data, such as spatially distributed river gauge and precipitation data and a map of the existing urban drainage or sewage systems (if existing) does not allow a more rigorous procedure.

It must also be stressed that this analysis has focused on flood mitigation, because water quality amelioration capacity of these interventions will not have any measurable benefit under the current levels of investment in sanitation and sewage systems, due to the overload of pollutants into the drainage system. Once these systems are in place, these stormwater management interventions will also be able to provide economic benefits in terms of ‘polishing’ of water quality.

Costs of the interventions

5.0.1 Riparian setback in lower floodplain

The number of buildings at risk in the setback zone is 2422, or 19% of the entire portfolio of 12 744 structures at risk. The structures identified are a mix of unplanned residential, commercial, industrial and utility buildings. Each of these has a different replacement cost and these costings per m2 of area can be found in Appendix 2. If required (i.e. if the setback policy has not already been enforced by the time of project implementation), the relocation of these buildings and people could require an initial cost of an estimated US$62.6 million. This includes the value of the buildings, an 8% disturbance allowance, and an additional 10% cost for demolition and removal of debris.

Note: It is understood that in December 2015 an estimated 700 unplanned structures were removed from the setback zone in the lower catchment. This is approximately 30% of the total number of structures identified during this assessment, which if taken into account would lower the cost to $41 million. However the resettlement of households was not successful, as plots were resold or people returned soon after evacuation because they had been moved to areas far from their social networks and places of work (M. Bitekerezo, World Bank, pers. comm.).

5.0.2 Combined GUD interventions

The proposed mitigation strategies affect about 125 ha and 20 ha in catchments 2 (Ubungo) and 3 (Sinza), respectively, and about 1200 ha in catchment 1 (Msimbazi). This scenario, described in more detail in Section 4.5, included improvement of the drainage in the lower river flood-prone areas by building swales and introducing a good solid waste management program for existing and new drainage, floodplain reconnection in the lower river, a river cleaning program in the lower catchment, and the rehabilitation of river buffers and reforestation in the mid to upper catchment of the Msimbazi RIver. Along the mid to upper catchment areas of the Lubango, Ubungo and Sinza Rivers mixed-use enhanced riparian and floodplain areas were also considered. These areas are currently occupied by approximately 4800 dwellings. In order to guarantee the functionality of the proposed mitigation strategies, operations of inspections and maintenance are required as well. Such costs are assumed to be 1% and 5% of the total initial cost per year, for inspection and maintenance, respectively. Moreover, a further community-based river cleaning programme of US$1 million per year is also considered. The total cost associated with the combined GUD interventions, and including maximum resettlement costs, is estimated to be $84 million. Cost details can be found in Section 4.5.6 and Table 4.7.

5.0.3 Additional storage in Scenarios 4 and 5

To estimate the construction costs of additional storage, three main elements have been considered: purchase of 50 ha of land, excavation of 3 million m^3 of soil, 20,000 m^3 of reinforced concrete works (about 7‰ of the entire flood plain volume, rough estimation of works for protection of the site, potential artificial levee in some areas, and all associated flow control structures), and a team of 100 foremen and labourers working for two years. The final value is then multiplied by a factor of 1.36 which represents the additional costs as a percentage of the total cost, i.e. indirect, preparation, administration and contingency costs (see Error! Reference source not found. for details). The cost breakdown is presented in Table 5.2.

Table 5.2 Cost breakdown of detention basin

ID	Unit	Unit cost ($)	Cost (US$ millions)
Purchase of land	50 ha	1000 $/ha	0.05
Excavation			
(90% of total volume)	2.7x106 m^3	8.6 $/$m^3$	23
Concrete works	20x103 m^3	255 $/$m^3$	5.1
Labor force (730 days)	100 people	8.48 $/day	0.62
Total cost (1)	≈ 29		
Total cost (2) = 1.36 x Total cost (1)	≈ 40		

Scenario evaluation approach

The different scenarios were evaluated in terms of their return on investment (ROI). Defined in general terms, ROI analysis (Reilly & Brown 2011) compares the desired target outcomes (i.e. benefits) an investment yields with the costs of that investment.

$$ROI = \frac{Benefit}{Investment} \quad (5.7)$$

ROI analysis is routinely applied in both the private and public sectors to evaluate the performance of competing financial investment opportunities, programs or projects, and is equally applicable to conservation projects (Boyd et al. 2012). If benefits are expressed in physical units (e.g. reduction in the number of buildings damaged by flooding), ROI analysis is equivalent to cost-effectiveness analysis; if benefits are monetized (e.g. value of avoided flood damages to buildings), ROI analysis is equivalent to fully-monetized benefit-cost analysis. Especially for projects that affect multiple outcomes of interest (e.g. damages to various types of infrastructure, human morbidity and mortality, agricultural production etc.) monetized ROI analysis is preferable as it allows for an easier, integrated comparison of the differential impacts of alternative investments (i.e. projects or programs) on those outcomes.

The EAL is the key input to a benefit-cost analysis of intervention scenarios. Specifically, the benefit of the intervention scenario is the difference in the present values (PV) of the expected annual (t) losses experienced in the baseline (S0) and intervention (SI) scenarios, respectively:

$$Benefit_{SI} = PV(EAL_{S0}, t) - PV(EAL_{SI}, t) = \sum_{t=1}^{n} \frac{EAL_{S0}}{(1+\delta)^t} - \sum_{t=1}^{n} \frac{EAL_{SI}}{(1+\delta)^t}$$

(5.8)

where EAL is the expected annual expenditures incurred to repair or replace damaged structures during their reference lifetime (n), and δ is the relevant interest rate on capital (= discount rate). Therefore, the benefit is the PV of the avoided expected annual losses due to the implementation of the mitigation strategy Si. All the scenarios were compared with the baseline scenario, for which an EAL of **US$47.30 million** was estimated.

The costs of the mitigation strategy (SI) were taken to include not only initial implementation cost C0 but also ongoing inspection (CI) and maintenance (CM) costs for the implemented interventions. The total investment associated with the generic mitigation strategy SI is then equal to:

$$Cost_{SI} = C_{0,SI} + C_{I,SI} + C_{M,SI} = C_{0,SI} + PV(C_i, t) + PV(C_m, t) = = C_{0,SI} + \sum_{t=1}^{n} \frac{C_i}{(1+\xi)^t} + \sum_{t=1}^{n} \frac{C_m}{(1+\xi)^t} \quad (5.9)$$

If the expected number of inspections and/or maintenance events is known, it is possible to estimate the mean expected annual cost of inspection (Ci) and maintenance (Cm). Here we follow common practice and assume that Ci and Cm are a percentage of the initial intervention cost.

It is now possible to rewrite the ROI as:

$$ROI = \frac{PV(\text{EAL}_{S0}, t) - PV(\text{EAL}_{SI}, t)}{C_{0,SI} + PV(C_i, t) + PV(C_m, t)} \quad (5.10)$$

The ROI time (TROI) or payback period represents the time necessary for the ROI of the intervention to reach unity (1). The ROI of the intervention is less than unity if total implementation costs of the intervention exceed the reduction in expected annual losses it produces.

In addition to ROI, the net present value (NPV) and internal rate of return (IRR) were also used to assess the viability of the different scenarios. For a project to be considered viable, the NPV must be positive. This places greater weight on values occurring closer to the present, which means that the future benefits of restoration projects will be down-weighted compared with the upfront investment costs, and have to be substantial in order for a project to be viewed positively. Projects can also be evaluated by estimating the IRR, which is the discount rate at which the total net present value of the project falls to zero.

Results

All of the scenarios resulted in a significant impact on EAL associated with flooding in the flood prone areas of the lower Msimbazi catchment, resulting in average annual cost savings ranging from $10 million to $26 million, or from 21% to 54% of present EAL (Table 5.3). The hydraulic results and the resultant hazard curves are presented in Appendices 8 and 9.

Table 5.3 Impacts of Scenarios 1 to 5 on expected annual losses (EAL), and the percentage change in EAL

		Reduce exposure →	
		No interventions in flood prone areas	People and structures removed from 60m buffer in flood prone areas
Reduce flood risk ↓	No interventions in catchment	**Baseline** US$47.30 million	**Scenario 1** US$37.24 million (-21%)
	GUD interventions in catchment	**Scenario 2** US$28.87 million (-39%)	**Scenario 3** US$23.16 million (-51%)
	GUD with additional storage	**Scenario 4** US$27.78 million (-41%)	**Scenario 5** US$ 21.64 million (-54%)

Creation of a development setback zone within 60 m of rivers in the flood prone area reduces the number of buildings at risk from 12 744 to 10 047. Implemented alone, this intervention would reduce damage costs by 21%. When implemented in conjunction with catchment interventions, the damage costs are further reduced. Note that the 60 m buffer only covers a portion of the flood prone area. While flood exposure could theoretically be eliminated by removing people from the entire flood prone area, it is likely to be impractical to achieve more than the legally-defined 60 m setback area since this area falls within Dar es Salaam's most built up area.

Taken alone, interventions to reduce flood risk, which are mainly implemented in the catchment area, can also have a significant effect on EAL (Table 5.3). The GUD interventions described in Scenario 2 were designed to have a significant cumulative effect on the flood hydrograph. This led to an estimated 19.6% reduction in the number of buildings at risk (i.e. 10 253 vs. 12 744) and a 39% decrease in EAL.

When GUD strategies were combined with the floodplain setback zone (Scenario 3), this resulted in both reduction of the exposure (due to relocation of buildings from a setback zone within the flood prone area) and reduction of the flood intensity (due to reduction in the hydrograph). The creation of a setback zone involves relocation of buildings and resettlement of households from these areas, plus the total number of buildings at risk is reduced (due to the lower flood intensity). Therefore the overall number of buildings at risk in the flood prone area was reduced to 15.5% (i.e. 2046 vs. 2422). This led to an even greater decrease in EAL in the order of 51%.

The combination of GUD interventions with additional storage (Scenario 4) did not have very much additional effect on EAL when compared to GUD interventions alone (Scenario 2). The main effect was the reduction of buildings at risk by 21.2% (i.e. 10 047 vs. 12 744). This is not so different to Scenario 2 because the floodplain storage affects mainly the last part of the first sub-domain and the fourth and fifth subdomains which have a low density of buildings (see Figure 3.17 for the numerical identification of the subdomains in the case study area). Additional storage resulted in a reduced discharge in the last part of the first subdomain.

The combination of all interventions in Scenario 5 does have the highest overall effect, as would be expected. Since the total number of buildings at risk is reduced, the number of buildings at risk in the buffer area is reduced as well to 18.4% (i.e. 1977 vs. 2422), and the EAL was reduced by 54%.

The initial costs, NPV, IRR and ROI of the different Scenarios are summarized in Table 5.4 and presented graphically below (Figure 5.2). Initial costs are seen to increase from Scenario 1 to 5. It should be noted that resettlement costs account for a large portion of the initial costs, especially for scenarios 2 and 3. In spite of high costs, all the options considered had positive outcomes.

Net present value was highest for Scenarios 2 and 3. However, return on investment was highest for Scenarios 1 and 2. A similar pattern is observed for IRR, which appears to exceed hurdle rates in most cases. The results suggest that the investment should initially be targeted at implementation of GUD measures in the catchment areas, and that if sufficient funds are available, these should be used to extend the investment to include resettlement from a setback zone as well (i.e. scenario 3). Factors such as the availability of financial resources, the ROI, the impact on the environment and society, should also be taken into account at a definitive design stage.

Table 5.4 Comparison of scenarios

Scenario	1	2	3	4	5
C_0 (US$ millions)	62.6	84	138.5	124	178.5
NPV (6%, 35 yrs., US$ millions)	88	125	115	72	69
IRR	19	21	14	12	10
ROI 10 Years	1.18	1.30	0.87	0.93	0.70
ROI 50 Years	2.53	2.34	1.63	1.75	1.33

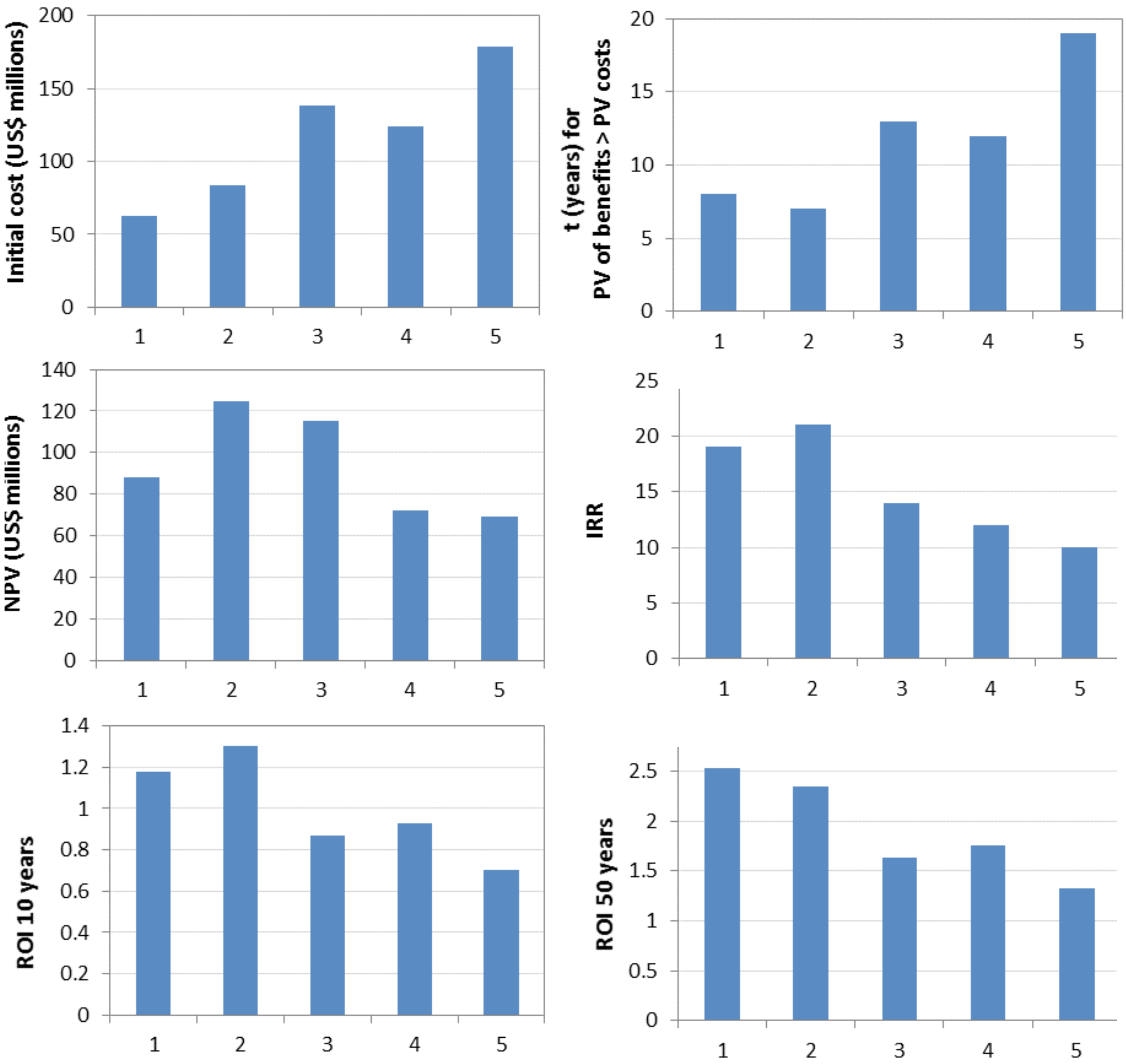

Figure 5.2 Graphical representation of the results shown in Table 5.4

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VI. SUMMARY AND CONCLUSIONS

Throughout Africa urbanisation has been taking place at a rate that often outpaces the capacity and planning structures of cities to provide the necessary services and regulation. This has led to deterioration of the environment, living conditions and quality of life within cities, a loss of values associated with green open space areas, and rising government costs associated with reducing risks to people that result from environmental problems, such as flooding. The notion of green urban development is therefore highly attractive, as it allows cities to grow in a way that maintains their resilience and standards of living. However, few studies have investigated what following a more sustainable, green urban development path will actually cost, and whether these costs can be justified. Moreover, what green urban development should look like is also not well defined, in terms of the degree to which it includes the conservation of river buffers and other natural areas, the mimicking of natural processes through innovative engineering design or the protection of downstream areas through conventional measures.

In this study we investigated the potential feasibility of investing in green urban development interventions to alleviate flooding problems in Dar es Salaam by analysing a range of stormwater management scenarios that considered measures that either reduced exposure to flooding, reduced flood risk, or a combination of these. The three types of measures considered - implementation of restoration and rehabilitation measures in the catchment, storage basins, moving people away from flood prone areas – all led to decreases in the damage costs of flooding. Absolute benefits therefore increase as more measures are combined, but so do costs. Taken alone, catchment rehabilitation measures provided higher net benefit than moving people from the flood prone areas, and also yielded the highest rates of return. The addition of a storage basin added least value, but largely because opportunities for the location of such an intervention were too low down in the catchment to be particularly effective. The results suggest that investment should be secured for the implementation of a combination of rehabilitation measures in the catchment that are specifically designed to attenuate flows and improve drainage, including formal solid waste management and community-based river cleaning programs, reforestation in the upper catchment, the rehabilitation of river buffers in the middle catchment and the reconnection of floodplains in the lower reaches. This could be part of an even broader catchment-to-coast rehabilitation programme for the Msimbazi River system which also aims to address water quality problems and the need for green open space within the rapidly-growing city.

It is important to note that this analysis did not capture all the costs and benefits associated with the implementation of GUD interventions. On the positive side, these include the amenity benefits associated with the creation of green open space areas along the riparian zones as well as improvement in biodiversity. A green urban development path would offer a variety of opportunities for enhancing the livability of the city. On the negative side, it should be acknowledged that relocation of people away from the setback areas could generate psychological suffering and anxiety in the affected individuals that is difficult to quantify or compensate in monetary terms.

Whilst conventional conveyance measures were not considered during this study it is important to acknowledge that solving the flooding and water quality problems in Dar es Salaam will likely require a combination of conventional and green urban development measures. Within the Msimbazi catchment a number of conveyance measures have been designed as part of the Dar es Salaam Metropolitan Development Project. These include the lining of 8.5 km of the main drainage channel of the Sinza River and 5.4 km of secondary drainage sections along the Msimbazi River. These engineering solutions have been designed for a 1:25 year flood on the Msimbazi River and for a 1:50 flood on the Sinza River. The unit cost of this is estimated to be $1500 - 2500 per m, with a total cost of $29 million. This is similar to the cost of the main GUD intervention included in this study; the rehabilitation and enhancement of middle catchment riparian and floodplain areas which cover 488 ha along the Msimbazi, Sinza and Ubungo Rivers.

The role of catchment riparian and floodplain areas in biodiversity conservation must be emphasised as these areas are considered critical for maintaining ecological connectivity between terrestrial systems, rivers and estuaries. These areas also include opportunities for other beneficial uses, such as sports fields and parks, and are more likely to reduce the chances of informal resettlement of the floodplain. Community-based river cleaning programmes also provide important co-benefits including education, social awareness and community development as evidenced by the effective operation of the Mlalakua River Restoration Project in Dar es Salaam. However the success of such programmes depends on active support and diversified and resilient funding. These green urban development interventions, while designed to control flooding impacts, also contribute to water quality enhancement and present opportunities for generating amenity value, other ecosystem services, and uplift communities. Many of the investments required in the Msimbazi catchment do involve costly rehabilitation (catchment land cover and river-floodplain connection) and relocation of unplanned settlements from river margins, demonstrating that better historic protection of both catchment and floodplain areas would have been a far more efficient development path. This is important for the city to bear in mind as it prepares for rapid expansion, especially toward the south.

Due to the limited availability of data, this study by necessity utilized simple models and assumptions. While the results strongly suggest that catchment rehabilitation interventions would yield a positive outcome in economic terms, the figures presented here are preliminary and warrant further investigation and refinement. The results, do however, provide a useful step towards informing policies and contributing to Dar es Salaam's green urban development path. It is recommended that investment is made into the development of better hydrological data, through establishment of flow and additional rainfall gauges, as well as development of detailed spatial datasets on soils, land cover, the built environment and the city's drainage systems. Moving forward these datasets can then be used to construct a more definitive analysis.

VII. REFERENCES

Aceves, M. C. & Fuamba, M. 2016. Methodology for Selecting Best Management Practices Integrating Multiple Stakeholders and Criteria. Part 2: Case Study. Water 8(2): 56.

AECOM 2015. Promoting green urban development in African Cities. Dar es Salaam, Tanzania Urban Environmental Profile. Prepared for the World Bank. AECOM Technical Services, Inc. April 2015

Allamano, P., Claps, P., Laio, F. & Thea, C. 2009. A data-based assessment of the dependence of short-duration precipitation on elevation. Physics and Chemistry of the Earth, Parts A/B/C, 34(10), 635-641.

Apel, H., Aronica, G.T., Kreibich, H., Thieken, A.H. 2009. Flood risk analyses—how detailed do we need to be? Nat. Hazard, 49(1) 79–98.

Armitage, N., Vice, M., Fisher-Jeffes, L., Winter, K., Spiegel, A., & Dunstan, J. 2013. Alternative Technology for Stormwater Management. The South African Guidelines for Sustainable Drainage Systems. WRC Report No. TT 558/13. Available at: http://www.wrc.org.za/Knowledge%20Hub%20Documents/Research%20Reports TT%20558-13.pdf. Accessed 1 March 2012

Aronica, G., Tucciarelli, T., & Nasello, C. 1998. 2D Multilevel Model for Flood Wave Propagation in Flood-Affected Areas. J. Water Resour. Plann. Manage. 124(4), 210–217.

Bates, P.D. & De Roo, A.P.J. 2000. A simple raster-based model for flood inundation simulation. Journal of hydrology, 236(1), 54-77.

Bates, P.D., Horritt, M.S., Aronica, G. & Beven, K. 2004. Bayesian updating of flood inundation likelihoods conditioned on flood extent data. Hydrological Processes, 18(17), 3347-3370.

Biscarini, C., Di Francesco, S., Nardi, F. & Manciola, P. 2013. Detailed simulation of complex hydraulic problems with macroscopic and mesoscopic mathematical methods. Mathematical Problems in Engineering. vol. 2013, Article ID 928309, doi:10.1155/2013/928309.

Boyd, J., Epanchin-Niell, R. S., & Siikamäki, J. 2012. Conservation return on investment analysis: a review of results, methods, and new directions. Resources for the Future Discussion Paper, (12-01).

Brown, W. & Schueler, T.R. 1997. The Economics of Stormwater BMPs in the Mid-Atlantic Region: Final Report: an Examination of the Real Cost of Providing Stormwater Control. Center for Watershed Protection, pp17.

Büchele, B., Kreibich, H., Kron, A., Thieken, A., Ihringer, J., Oberle, P. & Nestmann, F. 2006. Flood-risk mapping: contributions towards an enhanced assessment of extreme events and associated risks. Natural Hazards and Earth System Science, 6(4), 485-503.

BWM, Bureau of Watershed Management. 2010. Riparian Forest Buffer Guidance. Report available at: http://www.elibrary.dep.state.pa.us/dsweb/Get/Document-82308/394-5600-001.pdf. Accessed 1 March 2012.

Calvi, G. M. 2013. Choices and criteria for seismic strengthening. Journal of Earthquake Engineering, 17(6), 769-802.

Carozza, S., De Risi, R., Jalayer, F. 2013. Guideline to decreasing physical vulnerability in the three considered cities. CLUVA project deliverable D2.5. Available at http://www.cluva.eu/deliverables/CLUVA_D2.5.pdf. Accessed 1 March 2016.

Cavan, G., Lindley, S., Yeshitela, K., Nebebe, A., Woldegerima, T., Shemdoe, R., Kibassa, D., Pauleit, S., Renner, R., Printz, A., Buchta, K., Coly, A., Sall, F., Ndour, N.M., Ouédraogo, Y., Samari, B.S., Sankara, B.T., Feumba, R.A., Ngapgue, J.N., Ngoumo, M.T., Tsalefac, M., Tonye, E. 2012. Green infrastructure maps for selected case studies and a report with an urban green infrastructure mapping methodology adapted to African cities CLUVA project deliverable D2.7. http://www.cluva.eu/deliverables/CLUVA_D2.7.pdf. Accessed 1 March 2012

CCIAM 2013. Analysis of the impacts or urban land use and climate change on coastal forest ecosystem and management. Written by Sylivester Chaisamba and Pamela Levira. Tanzania Meteorological Agency. June 2013

Chang, S. & Shinozuka, M. 1996. Life-Cycle Cost Analysis with Natural Hazard Risk. Journal of Infrastructure Systems 2(3): 118–126.

Chang, L.F., Kang, J.L. & Su, M.D. 2009. Depth-Damage Curve for Flood Damage Assessments Industrial and Commercial Sectors. Proceedings of the 4th IASME / WSEAS Int. Conference on water resources, hydraulics & hydrology.

Charvet, I., Suppasri, A., Kimura, H., Sugawara, D. & Imamura, F. 2015. Fragility estimations for Kesennuma City following the 2011 Great East Japan tsunami based on maximum flow depths, velocities and debris impact, with evaluation of the ordinal model's predictive accuracy. Nat Hazards 79(3):2073–2099

Cobby, D.M., Mason, D.C., Horritt, M.S. & Bates, P.D. 2003. Two-dimensional hydraulic flood modelling using a finite-element mesh decomposed according to vegetation and topographic features derived from airborne scanning laser altimetry. Hydrological Processes, 17(10): 1979-2000.

Construction Industry Research and Information Association (CIRIA) 2007. The SUDS Manual (CIRIA C697). London.

Cornell, C.A. & Krawinkler, H., 2000. Progress and challenges in seismic performance assessment, PEER Center News 3, 4 p.

Daily, G. C. & Matson, P. A. 2008. Ecosystem services: From theory to implementation. Proceedings of the National Academy of Sciences, 105(28): 9455-9456

Daudi, L., Lugomela C., Nduku Uku, J. and De Trochal, M. 2012. Effect of nutrient enrichment on seagrass associated meiofauna in Tanzania. Marine Environmental Research 82: 49-58.

Daugherty R. L. & Franzini J. B. 1965. Fluid Mechanics, 6th ed. McGraw-Hill, New York. pp. 338-349.

Department of Environmental Protection. 2010. Riparian Forest Buffer Guidance. Bureau of Watershed Management, the Pennsylvania Clean Streams Law. Document 394-5600-00.

Department of Co-operative governance and Traditional Affairs (DoCGTA) 2010. Municipal Infrastructure: an industry guide to infrastructure service delivery levels and unit costs. Republic of South Africa.

De Martino, G., De Paola, F., Fontana, N., Marini, G., & Ranucci, A. 2012. Experimental assessment of level pool routing in preliminary design of floodplain storage. Science of the Total Environment, 416, 142-147.

De Paola, F., Ranucci, A., & Feo, A. 2013. Antecedent moisture condition (SCS) frequency assessment: a case study in southern Italy. Irrigation and Drainage, 62(S2), 61-71.

De Paola, F., Giugni, M., Topa, M. E., & Bucchignani, E. 2014. Intensity-Duration-Frequency (IDF) rainfall curves, for data series and climate projection in African cities. Springer Plus, 3(1), 133.

De Paola, F., Galdiero, E., Giugni, M., & Pugliese, F. 2015. Sustainable development of storm-water systems in African cities considering climate change. Procedia Engineering, 119, 1181-1191.

De Risi, R. 2013b. A probabilistic bi-scale frame work for urban flood risk assessment. PhD dissertation. Department of structures for Engineering and Architecture, University of Naples Federico II, Naples

De Risi, R., Goda, K., Mori, N., & Yasuda, T. (2016). Bayesian tsunami fragility modeling considering input data uncertainty. Stochastic Environmental Research and Risk Assessment, 1-17.

De Risi, R., Jalayer, F., Iervolino, I., Kyessi, A., Mbuya, E., Yeshitela, K., Yonas, N. 2012. Guidelines for vulnerability assessment and reinforcement measures of adobe houses. CLUVA project deliverable D2.4. Available at http:// www.cluva.eu/deliverables/CLUVA_D2.4.pdf. Accessed 1 March 2016.

De Risi, R., Jalayer, F., De Paola, F., Iervolino, I., Giugni, M., Topa, M.E., Mbuya, E., Kyessi, A., Manfredi, G. & Gasparini, P. 2013a. Flood Risk Assessment for Informal Settlements, Natural Hazards, 69(1), 1003-1032.

De Risi, R., Jalayer, F., Iervolino, I., Manfredi, G., & Carozza, S. 2013c. VISK: a GIS-compatible platform for micro-scale assessment of flooding risk in urban areas. In COMPDYN, 4th ECCOMAS Thematic conference on computational methods in structural dynamics and earthquake engineering. Kos Island, Greece.

De Risi, R., Jalayer, F., De Paola, F., & Giugni, M. 2014. Probabilistic delineation of flood-prone areas based on a digital elevation model and the extent of historical flooding: The case of Ouagadougou. Boletín Geológico Minero, 125, 329-340.

De Risi, R., Jalayer, F., & De Paola, F. 2015. Meso-scale hazard zoning of potentially flood prone areas. Journal of Hydrology, 527, 316-325.

De Wolf, H., Ulomi, S.A., Backeljau, T. and Blus, R. 2001. Heavy metal levels in the sediments of four Dar es Salaam mangroves accumulation in, and effect on the morphology of the periwinkle, Littoraria scabra (Mollusca: Gastropoda). Environment International 26: 243-249.

Di Baldassarre GD, Schumann G, & Bates P 2009. Near real time satellite imagery to support and verify timely flood modelling. Hydrological Processes, 23(5), 799-803.

Dym, C. L., Little, P., Orwin, E. J., & Spjut, R. E. 2009. The Design Process. Engineering design: a projectbased introduction, 17-32.

Dodov, B.A. & Foufoula-Georgiou, E. 2006. Floodplain morphometry extraction from a high-resolution digital elevation model: a simple algorithm for regional analysis studies. Geoscience and Remote Sensing Letters, IEEE, 3(3): 410-413.

Drake, C. W. 2014. Assessment of flood mitigation strategies for reducing peak discharges in the Upper Cedar River watershed. MS (Master of Science) thesis, University of Iowa. Available at: http://ir.uiowa.edu/etd/4617. Accessed 1 March 2016.

Dutta, D. & Tingsanchali, T. 2003. Development of loss functions for urban flood risk analysis in Bangkok, in 2nd International Conference on New Technologies for Urban Safety in Mega Cities of Asia. University of Tokyo, Japan. p. 229-238.

Ellingwood, B. R. & Wen, Y.K. 2005. Risk-benefit-based design decisions for low-probability/high consequence earthquake events in Mid-America. Progress in Structural Engineering Material, 7:56–70.

El-Nasr, A. A., Arnold, J. G., Feyen, J., & Berlamont, J. 2005. Modelling the hydrology of a catchment using a distributed and a semi-distributed model. Hydrological processes, 19(3), 573-587.

Environment Agency, 2007. Cost-benefit of SUDS retrofit in urban areas. Science Report – SC060024.

Ertas, A., & Jones, J. C. 1996. The engineering design process. New York: Wiley.

Faber, M.H. & Rackwitz, R. 2004. Sustainable decision making in Civil Engineering. Structural Engineering International, 3:237–242.

Fabio, P., Aronica, G.T. & Apel, H. 2010. Towards automatic calibration of 2-D flood propagation models, Hydrology and Earth System Sciences, 14(6), 911-924.

FEMA P-58-1. 2012. Seismic Performance Assessment of Buildings. Volume-1 – Mythology.

Fletcher, T., Duncan, H., Lloyd, S, & Poelsma, P. 2003. Stormwater Flow and Quality and the Effectiveness of Non-proprietary Stormwater Treatment Measures. Report for the NSW EPA.

April 2003. Cooperative Research Centre for Catchment Hydrology, Melbourne, Victoria.

Fletcher, T.D., Shuster, W.F., Hunt, W.F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J-L., Mikkelsen, P.S., Rivard, G., Uhl, M., Dagenais, D. & Viklander, M. 2015. SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water Journal 12:7. 525-542, DOI: 10.1080/1573062X.2014.916314.

FLO-2D S.I., FLO-2D® User's Manual. 2004: Nutrioso, Arizona.

Food and Agrciultural Organisation of the United Nations (FAO). 2011. Forests beneath the grass. Edited by Durst, P.B., Sajise, P. & Leslie, R.N. Proceedings of the Regional Workshop on Advancing the Application of Assisted Natural Regeneration for Effective Low-Cost Restoration.

Frangopol, D.M., Lin, K.Y. & Estes, A.C. 1997. Life-Cycle Cost Design of Deteriorating Structure. ASCE Journal of Structural Engineering, 123(10): 1390-1401.

Frangopol, D.M., Kallen, M.J. & Noortwijk, J.M. 2004. Probabilistic models for life-cycle performance of deteriorating structures: review and future directions. Progress in Structural Engineering Material, 6:197–212.

Gallant, J.C. & Dowling, T.I. 2003. A multiresolution index of valley bottom flatness for mapping depositional areas. Water Resources Research, 39(12).

Gencturk, B. & Elnashai, A. S. 2012. Life cycle cost considerations in seismic design optimization of structures. Structural Seismic Design Optimization and Earthquake Engineering: Formulations and Applications, 1-22.

Giandotti, M. 1940. Previsione empirica delle piene in base alle precipitazioni meteoriche, alle caratteristiche fisiche morfologiche dei bacini; Applicazione del metodo ad alcuni bacini dell'appennino ligure. Pubbl, 2, 5-13. (In Italian).

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., Theuray, N. & Lindley, S.J. 2008. Characterising the urban environment of UK cities and towns: a template for landscape planning in a changing climate. Landscape and Urban Planning 87: 210–222.

Gissing, A., & Blong, R. 2004. Accounting for variability in commercial flood damage estimation. Australian Geographer, 35(2), 209-222.

Giugni, M., De Paola, F., Topa M.E. 2012. Guidelines on engineering design and management of storm water systems. CLUVA project deliverable D2.2. Available at http://www.cluva.eu/deliverables/CLUVA_D2.2.pdf. Accessed 1 March 2016.

Goda, K., & Hong, H. P. (2008). Estimation of Seismic Loss for Spatially Distributed Buildings. Earthquake Spectra, 24(4), 889-910.

Guha-Sapir, D., Below, R., Hoyois, P.H. 2015. EM-DAT: international disaster database. Available viawww.emdat.be. Accessed 1 March 2016.

Hallegatte, S. & Przyluski, V. 2010. The Economics of Natural Disasters: Concepts and Methods. World Bank Policy Research Working Paper 5507. Washington DC: The World Bank. https://openknowledge.worldbank.org/bitstream/handle/10986/3991/WPS5507.pdf

Hamilton, R.A. 2015. Available at: http://www.treeimprovement.org/sites/default/files/reforestation_investment_does_it_pay.pdf. Accessed 1 March 2012.

Hagen, E., & Lu, X. X. (2011). Let us create flood hazard maps for developing countries. Natural hazards, 58(3), 841-843.

Herath, S., Dutta, D., & Musiake, K. (1999). Flood damage estimation of an urban catchment using remote sensing and GIS. In Proc. the Eighth International Conference on Urban Storm Drainage.

Hill, A. & Linder, C. 2010. Modelling informal urban growth under rapid urbanisation. Prepared for the TU Dortmund University. June 2010

Hull City Council, 2015. Hull City Council Local Flood Risk Management Strategy. United Kingdom

ISO 15686-5. 2006. Buildings – Service life planning – Part 5: Life cycle costing. International Organization for Standardization.

International Union for the Conservation of Nature (IUCN), World Wide Fund for Nature (WWF). 2002. Forest landscape restoration; the opportunities and challenges for Eastern Africa. A synthesis report of a regional workshop in Mombasa, Kenya.

Jiang, Y., Yuan, Y. & Piza, H. 2015. A review of applicability and effectiveness of low impact development/ green infrastructure practices in arid/semi-arid United States. Environments 2: 221–249; doi:10.3390/ environments2020221

Jacobi P. 1997. Importance of vegetable production systems in Dar es Salaam, Tanzania. Dar es Salaam: Urban Vegetable Promotion Project.

Jalayer, F., De Risi, R., Manfredi, G., De Paola, F., Topa, M.E., Giugni, M., Bucchignani, E., Mbuya, E., Kyessi, A. & Gasparini, P. 2013a. From climate predictions to flood risk assessment for a portfolio of structures, 4881-4888, 11th International Conference on Structural Safety & Reliability (ICOSSAR 2013), Columbia University, New York, NY, June 16-20, 2013.

Jalayer, F., De Risi, R., Herslund, L., Garcia-Aristizabal, A. & Carozza, S. 2013b. Report describing the developed methods and its possible relevance for planning and decision-making. CLUVA project deliverable D2.5. Available at http://www.cluva.eu/deliverables/CLUVA_D2.17.pdf. Accessed 1 March 2016.

Jalayer, F., De Risi, R., De Paola, F., Giugni, M., Manfredi, G., Gasparini, P., ... & Cavan, G. 2014. Probabilistic GIS-based method for delineation of urban flooding risk hotspots. Natural hazards, 73(2), 975-1001.

Jalayer, F., De Risi, R., Kyessi, A., Mbuya, E., & Yonas, N. 2015. Vulnerability of Built Environment to Flooding in African Cities. Book chapter in Urban Vulnerability and Climate Change in Africa, Future City 4, S. Pauleit et al. (eds.). (pp. 77-106). Springer International Publishing, Switzerland.

Jalayer, F., Carozza, S., De Risi, R., Manfredi, G., & Mbuya, E. 2016. Performance-based flood safety-checking for non-engineered masonry structures. Engineering Structures, 106, 109-123.

Joksimovic, D. & Alam, Z. 2014. Cost efficiency of low impact development (LID) stormwater management practices. Procedia Engineering 89: 734 – 741.

Jonkman, S.N., Vrijling, J.K. & Vrouwenvelder, A.C.W.M. 2008a. Methods for the estimation of loss of life due to floods: a literature review and a proposal for a new method, Nat. Hazard, 46:353–389

Jonkman, S. N., Bočkarjova, M., Kok, M., & Bernardini, P. 2008b. Integrated hydrodynamic and economic modelling of flood damage in the Netherlands. Ecological economics, 66(1), 77-90.

Kang, J.L., Su, M.D. & Chang, L.F. 2005. Loss functions and framework for regional flood damage estimation in residential area. Journal of Marine Science and Technology, 13(3). 193-199.

Kassenga, G. R. & Mbuligwe, S. E. 2009. Impacts of a solid waste disposal site on soil, surface water and groundwater quality in Dar es Salaam City, Tanzania. Journal of Sustainable Development in Africa 10(4): 73-94.

Khan S. & Kelman I (2012). Progressive climate change and disasters: connections and metrics. Natural hazards, 61(3), 1477-1481.

Kihampa, C. 2013. Environmental exposure and public health concerns of municipal solid waste disposal in Dar es Salaam, Tanzania. Journal of Sustainable Development in Africa 15(3): 198-208.

Kirpich, Z. P. 1940. Time of concentration of small agricultural watersheds. Civil Engineering, 10(6), 362.

Klingner, W. 2014. The effects of increased infiltration and distributed storage on reducing peak discharges in an agricultural Iowa watershed: the Middle Raccoon River. MS (Master of Science) thesis, University of Iowa. Available at: http://ir.uiowa.edu/etd/4664. Accessed 1 March 2016.

Kong, J. & Frangopol, D. 2003. Evaluation of Expected Life-Cycle Maintenance Cost of Deteriorating Structures. Journal of Structural Engineering, 129(5), 682–691.

Kowalik, T. & Walega, A. 2015. Estimation of CN parameter for small agricultural watersheds using asymptotic functions. Water, 7(3), 939-955.

Kundzewicz, Z. W. 2002. Non-structural flood protection and sustainability. Water International, 27(1), 3-13.

Leader, T. & Wallingford, H.R. 2009. Language of risk. Deliverable D32.2. FLOODsite project. http://floodsite.net/html/partner_area/project_docs/T32_04_01_FLOODsite_Language_of_Risk_D32_2_v5_2_P1.pdf. Accessed 01 March 2016

Liu, Y., Bralts, V.F. & Engel, B.A. 2015. Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. Science of the Total Environment 511: 298–308.

Lynch, L. & Tjaden, R. 2000. When a Landowner Adopts a Riparian Buffer – Benefits and Costs. University of Maryland, Department of Environmental Protection. Report available at: https://extension.umd.edu/sites/default/files/_docs/programs/riparianbuffers/FS774.pdf. Accessed 01 March 2016

Machiwa, J.F. 1992. Heavy metal content in coastal sediments of Dar es Salaam, Tanzania. Environment International 18(4):409-415.

Maione, U. & Mosiello, U. 1993. Elementi di statistica per l'idrologia. (In Italian).

Marco, J.B. 1994. Flood risk mapping. Chapter 20 in Coping with Floods. Rossi G, Harmancioğlu N & Yevjevich V (eds.) Springer Netherlands; 257, 353-373.

McPherson, G., Simpson, J.R., Peper, P.J. & Xiao, Q. 1999. Benefit-Cost analysis of Modesto's Municipal urban forest. Journal of Arboriculture 25(5): 235-248.

Merz, B., Thieken, A.H. & Gocht, M. 2007 Flood Risk Mapping At The Local Scale: Concepts and Challenges. Chapter 13 of Flood Risk Management in Europe. Begum S, Stive MF, Hall J, (eds.) Springer Netherlands; 25, 231-51.

Mockus, V. 1972. National engineering handbook, Section 4, hydrology. US Soil Conservation Service, Washington, DC.

Morales Torres, A., Perales Momparler, S., Jefferies, C. & Domenech, I.A. 2015. Report on Stormwater Management. E2STORMED PROJECT, Improvement of energy efficiency in the water cycle by the use of innovative storm water management in smart Mediterranean cities, www.e2stormed.eu

Michie, R. 2010. Cost Estimate to Restore Riparian Forest Buffers and Improve Stream Habitat in the Willamette Basin, Oregon. State of Oregon, Department of Environmental Quality, Watershed Management Section. Report available at: http://www.deq.state.or.us/wq/tmdls/docs/WillametteRipCost030310.pdf. Accessed 01 March 2016.

Mozambique-LNG. 2015. Mozambique Gas Development Project, Resettlement Action Plan. Anadarko Mozambique Area 1. Document number: EA-MZ-SR0000-RRG-U14-00006-29.

Mremi, S.D. & Machiwa, J.F. 2003. Heavy metal contamination of mangrove sediments and the associated biota in Dar es Salaam, Tanzania. Tanzania Journal of Science 29(1): 61-76.

Mrutu, A., Nkotagu, H. & Luilo, G. 2013. Spatial distribution of heavy metals in Msimbazi River mangrove sediments in Dar es Salaam coastal zone, Tanzania. International Journal of Environmental Sciences 3(5):1641-1655.

Mtanga, A. & Machiwa, J. 2007. Assessment of heavy metal pollution in sediment and polychaete worms from the Mzinga Creek and Ras Dege mangrove ecosystems, Dar es Salaam, Tanzania. Western Indian Ocean Journal of Marine Science 6(2):125–135.

Muzuka, A.N.N. 2007. Distribution of heavy metals in the coastal marine surficial sediments in the Msasani Bay-Dar es Salaam harbour area. Western Indian Ocean Journal of Marine Science 6(1):73–83.

Mwegoha, W.J.S. & Kihampa, C. 2010. Heavy metal contamination in agricultural solid and water in Dar es Salaam city, Tanzania. African Journal of Environmental Science and Technology 4(11): 763-769

Nadal NC, Zapata RE, Pagán I, López R and Agudelo J 2010. Building Damage due to Riverine and Coastal Floods. Journal of Water Resources Planning and Management, 136(3), 327-336.

Natural Resources Conservation Service (NRSC) 2005. Economics and Survival of Hand-Planted Riparian Forest Buffers in West Central Maine. US Department of Agriculture, Maine.

NEMC 2009. Dar es Salaam River Basin Management Project. Draft Project Concept.

O'Brien, J.S., Julien, P.Y. & Fullerton, W.T. 1993. Two-dimensional water flood and mudflow simulation. Journal of hydraulic engineering, 119(2), 244-261.

Paths for all. 2014. Estimating price guide for path projects. Scotland.

Pauleit, S. & Duhme, F. 2000. Assessing the environmental performance of land cover types for urban planning. Landscape and Urban Planning, 52(1): 1-20.

Pistrika, A. & Tsakiris, G. 2007. Flood Risk Assessment: A Methodological Framework, Water Resources Management: New Approaches and Technologies, European Water Resources Association, Chania, Crete - Greece, 14-16 June.

Pistrika, A.K. 2010. Flood damage estimation based on flood simulation scenarios and a GIS platform, European Water, 30: 3-11.

Pistrika, A.K. & Jonkman, S.N. 2010. Damage to residential buildings due to flooding of New Orleans after hurricane Katrina. Nat. Hazard, 54:413–434

Porter, K., Kennedy, R., & Bachman, R. 2007. Creating fragility functions for performance-based earthquake engineering. Earthquake Spectra, 23(2), 471-489.

Prime Minister's Office Regional Administration and Local Government (PMO-RALG) 2014a. Resettlement Action Plan (RAP) for the Proposed Mto Ng'ombe Sub-project, Kinondoni Municipality. Surface Water Drainage System Subproject under the Dar es Salaam Metropolitan Development Project (DMDP). Tanzania Strategic Cities Project (TSCP).

Prime Minister's Office Regional Administration and Local Government (PMO-RALG) 2014b. Environmental impact statement of the proposed rehabilitation/improvement of surface water drainage system in Ilala Municipality, Dar es Salaam Region. Surface Water Drainage System Subproject under the Dar es Salaam Metropolitan Development Project (DMDP). Tanzania Strategic Cities Project (TSCP).

Reese, S., Bradley, B. A., Bind, J., Smart, G., Power, W., & Sturman, J. 2011. Empirical building fragilities from observed damage in the 2009 South Pacific tsunami. Earth-Science Reviews, 107(1), 156-173.

Reilly, F. & Brown, K. 2011. Investment analysis and portfolio management. 10th Edition. Cengage Learning. Australia. pp 1058.

Sakijege, T., Sartohadi, J., Marfai, M.A., Kassenga, G.R. & Kasala, S.E. 2014. Assessment of adaptation strategies to flooding: a comparative study between informal settlements of Keko Machungwa in Dar es Salaam, Tanzania and Sangkrah in Surakarta, Indonesia. Jàmbá:Journal of Disaster Risk Studies 6(1), 1-10.

Scawthorn, C., Blais, N., Seligson, H., Tate, E., Mifflin, E., Thomas, W., Murphy, J. & Jones, C. 2006a. HAZUS-MH Flood Loss Estimation Methodology. I: Overview and Flood Hazard Characterization. Natural Hazards Review 7, SPECIAL ISSUE: Multihazards Loss Estimation and HAZUS, 60–71.

Scawthorn, C., Flores, P., Blais, N., Seligson, H., Tate, E., Chang, S., Mifflin, E., Thomas, W., Murphy, J., Jones, C. & Lawrence, M. 2006b. HAZUS-MH Flood Loss Estimation Methodology. II. Damage and Loss Assessment. Natural Hazards Review 7, SPECIAL ISSUE: Multihazards Loss Estimation and HAZUS, 72–81.

Schwarz, J. & Maiwald, H. 2008. Damage and loss prediction model based on the vulnerability of building types. 4th International symposium of Flood Defence, Toronto, Canada, May 6-8.

Severn Trent Water, 2015. Severn Trent Environmental Protection Scheme (STEPS). United Kingdom

Smith, D.I. 1994. Flood damage estimation - A review of urban stage-damage curvesand loss function. - Water SA, 20(3), 231-238.

Soil Conservation Service, 1972. National engineering handbook, Section 4, Hydrology. U.S. Department of Agriculture, Washington D.C., 762 p.

Soil Conservation Service, 1975. Urban hydrology for small watersheds, U.S. Department of Agriculture, Washington D. C., updated 1986.

Suppasri, A., Mas, E., Charvet, I., Gunasekera, R., Imai, K., Fukutani, Y., ... & Imamura, F. 2013. Building damage characteristics based on surveyed data and fragility curves of the 2011 Great East Japan tsunami. Natural Hazards, (2), 319-341.

Tanzania Meteorological Agency (TMA) 2011. Urban Poverty & Climate Change in Dar es Salaam, Tanzania: A Case Study. March 10, 2011.Matari et al. 2008

Tanzania Standards for Receiving Water, Effluents and soils (TZS 789:2003). Tanzania Bureau of Standards.

TEEB. 2010. The Economics of Ecosystems and Biodiversity: Mainstreaming the Economics of Nature: A Synthesis of the Approach, Conclusions and Recommendations of TEEB.

Thampapillai, D.J., & Musgrave, W.F. 1985. Flood damage mitigation: a review of structural and nonstructural measures and alternative decision frameworks. Water Resources Research, 21(4), 411-424.

TNC, 2015. Upper Tana-Nairobi Water Fund: A Business Case. Available at: http://www.nature.org/ourinitiatives/regions/africa/upper-tana-nairobi-water-fund-business-case.pdf. Accessed 1 March 2012.

Topa, M. E., Giugni, M., & De Paola, F. 2014. Off-stream floodplain storage: Numerical modeling and experimental analysis. Journal of Irrigation and Drainage Engineering, 141(1), 04014040.

Toronto and Region Conservation Authority (TRCA) 2013. Assessment of Life Cycle Costs for Low Impact Development Stormwater Management Practices. Sustainable Technologies Evaluation Program.

Xiao, Q. & McPherson, G. 2002. Rainfall interception by Santa Monica’s municipal forest. Urban Ecosystems 6: 291-302.

UN Habitat 2010. Citywide action plan for upgrading unplanned and unserviced settlement in Dar es Salaam. United Nations Human Settlements Programme, Kenya.

URS, 2003. Water Sensitive Urban Design Technical Guidelines for Western Sydney. Report prepared for the Upper Parramatta River Catchment Trust, Sydney, New South Wales.

URT, 2014 TSCP. Tanzania Strategic Cities Project (TSCP) Environmental Impact Statement of the Proposed Rehabilitation/Improvement of Surface Water Drainage System in Kinondoni Municipality, Dar es Salaam Region. Prepared by COWI in association with PROCESL. November 12, 2014.

Viparelli, C. 1963. Ricostruzione dell’idrogramma di piena. L’Energia Elettrica, 6, 421-428 (In Italian)

Waidler, D., White, M., Steglich, E. Wang, S. Williams, J., Jones, C.A. & Srinivasan, R. 2009. Conservation practice modeling guide for SWAT and APEX. Draft - August 2009, provided by Spatial Sciences Laboratory, Texas A&M University, College Station, Texas

Watkiss, P. Downing, T., Dyszynski, J., Pye, S. et al. 2011. The Economics of Climate Change in the United Republic of Tanzania. Report to Development Partners Group and the UK Department for International Development. Published January 2011.Kihampa 2013.

World Health Organization (WHO). 2004. Guidelines for Drinking Water Quality. 3rd Ed., World Health Organization, ISBN: 92-4-154638-7, 516.

Yang, T.H., Chen, Y.C., Chang, Y.C., Yang, S.C. & Ho, J.Y. 2015. Comparison of Different Grid Cell Ordering Approaches in a Simplified Inundation Model. Water, 7(2), 438-454.

APPENDIX I: BASELINE INUNDATION RESULTS

First sub-domain

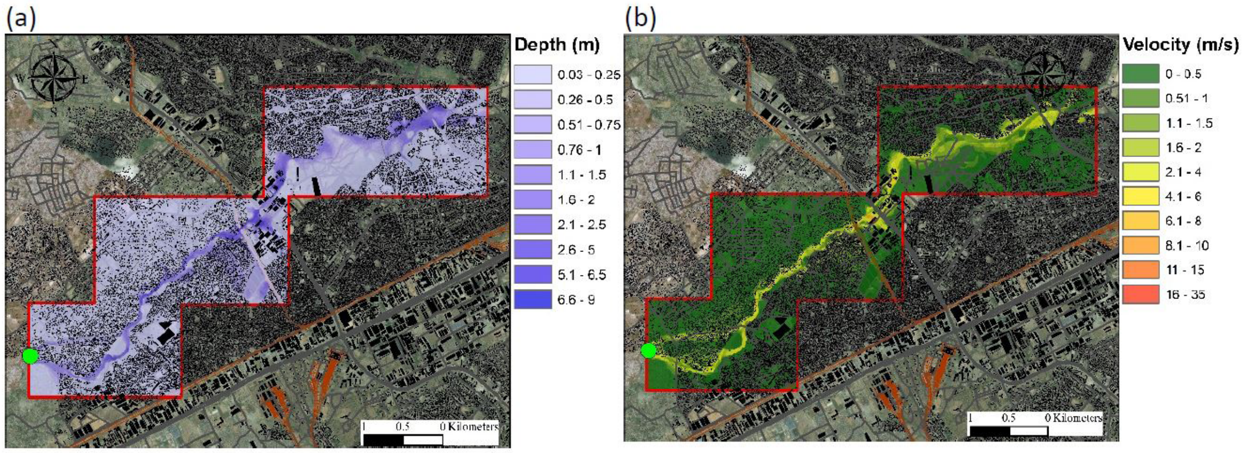

Figure A1. 1. Inundation results for the first sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

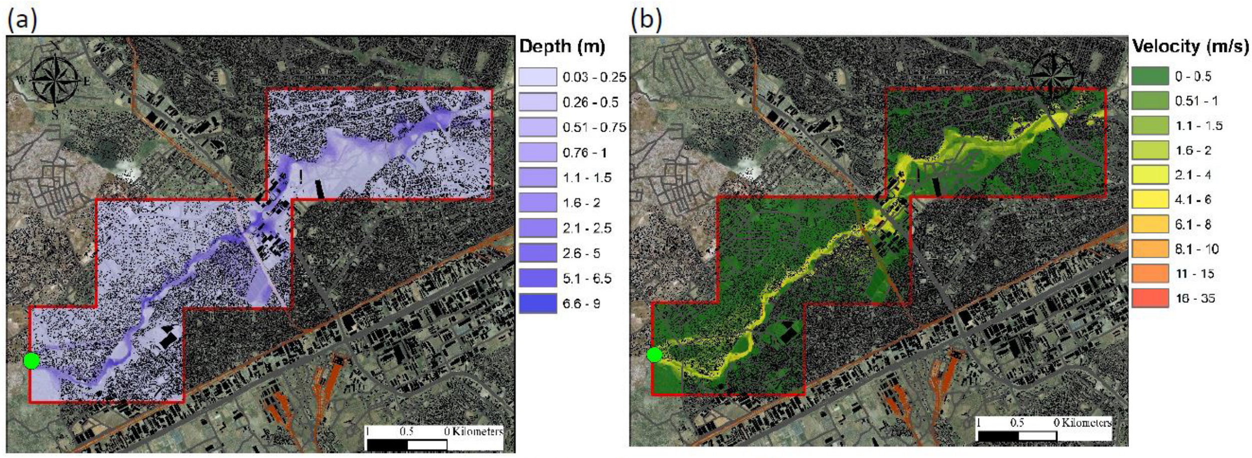

Figure A1. 2. Inundation results for the first sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

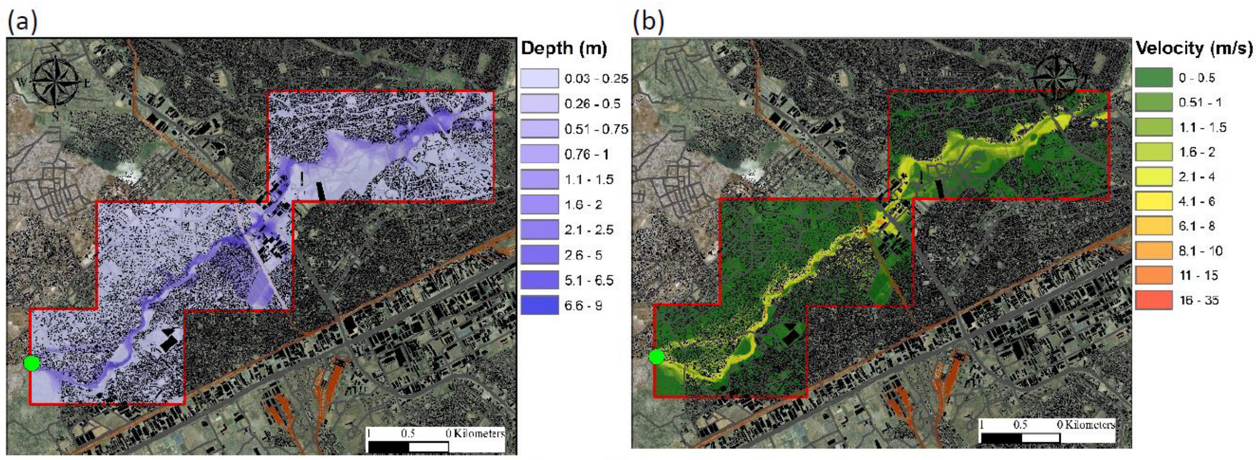

Figure A1. 3. Inundation results for the first sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

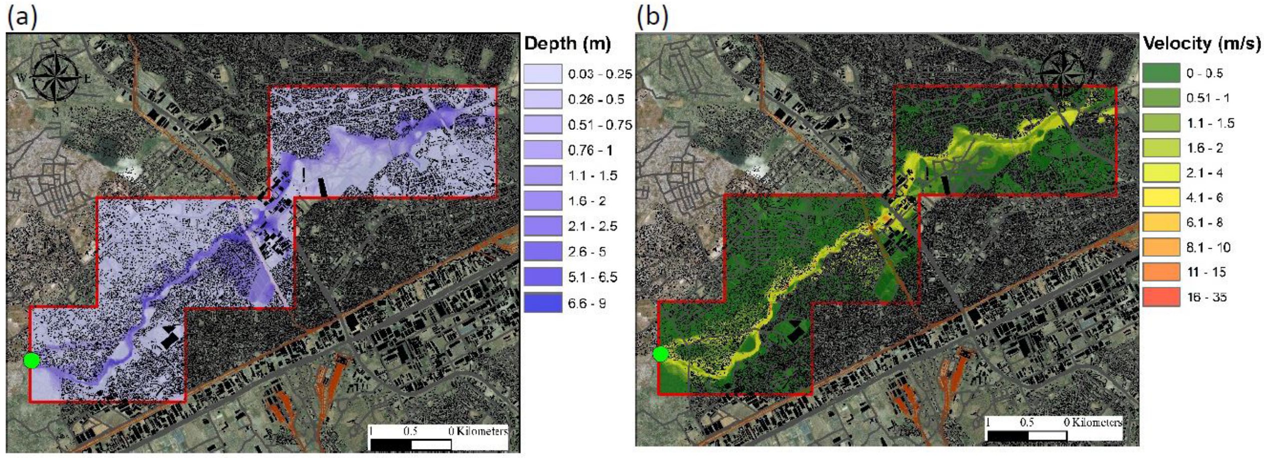

Figure A1. 4. Inundation results for the first sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

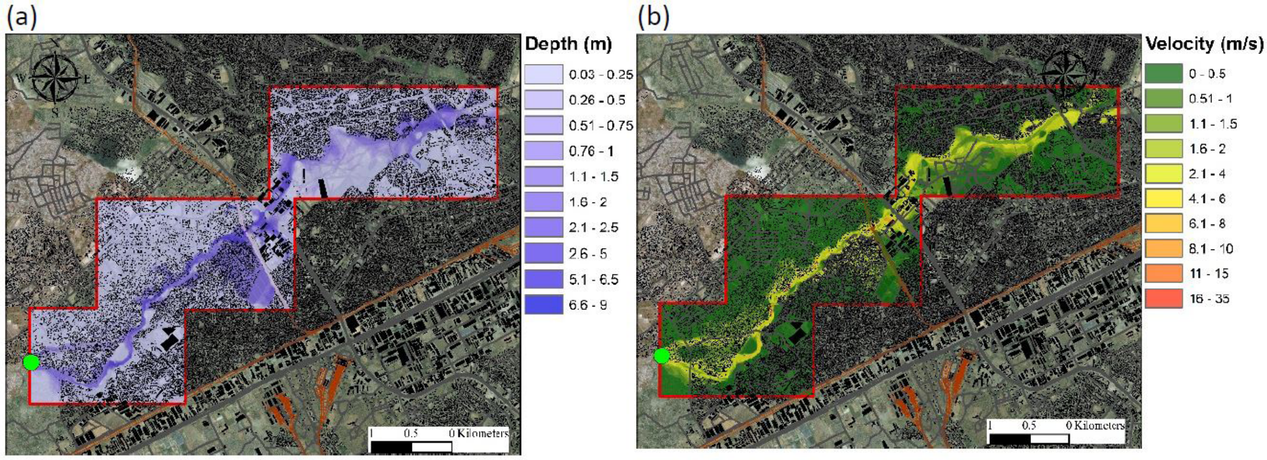

Figure A1. 5. Inundation results for the first sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

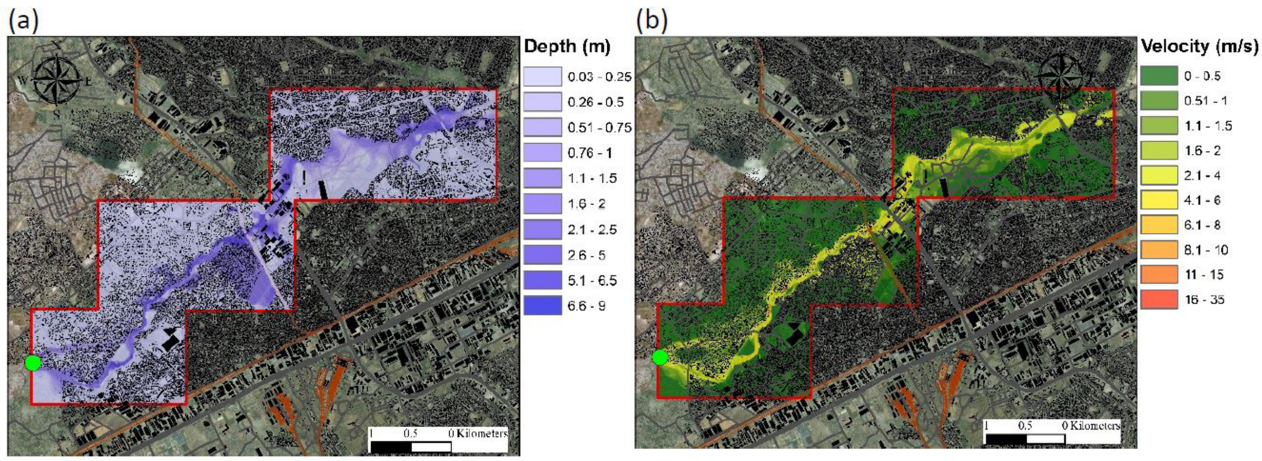

Figure A1. 6. Inundation results for the first sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

Second sub-domain

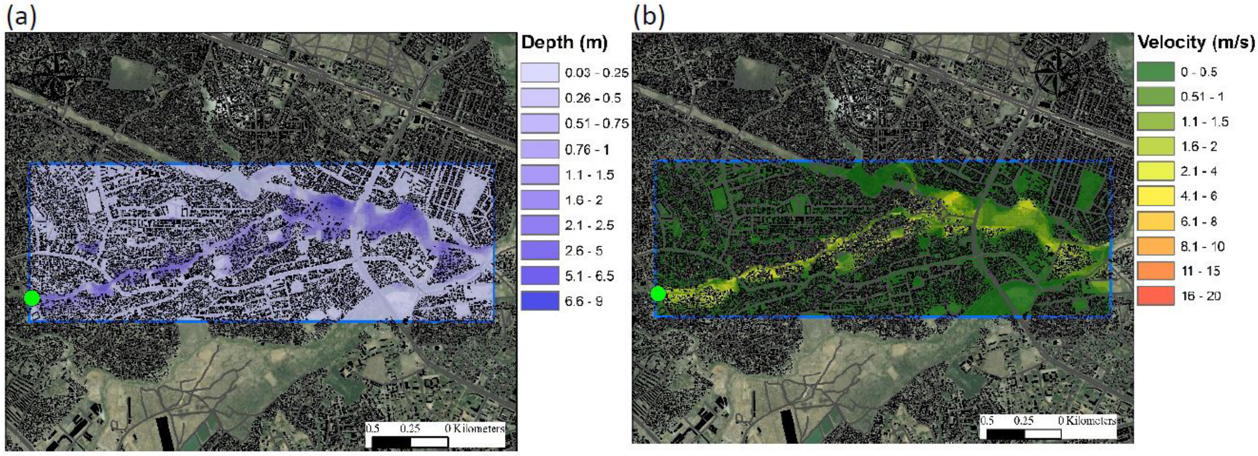

Figure A1. 7. Inundation results for the second sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

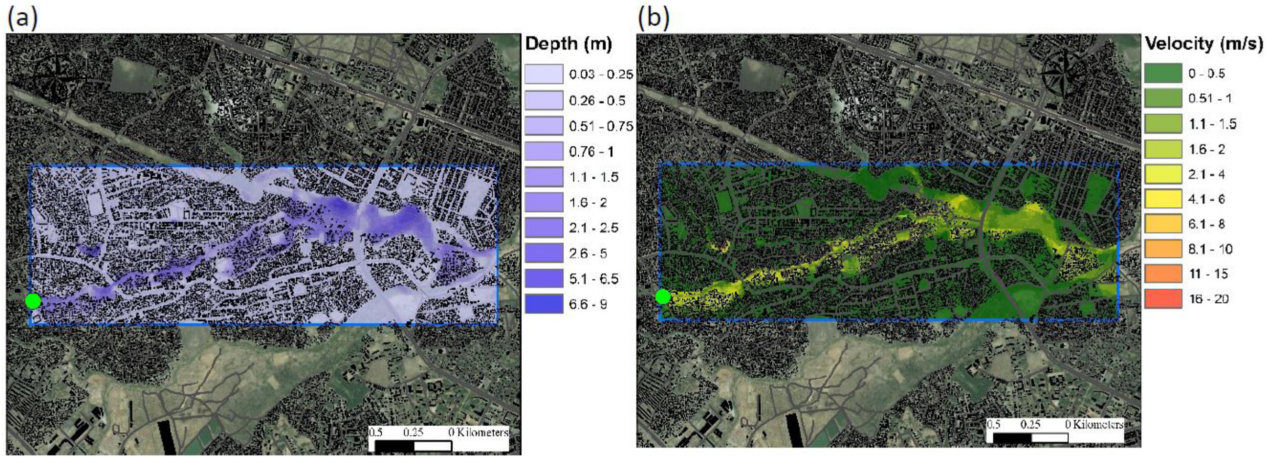

Figure A1. 8. Inundation results for the second sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

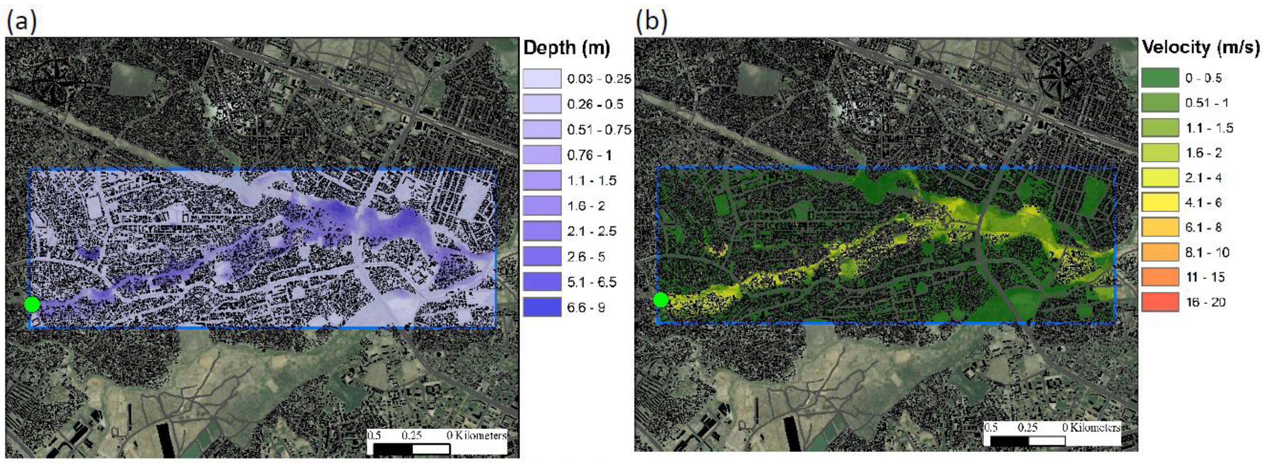

Figure A1. 9. Inundation results for the second sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

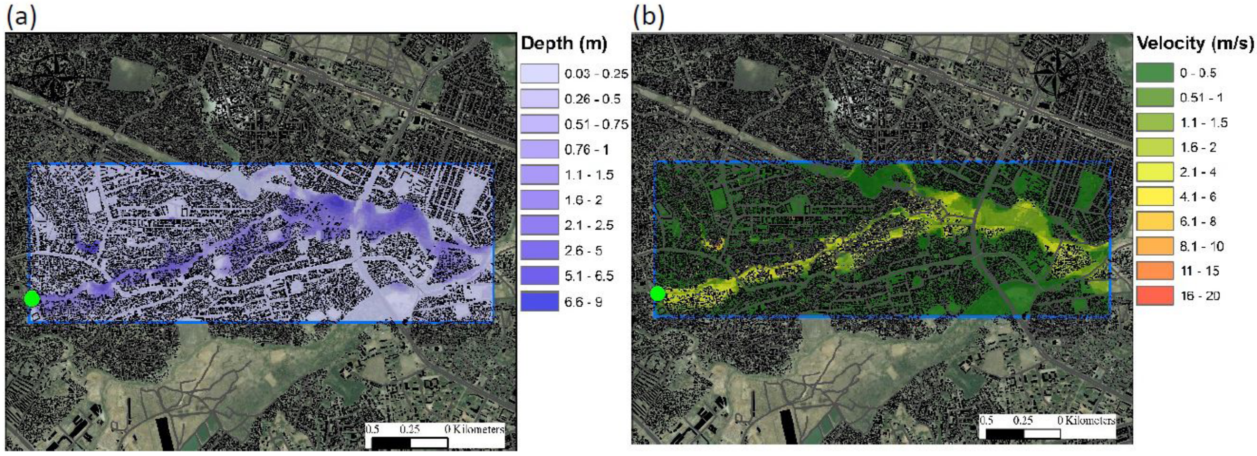

Figure A1. 10. Inundation results for the second sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

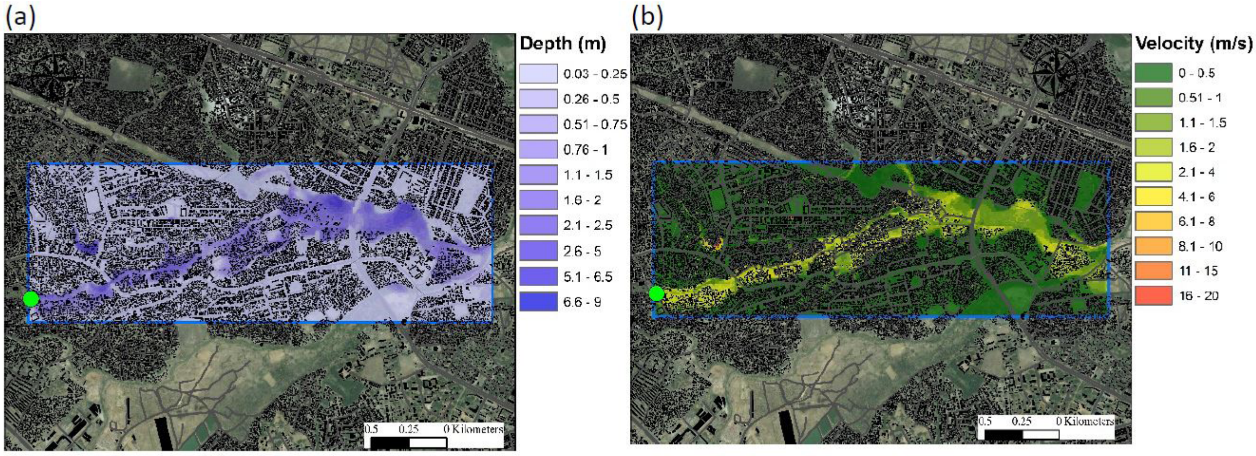

Figure A1. 11. Inundation results for the second sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

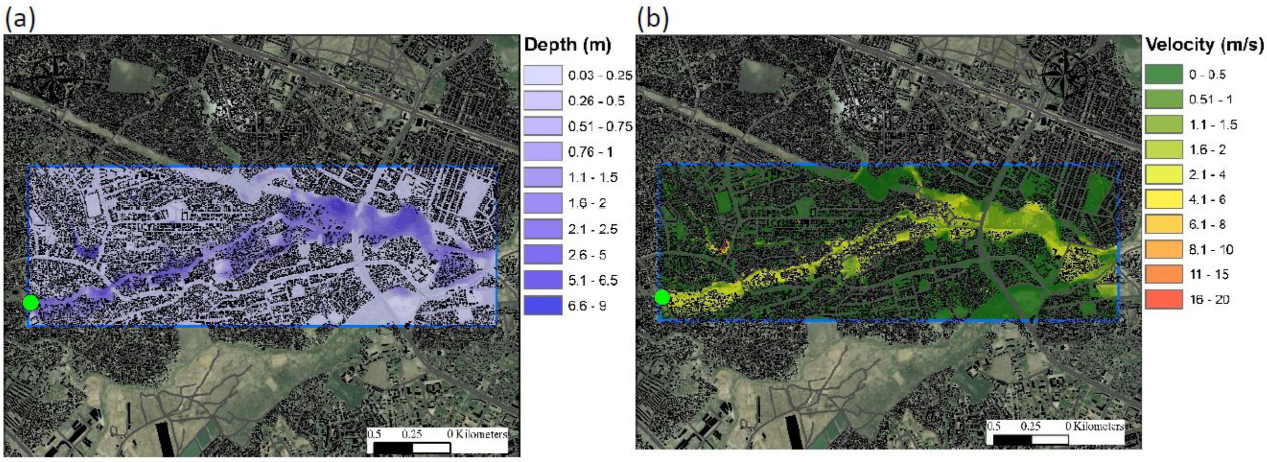

Figure A1. 12. Inundation results for the second sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Third sub-domain Third sub-domain

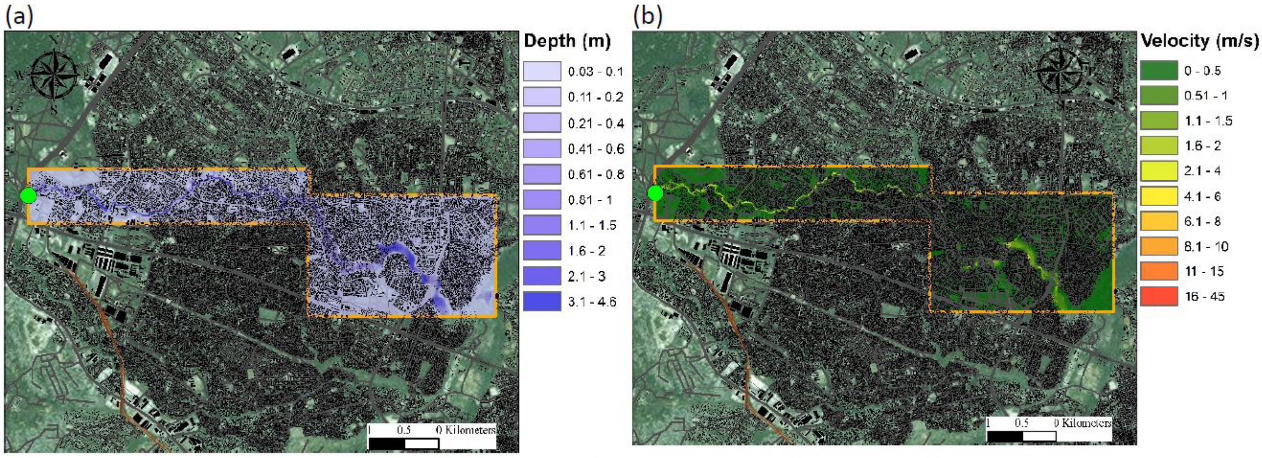

Figure A1. 13. Inundation results for the third sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

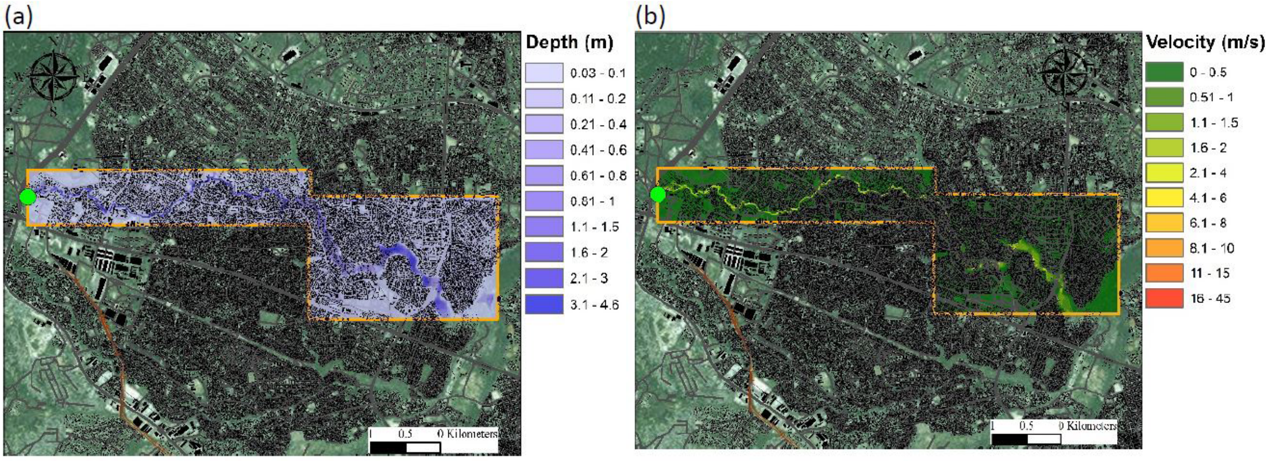

Figure A1. 14. Inundation results for the third sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

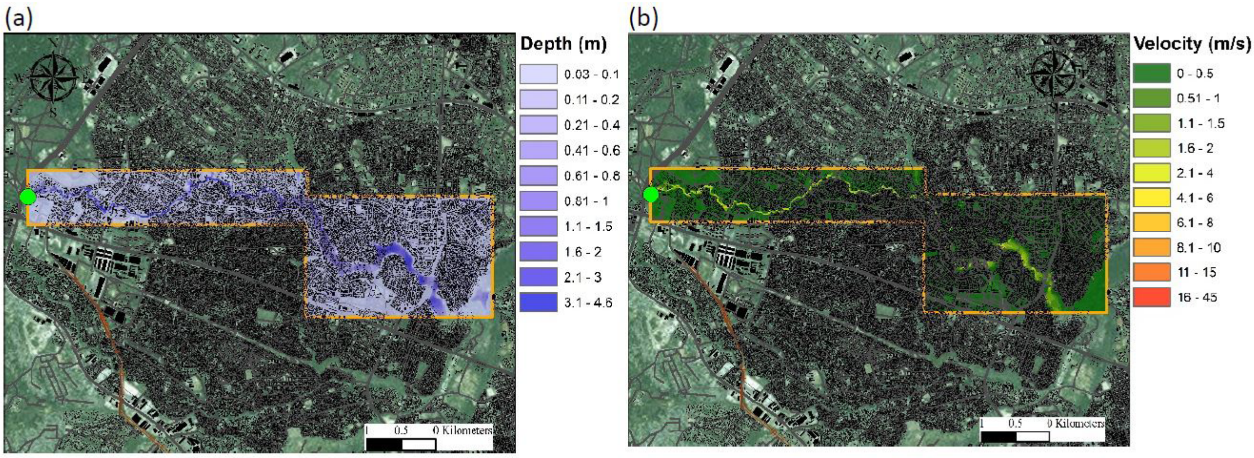

Figure A1. 15. Inundation results for the third sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

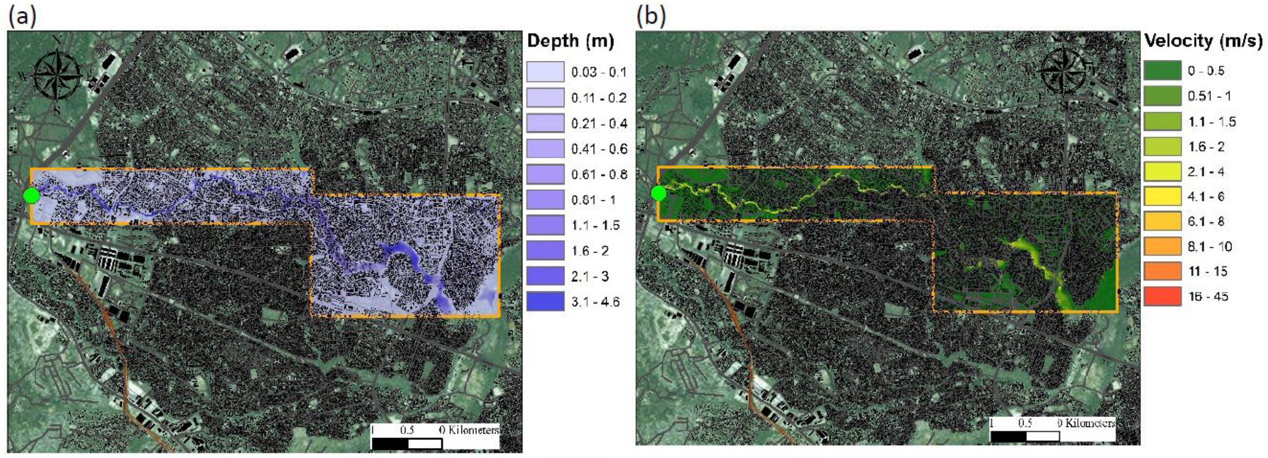

Figure A1. 16. Inundation results for the third sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

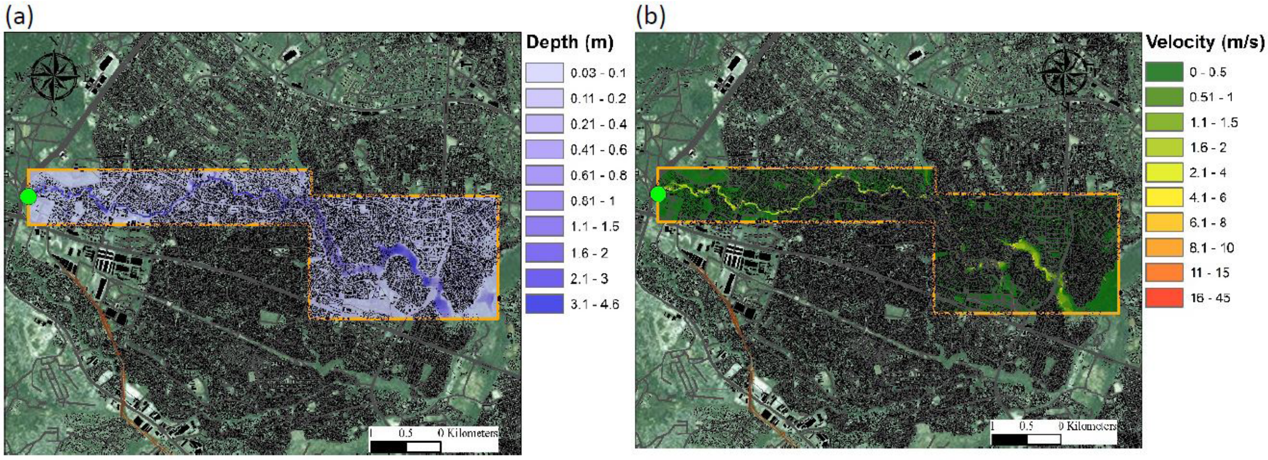

Figure A1. 17. Inundation results for the third sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

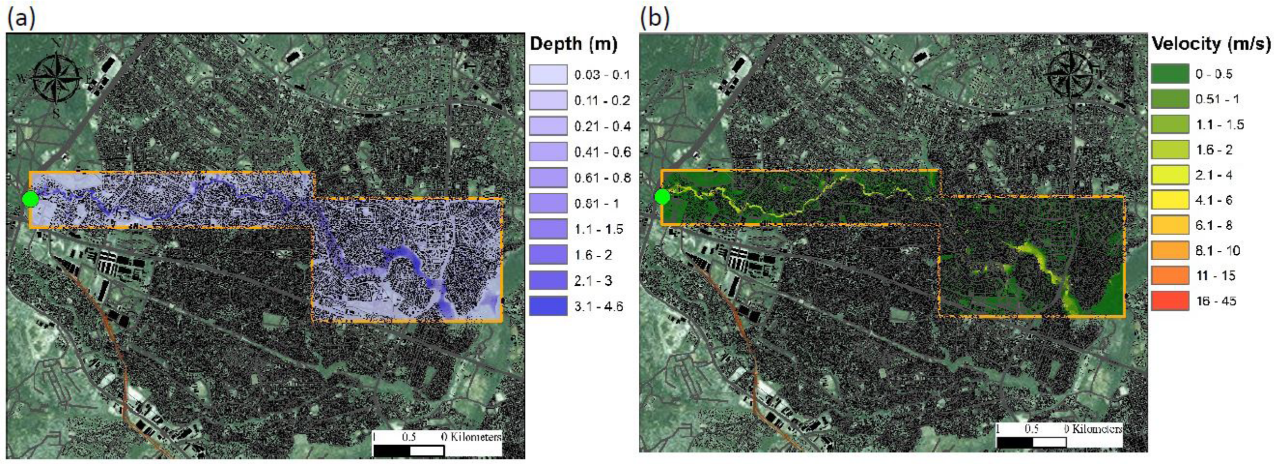

Figure A1. 18. Inundation results for the third sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Fourth sub-domain

(a) (b)

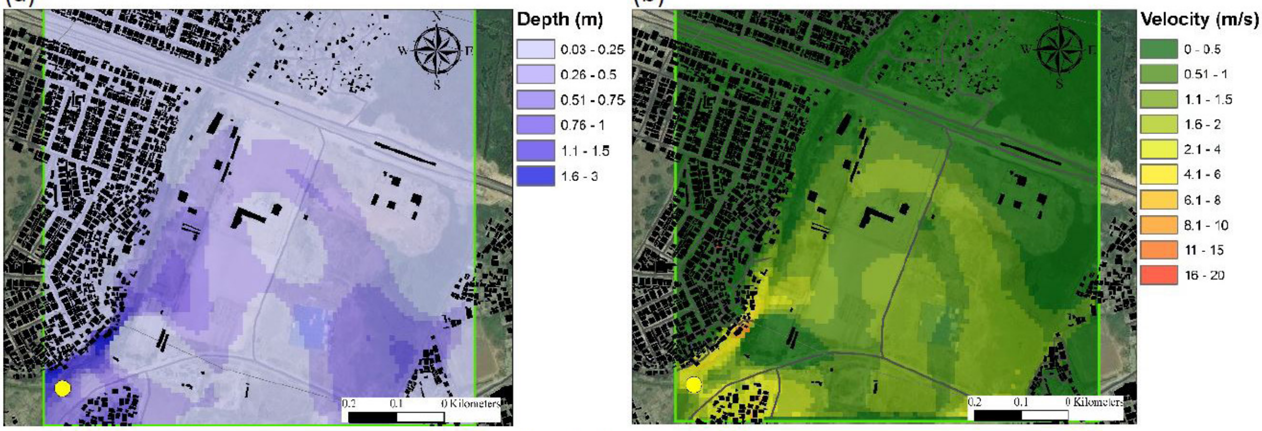

Figure A1. 19. Inundation results for the fourth sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

(a) (b)

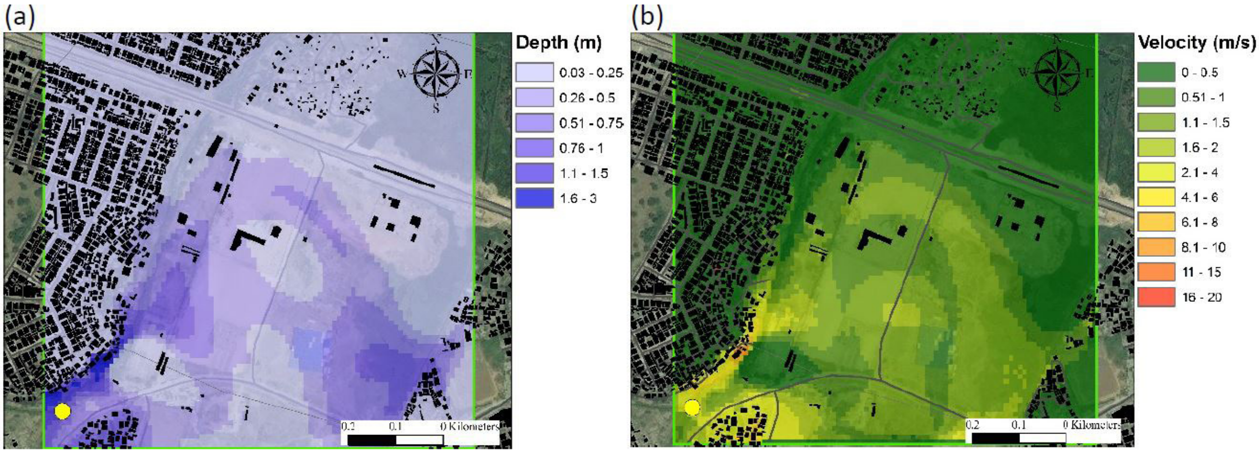

Figure A1. 20. Inundation results for the fourth sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

(a) (b)

Figure A1. 21. Inundation results for the fourth sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

Figure A1. 22. Inundation results for the fourth sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

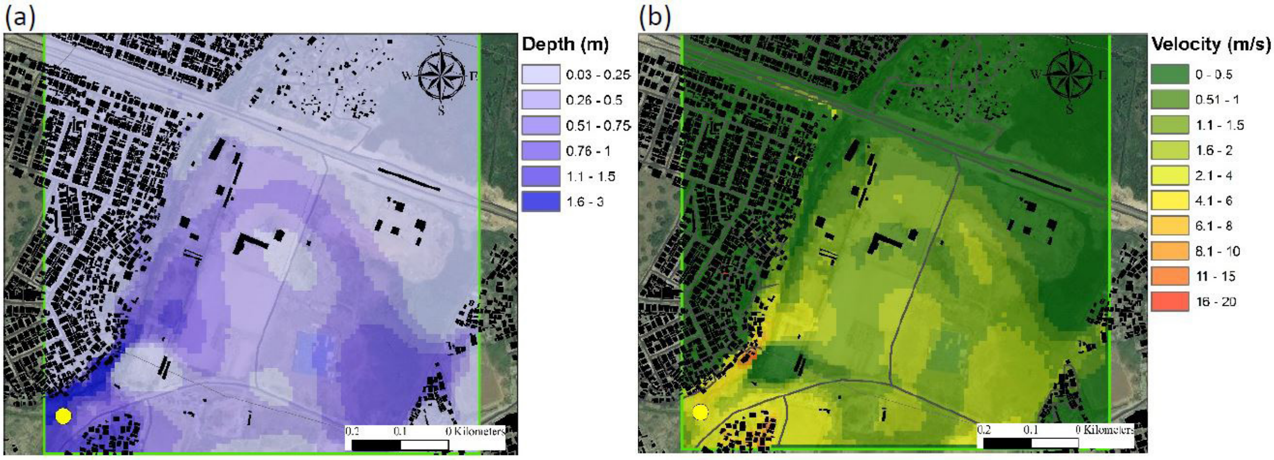

Figure A1. 23. Inundation results for the fourth sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

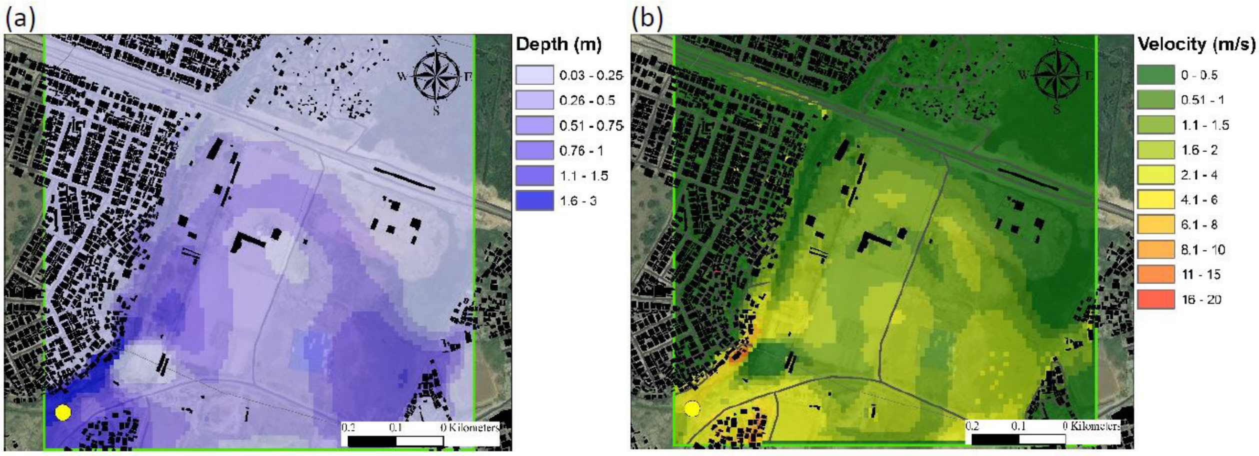

Figure A1. 24. Inundation results for the fourth sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Fifth sub-domain

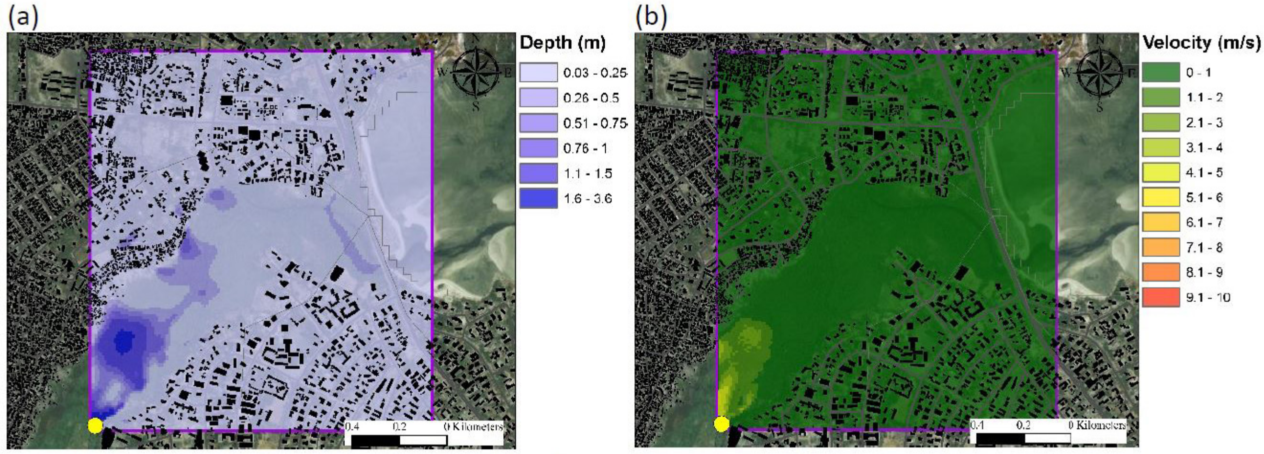

Figure A1. 25. Inundation results for the fifth sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

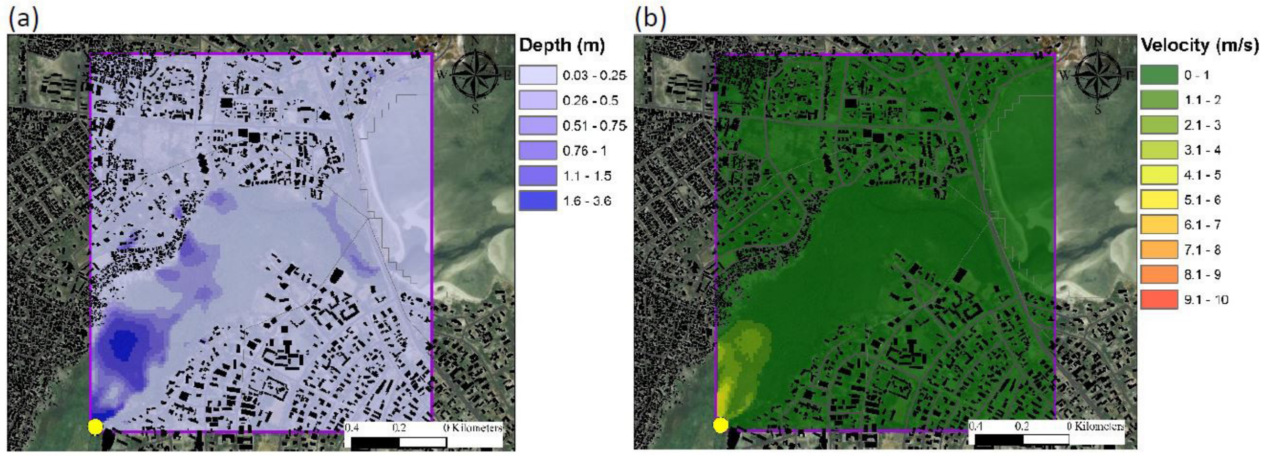

Figure A1. 26. Inundation results for the fifth sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

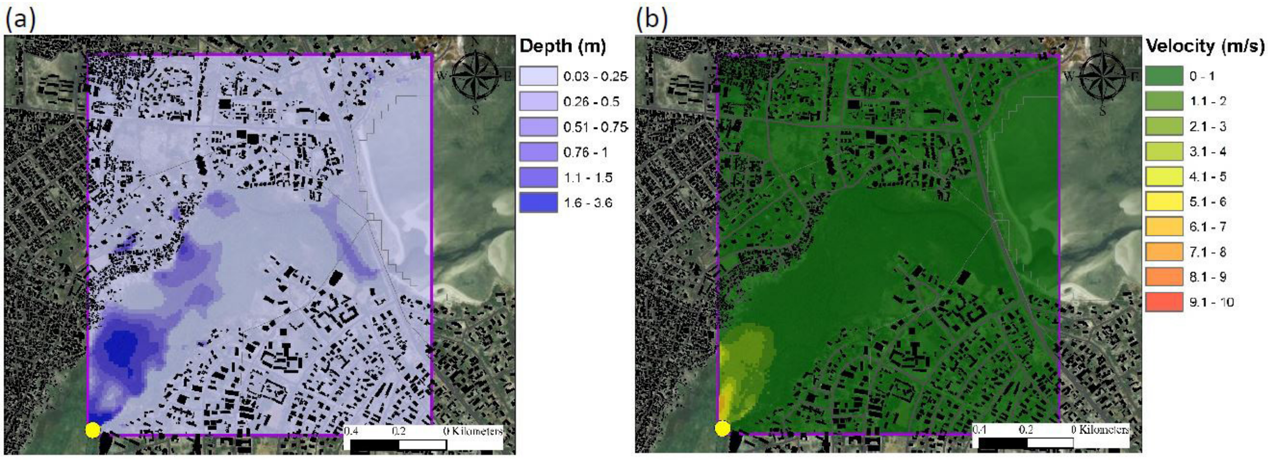

Figure A1. 27. Inundation results for the fifth sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

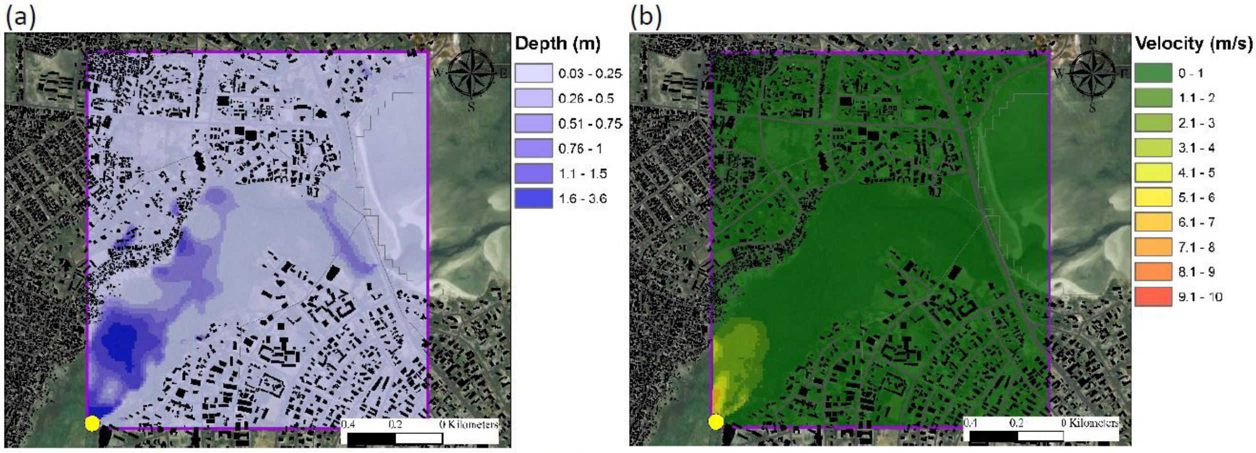

Figure A1. 28. Inundation results for the fifth sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

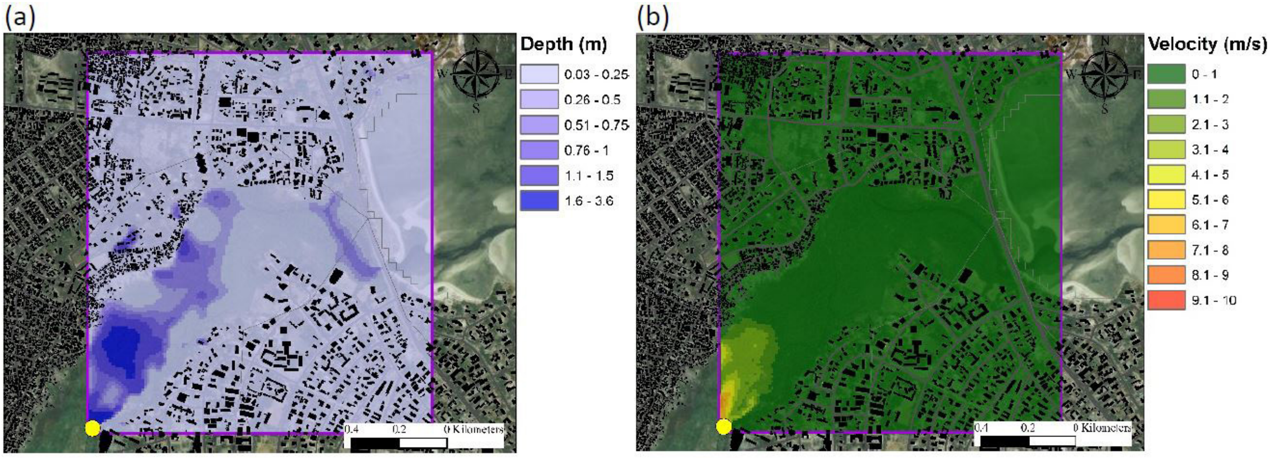

Figure A1. 29. Inundation results for the fifth sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

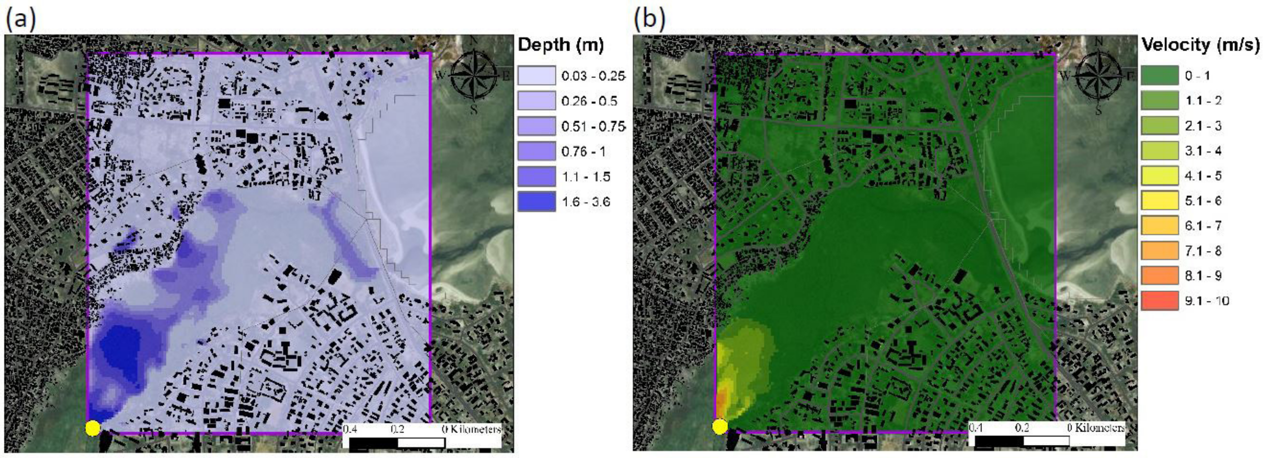

Figure A1. 30. Inundation results for the fifth sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

APPENDIX II. BUILDING COST ESTIMATES

In this appendix the costs used to estimate the total potential losses for the buildings affected by flooding is presented.

Two main sources have been used: the National Construction Council of Tanzania (www.ncc.org.zm) and the 26th edition of annual African Property and Construction Handbook (http://www.coolrooftoolkit.org/wp-content/uploads/2014/07/AEcom-ConstructionHandbookFinal_v2.pdf) released by AECOM.

Table A2.1 lists the unit construction cost for different building typologies in Dar es Salaam.

Table A2.1 Unit construction costs for different building typologies in Dar es Salaam

Building type	Unit cost $/m^2
Swahili house	100
Bungalow, corrugated iron sheet roofing	120
Bungalow, tiled roof	150
Bungalow, slab roof	180
Maisonette double storey, slab roof	170
Flats	150
Residential average multi-unit high-rise	667
Residential Luxury unit high rise	894
Residential Individual prestige house	964
Commercial Standard office high rise	823
Commercial Prestige office high rise	1041
Commercial Major shopping centre	765
Industrial light duty factory	616
Industrial heavy duty factory	1100
Car park	490

Table A2.2 Unit construction costs for different Hotels Dar es Salaam

Building type	Unit cost $/key
Budget	90,000
Midmarket	210,000
Upscale	280,000

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APPENDIX III. CHARACTERIZATION OF THE BUILDINGS IN THE FLOOD PRONE AREA

The breakdown of the buildings in the flood prone area are shown in the following tables according to their characteristics.

Table A3.1 Breakdown according to the OpenStreet information

Type	Number of buildings in flood prone area
Apartments	2
Commercial	219
Commercial / Residential	357
Construction	177
House	6
Industrial	4
Mosque	1
Public	24
Residential	8887
School	9
Utility	1
Not available	3057

Table A3.2 Breakdown according to the UMT information (Generic)

Type	Number of buildings in flood prone area
Dwelling	11319
Feeder Road	8
Green Belt	745
Hazard Land	384
Horticulture	15
Industrial	160
Play Ground	8
Primary School	4
Religious	12
Residential/Commercial	80
Not available	9
Not available	3057

Table A3.3 Breakdown according to the UMT information (Specific)

Type	Number of buildings in flood prone area
Education & culture	4
Horticulture	15
Major road corridor	8
Mangrove	12
Manufacturing	169
Mixed	7655
Mud/wood/sand brick construction	2423
Other open space	8
Religion	12
Riverine	1565
Villa & single story stone/concrete	873
Not available	3057

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APPENDIX IV. FLOODPLAIN STRUCTURAL IDENTIFICATION AND BUILDING COSTS

In this appendix, the criterion adopted for the structural identification and for the cost assessment is reported. Such criterion is based on the analysis of all the potential combination of the characteristics reported in Appendix 2 and 3. Sixty-two potential combination are recognized and interpreted in terms of structural typology and building unit costs.

Three main structural typology are identified: IM (i.e. informal masonry), FM (i.e. formal masonry), and RCF (i.e. reinforced concrete frame). These are used in the vulnerability assessment.

Because of the degree of uncertainty on the typology identification, the types of buildings used to estimate the costs of resettlement were reduced to six types (Table A4.2).

Table A4.1 Structural identification and cost assessment criterion

Characteristics	Structural Typology	Unit Cost
$/m2		
Apartments + Green Belt + Riverine	IM	120
Commercial + Dwelling + Mixed	RCF	745
Commercial + Dwelling + Mud/wood/sand brick construction	IM	471
Commercial + Dwelling + Villa & single storey stone/concrete	FM	487
Commercial + Feeder + Road Major road corridor	FM	487
Commercial + Green + Belt Riverine	FM	487
Commercial + Hazard + Land Riverine	IM	120
Commercial + Industrial + Manufacturing	RCF	858
Commercial/residential + Dwelling + Mixed	FM	487
Commercial/residential + Dwelling + Mud/wood/sand brick construction	IM	471
Commercial/residential + Dwelling + Riverine	IM	471
Commercial/residential + Dwelling + Villa & single storey stone/concrete	FM	487
Commercial/residential + Feeder + Road Major road corridor	FM	487
Commercial/residential + Green Belt + Riverine	IM	471
Commercial/residential + Hazard + Land Riverine	IM	471
Commercial/residential + Play Ground + Other open space	FM	487
Commercial/residential + Primary School + Education & culture	FM	487
Commercial/residential + Residential/Commercial + Mixed	IM	471
Construction + Dwelling + Mixed	IM	120
Construction + Dwelling + Mud/wood/sand brick construction	IM	120
Construction + Dwelling + Riverine	IM	120
Construction + Dwelling + Villa & single storey stone/concrete	FM	150
Construction + Green Belt + Riverine	IM	120
Construction + Hazard Land + Mangrove	IM	120
Construction + Hazard Land + Riverine	IM	120
Construction + Industrial + Manufacturing	RCF	858
House + Dwelling + Mixed	IM	120
House + Green Belt + Riverine	IM	120
Industrial + Green Belt + Riverine	RCF	858

Table A4.1 Structural identification and cost assessment criterion (continued)

Characteristics	Structural Typology	Unit Cost
Industrial + Industrial + Manufacturing	RCF	858
Mosque + Dwelling + Mixed	FM	150
Public + Dwelling + Mixed	FM	150
Public + Dwelling + Mud/wood/sand brick construction	IM	120
Public + Dwelling + Villa & single storey stone/concrete	FM	150
Public + Hazard Land + Riverine	IM	120
Residential + Dwelling + Mixed	IM	120
Residential + Dwelling + Mud/wood/sand brick construction	IM	120
Residential + Dwelling + Riverine	IM	120
Residential + Dwelling + Villa & single storey stone/concrete	FM	150
Residential + Feeder + Road Major road corridor	IM	120
Residential + Green Belt + Riverine	IM	120
Residential + Hazard Land + Mangrove	IM	120
Residential + Hazard Land + Riverine	IM	120
Residential + Industrial + Manufacturing	RCF	858
Residential + Play Ground + Other open space	IM	120
Residential + Primary School + Education & culture	FM	150
Residential + Religious + Religion	FM	150
Residential + Residential/Commercial + Mixed	IM	471
School + Dwelling + Mixed	IM	120
School + Dwelling + Mud/wood/sand brick construction	IM	120
Utility + Dwelling + Mixed	FM	150
Not Available + Not Available + Manufacturing	RCF	858
Not Available + Not Available + Villa & single storey stone/concrete	FM	150
Not Available + Dwelling + Mixed	IM	120
Not Available + Dwelling + Riverine	IM	120
Not Available + Dwelling + Villa & single storey stone/concrete	FM	150
Not Available + Green Belt + Riverine	IM	120
Not Available + Hazard Land + Riverine	IM	120
Not Available + Horticulture + Horticulture	IM	120
Not Available + Industrial + Manufacturing	RCF	858
Not Available + Residential/Commercial + Mixed	IM	471
Not Available + Residential/Commercial + Riverine	IM	471

Table A4.2 Unit construction costs for different building typologies in Dar es Salaam

Building type	Mean of following types in D-1	Unit cost \$/m²
Informal Masonry residential	Bungalow, corrugated iron sheet roofing	120
Formal Masonry residential	Bungalow, tiled roof; Flats	150
Informal Masonry commercial	Bungalow, corrugated iron sheet roofing; Commercial Standard office	472
Formal Masonry commercial	Bungalow, tiled roof; Flats; Commercial Standard office	374
Reinforced Concrete Frame commercial or residential	Residential average multi-unit high-rise; Commercial Standard office high rise	745
Reinforced Concrete Industrial	Industrial light duty factory Industrial heavy duty factory	858

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APPENDIX V. URBAN STORMWATER MANAGEMENT OPTIONS

Passive engineering measures to improve conveyance

These measures are designed to protect areas from flooding by avoiding or mitigating the water flow off stream over the riverbanks, or accommodating the flood adjusting the riverbed carrying out channel improvement. Therefore, these kinds of measures try to constrain the inundation without modification of the hydrograph. Examples are levees, cleaning from debris or increasing of section of the riverbed, and hydraulic bypass, also known as waterways. They involve physical construction to reduce or avoid possible impacts of hazards, or application of engineering techniques to achieve hazard-resistance and resilience in structures or systems. These kind of measures alter the streamflow of rivers and channels, resulting in the reduction of the frequency and severity of floods. For example, reservoirs reduce peak flows; levees and flood walls confine flows within predetermined channels; improvements to channels reduce the peak stages; and flood ways help divert excess flow.

A5.1.1 Drains and swales

These convey flows from built-up areas via small channels, and can generally deal with small floods of 1-2 year return period.

A5.1.2 Enlargement of river channel/canalisation/levees/dredging

Excavation of a river channel involves either deepening or widening the channel to increase flood control capacity. A river can be made to carry larger discharges by improving the hydraulic condition of the channel through measures such as dredging. Similarly, levees (embankments) can be built to increase the conveyance capacity of the channel.

Levees are generally built as an embankment (i.e. earthwork). In the urban context, if there is not enough land area to build such earth structures, then they are constructed with reinforced concrete or masonry walls. The levees location is designed according to the inundation analyses; their scope is to prevent the inundation of floodplain. Their height is designed to prevent the inundation associated to a specific return period. Once the height is defined, their design will follow geotechnical rules if they are made with earth, or structural rules if they are concrete walls. To analyse the efficiency of such structures, they are modelled in the hydraulic routine as a modification of the digital elevation model.

A5.1.3 Hydraulic bypass

A hydraulic bypass is a new channel built to laminate the peak discharge crossing the floodable area in the urban context. The new channel takes part of the discharge and brings it to the final destination through an alternative path. Construction of a hydraulic bypass is very expensive and requires the identification of the alternative path for the new channel.

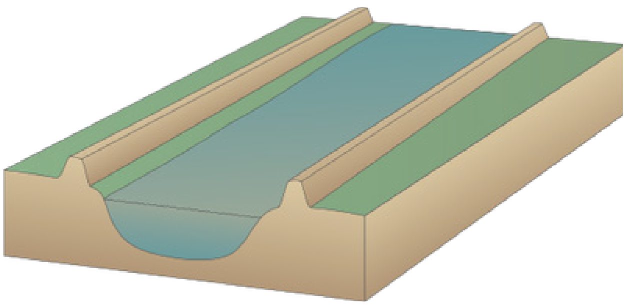

Figure A5.1 Schematic representation of levees at two side of the watercourse

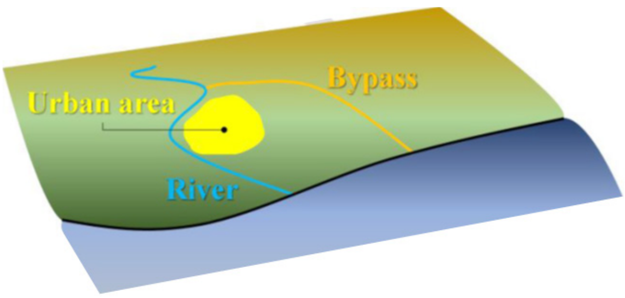

Figure A5.2 Schematic representation of a hydraulic bypass

A5.2 Active engineering measures to retard runoff

The active structural measures are to modify the hydrograph by reducing and delaying the maximum peak discharge. Examples include floodplain storage (in-line or off-line) that stores the flood volume temporarily in an adequate upstream capacity, leading to flood attenuation as a result of the discharge being gradually released (Topa *et al.* 2014). When the discharge falls below the maximum allowable flow, the flood volume is released back to the river (De Martino *et al.* 2012). Off-stream floodplain storages are often used since they do not interfere with the natural drainage pattern between the stream and the floodplain, and only an outlet structure is needed to regulate the outflow discharge.

A5.2.1 Permeable pavements

Permeable pavements refer to pavements that are constructed in such a way that they promote the infiltration of stormwater runoff through the surface into the sub-layers or underlying substrata (Armitage *et al.* 2013). Permeable paving provides a surface that is suitable for pedestrian and/or vehicular traffic while allowing rainwater to infiltrate through the surface. There are a number of different alternatives for the surface material, including brick pavers, porous concrete, porous asphalt, stone chip, and permeable concrete block pavers (Armitage *et al.* 2013). Permeable paving is usually constructed on top of a coarse gravel base which creates the temporary storage facilities and allows stormwater runoff to infiltrate into the substratum, ultimately promoting the recharge of the groundwater table. The stored rainwater can also be reused for a number of purposes such as watering gardens and lawns (Armitage *et al.* 2013).

Permeable pavements generally do not remove litter and other debris from stormwater runoff as it tends to remain on the surface as the water infiltrates. Soluble pollutants, however, do pass through the permeable layer and surfaces that have an aggregate sub-base can provide good water quality treatment. Permeable paving can be used in a variety of locations, such as parking lots, private and public roads, industrial storage and loading areas, bike lanes, walkways and terraces (Armitage *et al.* 2013). The use of this paving is however restricted to slopes that are less than 5%, or ideally flat, as the high velocity stormwater from steep slopes does not have sufficient time to infiltrate before being washed away.

To ensure the long term effectiveness of permeable pavements regular inspections and maintenance are recommended. Blockage of the fine stone aggregate can sometimes be an issue and requires cleaning or replacing if this does occur. This fine aggregate in the joints and slots is known to trap the most pollutants, including heavy metals. While clogging may be a maintenance concern, the often enormous infiltration capacity of permeable pavement systems means that considerable clogging can be tolerated (Armitage *et al.* 2013).

Permeable pavements are relatively expensive to construct and can have high maintenance costs. However, they are incredibly efficient at reducing peak flows and reducing runoff volume as well as reducing pollutants. They remove approximately 60-95% of TSS, 70-90% of hydrocarbons, 50-80% of total phosphorous, 65-80% of total nitrogen and 60-95% of heavy metals (Armitage *et al.* 2013). Permeable pavements do not provide any amenity, social or ecological benefits.

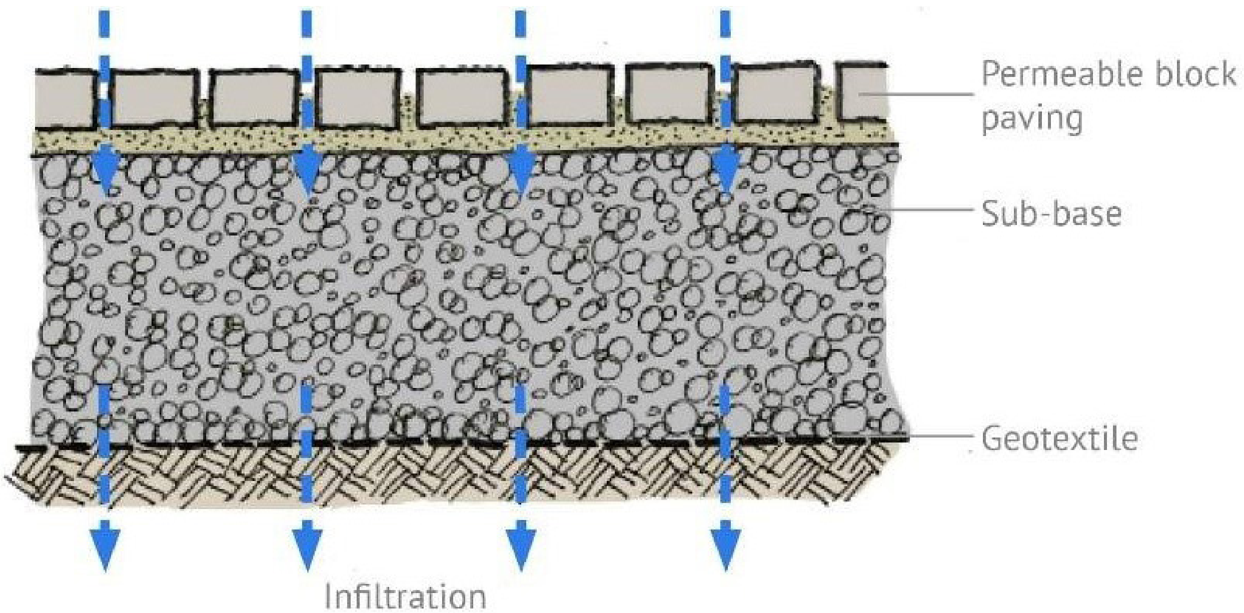

Figure A5.3 Permeable paving allows water to soak into the gravel sub-base, temporarily holding the water before it soaks into the ground, or passes to an outfall

Source: susdrain, www.susdrain.org

Advantages	Limitations
Significantly reduce stormwater discharge rates and volumes from impervious areas	Cannot be used where large sediment loads may be washed or carried onto the surface of the paving
Reduce peak flows to watercourses reducing the risk of flooding downstream and reduce the effects of pollution in runoff on the environment	The implementation is generally limited to sites with slopes less than 5%
Flexible and tailored solution that can suit the proposed usage and design life	Risk of long-term clogging and weed growth if poorly maintained
Allows for dual use of space, so there is no additional land take. They increase the 'usable' area by utilising roadways, driveways and parking lots as stormwater drainage areas	Not normally suitable for high traffic volumes and speeds greater than about 50 km/hr, or for usage by heavy vehicles and/or high point loads
Good community acceptability	The pollutant removal ability of permeable pavements is lower than most other SuDS options.
Stormwater runoff that is stored can be used to recharge the groundwater table and also be used for several domestic purposes	
Lined permeable pavement systems can be	
utilised where foundation or soil conditions	
limit infiltration processes	

Advantages	Limitations
Increases stormwater infiltration and corresponding groundwater recharge	If situated in coarse soil strata, groundwater contamination is a possibility
Decrease the frequency and extent of flooding	Restricted to areas with permeable soils
Effective in removing suspended particulates from stormwater	Not appropriate on unstable or uneven land, or on steep slopes
Due to their relatively narrow cross section, they can be utilised in most urban areas	Prone to failure if sediment, debris and/or other pollutants are able to clog the gravel surface and/or
backfilled aggregate material	The pollutant removal ability of permeable pavements is lower than most other SuDS options.
Negligible visual impact as they are generally below ground	
Lined permeable pavement systems can be	
utilised where foundation or soil conditions	
limit infiltration processes	

A5.2.2 Infiltration trenches

Infiltration trenches are excavated trenches which are lined with geotextile and filled with rock, or other granular materials, and are designed to receive stormwater runoff from contiguous properties in urban areas (Armitage *et al.* 2013). They create temporary subsurface storage of stormwater runoff thereby enhancing the natural capacity of the ground to store and drain water. Infiltration trenches allow water to infiltrate into the surrounding soils from the bottoms and sides of the trench. They usually have a rectangular vertical cross-section and are designed to receive stormwater runoff from adjacent properties and transportation links such as asphalt roads and footpaths (Armitage *et al.* 2013). The amount of water that can be disposed of by an infiltration trench within a specified time is dependent on the infiltration potential of the surrounding soil, the size of the trench, and the bulk density of the fill material. Stormwater runoff is treated by physical filtration to remove solids, adsorption onto the material in the trench and biochemical reactions involving micro-organisms in the soil.

In the first year of construction maintenance is important, especially after the first large rainfall event. The trench needs to be assessed for performance and any sediment and debris build up which can cause clogging (Armitage *et al.* 2013). Removal and cleaning of stone may be necessary.

The construction costs associated with infiltration trenches are not very high, making them one of the more cost effective options in terms of their ability to reduce runoff volume and treat pollutants. Their maintenance costs can be higher than other interventions, especially in areas that have fine grained soils. Infiltration trenches remove approximately 70-80% of TSS, 60-80% of total phosphorous, 25-60% of total nitrogen, and 60-90% of heavy metals (Armitage *et al.* 2013). Their amenity and conservation value is poor, however they are generally constructed under the ground and so the aesthetic impact is negligible.

A5.2.3 Soakaways (sub-surface infiltration trenches)

Soakaways usually comprise an underground storage area that is packed with course aggregate or other porous media that gradually discharges stormwater into the surrounding soil (Armitage *et al.* 2013). Soakaways are similar to infiltration trenches in their operation and are also known as sub-surface infiltration beds or sub-surface infiltration trenches). They usually handle roof runoff from single buildings, such as large industrial buildings. Multiple soakaways can be linked to each other to drain larger areas such as parking lots or major roadways. The type of aggregate material used determines the infiltration characteristics of the device. Modular geo-cellular structures provide relatively high stormwater treatment and rates of groundwater recharge (Armitage *et al.* 2013).

The size of the soakaway is dependent on the porosity of the aggregate used to fill the excavated pit. The soakaway empties either by percolation of the stormwater directly into the underlying soil or via perforated sub-drains installed within the pit. Soakaways are usually designed to store the entire volume from a design storm and be able to infiltrate at least half of this volume within 24 hours to create further capacity for the runoff from subsequent rainfall events (Armitage *et al.* 2013). A single soakaway can serve an area of roughly 1000 m^2 but groups of soakaways can serve areas as large as 100 000 m^2 (Armitage *et al.* 2013). They range in depth from between 1 – 4 metres but are usually approximately 1.5 metres in depth when serving a single building.

The basic construction costs include clearing and removing of topsoil, surface bed preparation, pit excavation, supplying and laying filter fabric or geotextile, supplying and laying of aggregate fill or porous media, supplying and laying of building sand, supplying and laying of slotted pipes, top soiling of verged areas, and grassing of surface area.

The amount of water disposed of by soakaways depends on the infiltration potential of the surrounding soil, the size of the pit and the bulk density of the fill material. The amount of water retained by a soakaway is based on the roof area of the building and the peak rainfall event (mm) during the flood season. Soakaways are estimated to be retain 70-80% of TSS, 25-60% of total nitrogen, 60-80% of total phosphorous, 60-90% of E.coli and 60-90% of heavy metals. Soakaways are relatively cost-effective in terms of runoff reduction as well as in terms of their ability to remove suspended solids. Their ability to remove dissolved nutrients is not as effective as some other interventions.

Advantages	Limitations
Have reasonable design lives of up to 20 years if maintained properly and relatively easy to construct	Usually limited to relatively small connected areas
Significantly decrease stormwater runoff volume, peak flow and rate	They do not function well when constructed on steep slopes or in unstable areas
Particularly effective in removing particulate and suspended stormwater runoff pollutants	Sub-drain piping systems must be utilised
when soakaways are implemented in very	
fine silt and clay stratum because of the low	
infiltration rates	
Reduce downstream erosion and flooding	Sedimentation within the collection
chambers will cause a gradual reduction in	
the storage capacity	
Minimal net land take	Ecological and amenity value is poor

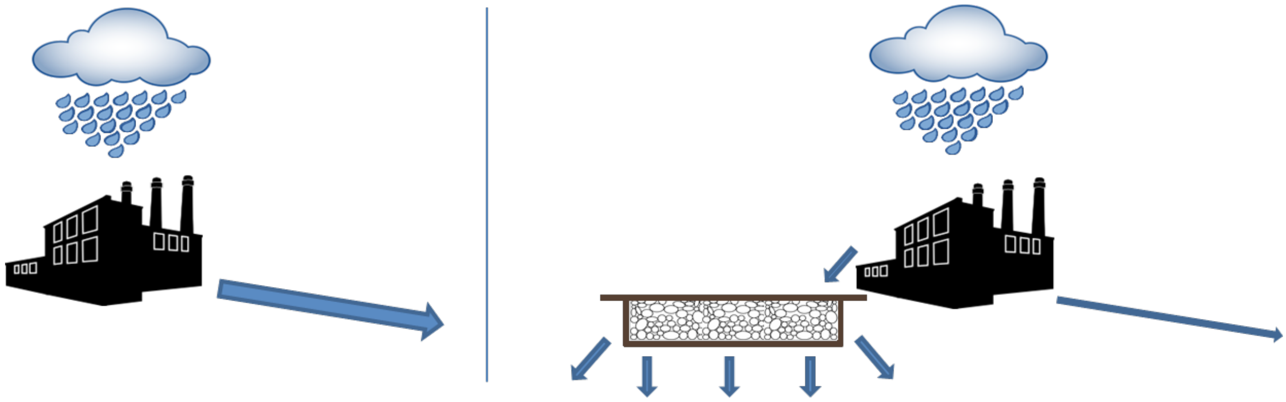

Figure A5.4 Soakaways are square or circular excavations either filled with rubble or other aggregate fill that are able to attenuate and treat significant amounts of stormwater. They can be grouped and linked together to drain large areas such as highways and industrial areas reducing the amount of runoff entering streams and rivers.

A5.2.4 Green roofs

Green roofs comprise a multi-layered system that covers the roof of a building with vegetative cover (Armitage *et al.* 2013). The use of vegetative roof covers and roof gardens is an important source control for stormwater runoff as they are designed to intercept and retain precipitation close to where it falls (i.e. at the source) reducing the volume of runoff and attenuating peak flows. Green roofs provide great benefits in densely urbanised areas where there tends to be less space for some of the other BMP interventions. Green roofs are usually constructed on flat or gently sloping roof tops no greater than 30 degrees. The vegetative layer sits upon a drainage layer which in turn lies upon a water proof membrane to prevent any leakage below (Armitage *et al.* 2013). Green roofs that are constructed in this manner typically have weights of between 40 – 60 kg per m^2. The structural design of the green roof needs to account for the additional weight of the green roof component materials and expected water detention volumes (Armitage *et al.* 2013).

Green roofs are particularly effective when constructed on roofs with large surface areas such as commercial or industrial buildings or large residential blocks. Irrigation may be required to keep the roof green during particularly dry periods.

There are three main types of green roofs, namely: extensive green roofs, intensive green roofs and simple intensive green roofs (Armitage *et al.* 2013). Extensive green roofs generally incorporate low growing and low maintenance vegetation that covers the whole roof surface. The roof is only accessed for maintenance purposes. Usually indigenous vegetation such as mosses, herbs and grasses are used as they are relatively self-sustaining. Intensive green roofs incorporate planters and trees and tend to have a high level of accessibility (Armitage *et al.* 2013). Rainwater harvesting interventions are often used as the primary irrigation source for intensive green roof flora. These roof systems require more intensive and frequent maintenance. Simple intensive green roofs are a combination of both extensive and intensive green roofs, having both larger plants as well as low lying ground cover. These roofs generally require high levels of maintenance such as cutting, fertilizing and watering – which requires increased accessibility (Armitage *et al.* 2013).

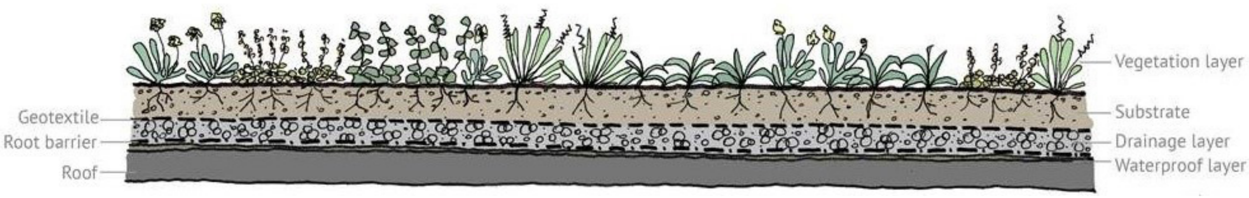

Figure A5.5 Green roofs achieve runoff treatment and infiltration through the construction of vegetative cover on roofs which increases storage, evapotranspiration and attenuation

Source: susdrain, www.susdrain.org

Advantages	Limitations
Good removal capability of atmospherically deposited urban pollutants	More costly than conventional roof-runoff practices due to their added structural, vegetative and professional requirements (professionals are required to ensure implementation of the waterproofing and plant requirements
Can be designed to closely mimic the pre-development state of buildings	Opportunities for retrofitting may be limited by roof structure (size, strength etc.)
Ecological, aesthetic and amenity benefits	Not appropriate for steep roofs
Can be constructed on both new and already existing buildings	Detention of water within green roof storage layer may result in failure to the waterproofing membranes which in turn may cause leakage or cause roof collapse
Help to insulate and regulate buildings against temperature extremes	Plant varieties may be quite limited. Using indigenous vegetation is best
Can be applied to high density urban areas	
May improve air quality	
No additional land take	

Maintenance of green roofs include irrigation during establishment of vegetation, inspection for bare patches, weeds and plants that require replacement. Leaf litter removal may be required for certain systems and any possible stresses related to the roof and building structure need to be checked.

Green roofs are expensive to construct and are one of the least cost-effective options in terms of the cost per unit reduction of runoff volume or pollutant loads. Green roofs remove approximately 60-95% of TSS and 60-95% of heavy metals (Armitage *et al.* 2013). They provide a number of social and aesthetic benefits such as air quality improvement in urban areas, temperature control, and amenity value.

A5.2.5 Rainwater Harvesting

Rainwater harvesting systems collect and store rainfall from hardened surfaces for later use. With minimal treatment the water that is collected could be used to supplement the potable water supply and can be used for a number of activities such as toilet flushing and irrigating crops and gardens (Armitage *et al.* 2013). Storage of runoff from roofs and other elevated impervious surfaces is provided by rainwater tanks, barrels, cisterns or other storage structures until the water is required (Armitage *et al.* 2013). The utilisation of stormwater as a water source not only saves potable water but it also significantly reduces the stormwater discharge from roofs. Rainwater harvesting systems are known to be particularly useful during extreme rainfall events as they help to protect receiving streams and rivers by reducing the initial runoff volumes and the associated polluted (Armitage *et al.* 2013).

There are two types of stormwater collection and reuse systems that are generally applicable to residential, commercial and industrial uses; namely the pumped supply system and the gravity supply system. In Dar es Salaam the gravity supply system would be the most practical. The water collected in the tank from the rooftop is then gravity fed into specified application points in and around the building. The harvesting system could just involve the collection of rainwater from rooftops via gutters into a storage tank where water can then be collected for use. One large tank could be connected to and supply a number of houses.

There are a number of different types of stormwater collection and storage systems that are commercially available. An effective system will include strategically placed roof gutters and pipes, a filter sock to catch leaves/debris, a rainwater storage facility such as a tank or barrel, and a UV disinfection device. Storage facilities that are child proof, insect and vector proof should be given preference during the selection process, especially if the systems are to be placed in residential areas (Armitage *et al.* 2013). The following water balance equation is often used to calculate the volume of usable rainfall or the annual collectable rainfall:

$V = R \times A \times C \times FE$

Where:

V = volume of usable rainwater (l)

R = average rainfall over a period (mm)

A = Area contributing to runoff (m^2)

C = runoff coefficient (0-1)

FE = filter efficiency (0-1)

For a standard flat roof the runoff coefficient is 0.4 and the filter efficiency is generally recommended to be 0.9 as a conservative estimate (Armitage *et al.* 2013).

The initial construction costs associated with the rainwater harvesting system are relatively expensive with the tank constituting the most significant cost. However, maintenance costs can be low and the water that the tanks supply to households is an extremely important benefit, especially in areas where access to running water is limited.

A5.2.6 Vegetated swales

Swales are shallow vegetated channels with flat and sloped sides that are designed to store and convey runoff as well as remove pollutants. Although swales are usually lined with grass, a variety of different types of vegetation can be used to suit the specific site (Armitage *et al.* 2013). Swales serve as an alternative option to the more typical roadside kerb or gutter and generally have a larger stormwater storage capacity so they help to reduce runoff volumes and peak stormwater flows (Armitage *et al.* 2013). Their ability to store and convey significant volumes means that they require relatively large surface areas in order to function effectively.

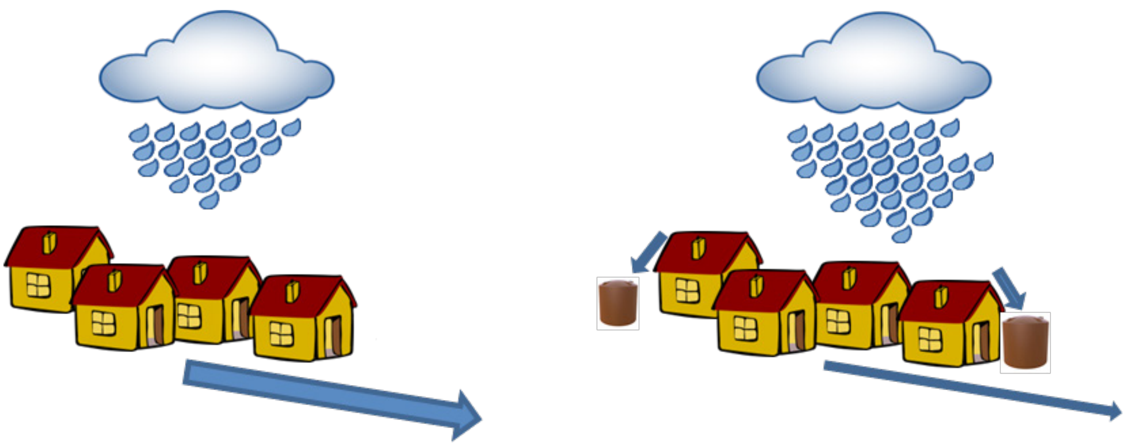

Figure A5.6 Diagram of a rainwater harvesting system. The first picture shows high stormwater runoff with none of the rain being collected whereas the second picture shows how rainfall is trapped and collected from the roofs in tanks and the amount of runoff entering streams and rivers is significantly reduced.

Advantages	Limitations
Can significantly reduce potable water consumption or provides significant amounts of water to those that have no access to potable water	Water quality needs to be monitored and is generally such that the water can only be used for supplementary purposes
Reduces pollutant loads that enter nearby watercourses	Rainwater reuse on a domestic scale is relatively expensive with the storage tanks constituting the most significant cost of the system
Attenuates flood peaks	
Wide variety of storage containers available and generally easy to install	

Swales are commonly used in combination with other systems, such as buffers and bio-retention interventions, to form a treatment train. In doing so runoff is retained and dissolved pollutants in stormwater runoff are also removed. The combination of infiltration and bio-infiltration removes the dissolved pollutants and the larger particles are filtered by the vegetation (Armitage *et al.* 2013). A swale that has been well designed should provide reduction in impervious cover, pronouncement of the surrounding natural landscape and multiple aesthetic enhancements, and they should be designed to meet flow conveyance requirements and effective stormwater pre-treatment (Armitage *et al.* 2013). They are usually suitable for road medians, verges, car parking runoff areas, park and recreational edges.

The effective design life of a swale is directly related to the standard of maintenance, particularly in the first two years during the period of plant establishment which often requires frequent weed control and replanting (Armitage *et al.* 2013). Swales have the potential to manage stormwater indefinitely if they are properly maintained. Maintenance activities tend to include regular mowing of grassed surfaces, weed control, re-seeding of bare ground, frequent clearing of litter and debris, and watering during extended dry periods.

Vegetated swales have low capital costs and are cost-effective in their ability to reduce peak flows and runoff volumes and to reduce pollutants. They have medium to good amenity potential in that they provide a green alternative to grey infrastructure in urban environments. Vegetated swales remove approximately 60-90% of TSS, 70-90% of hydrocarbons, 25-50% of total phosphorous, 30-90% of total nitrogen and 40-90% of heavy metals.

A5.2.7 Filter strips

Filter strips are maintained grassed areas of land that are used to manage shallow overland stormwater runoff through several filtration processes in a very similar manner to buffer strips (Armitage *et al.* 2013). Filter strips are usually gently sloping and provide opportunities for slow conveyance and infiltration. They therefore help to attenuate floods peaks and retain pollutants. They are commonly designed to accept runoff from upstream development and are usually located between hard-surfaced areas and a receiving stream, surface water collection or treatment system. They may also be used downstream of agricultural land to infiltrate and intercept runoff from these areas.

Advantages	Limitations
Usually less expensive and more aesthetically pleasing than kerbs and their associated concrete- and stone-lined channels	Usually require a larger land area than conventional kerb and channel drainage systems
Runoff from adjacent impermeable areas is often completely infiltrated in-situ using swales	Not suitable for steep areas or areas with roadside parking
Reduce stormwater runoff volumes and delay runoff peak flows	Risks of blockages in connecting pipe work
Retain particulate pollutants as close to the source as possible	Limited removal capabilities for soluble pollutants and fine sediment
Easy to incorporate into landscaping with low capital costs	Standing water in swales has the potential to result in the breeding of mosquitoes and the generation of foul odours
Pollution and blockages are visible and easily dealt with	

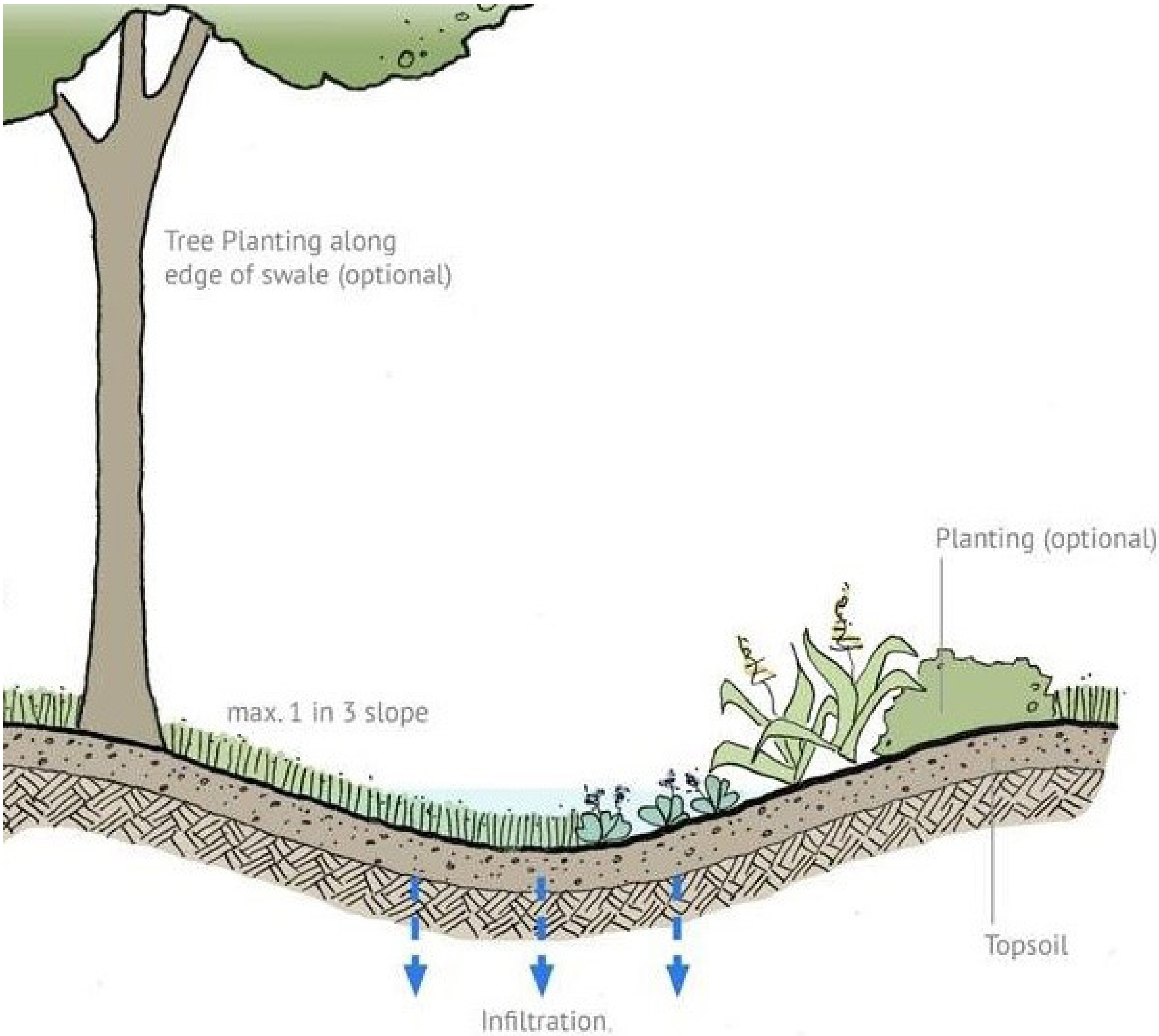

Figure A5.7 Swales are shallow grassed or vegetated channels used to collect and/or move water
Source: susdrain, www.susdrain.org

Filter strips use vegetative filtering as a primary means of stormwater runoff pollutant removal and if properly designed are able to remove most sediment and other settleable solids such as hydrocarbons (Armitage *et al.* 2013). Soluble nutrients and heavy metals, however, are often not adequately removed. The pollutant removal and water retention characteristics of filter strips is determined by the relationship between the length, width, slope and soil permeability compared to the stormwater runoff rate and velocity (Armitage *et al.* 2013).

Filter strips are designed specifically to control for nutrients and pollution more so than water quantity and are therefore more efficient at trapping and reducing TSS and pollutants than they are at reducing stormwater runoff. Grass filter strips remove approximately 50-85% of TSS, 70-90% of hydrocarbons, 10-20% of total phosphorous, 10-20% of total nitrogen and 25-40% of heavy metals.

Advantages	Limitations
Installation and maintenance costs are relatively low and layout and design is flexible	Clogging of subsurface drainage media can occur if maintenance is poor
Significant removal of suspended solids and hydrocarbons. They trap the pollutants close to source	Limited potential for the removal of fine sediments and dissolved pollutants
Infiltration of stormwater runoff helps to attenuate flood peaks	Stormwater runoff needs to be spread out in order for the strips to operate optimally
Integrate well within the natural landscape and can provide open space areas for recreation as well as amenity value	Minimal stormwater storage capacity and not good at treating high velocity flows. They are not suitable for steep slopes.

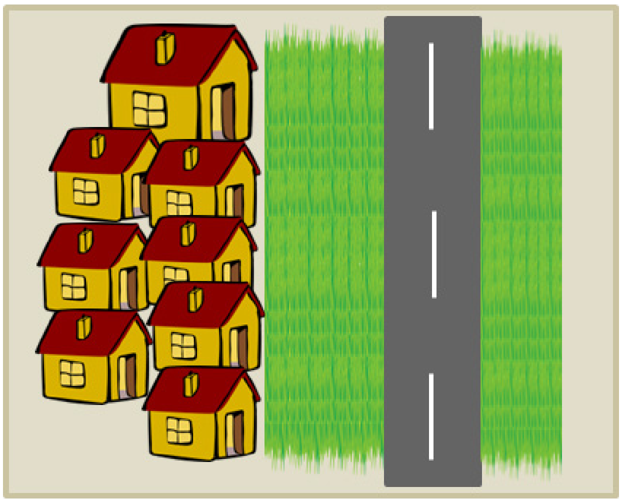

Figure A5.8 Swales are shallow grassed or vegetated channels used to collect and/or move water

Source: susdrain, www.susdrain.org

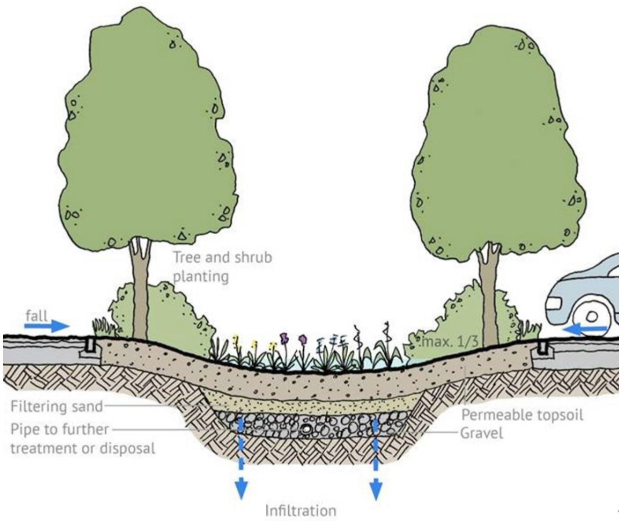

Figure A5.9 Bio-retention areas are landscaped depressions employed to manage runoff by passing it through several natural processes. Rain gardens are an example of a bio-retention area.

Source: susdrain, www.susdrain.org

A5.2.8 Sand filters

There are many different forms of sand filters. They usually comprise of a sedimentation chamber that is linked to an underground filtration chamber comprising sand or other media through which stormwater runoff can pass (Armitage *et al.* 2013). The sedimentation chamber facilitates the removal of suspended particulates and heavy metals, whilst the filtration chamber removes smaller particulate pollutants. The removal mechanism is partly through filtration by the sand bed and partly through microbial action within the media (Armitage *et al.* 2013). Sand filters tend to be installed for use in impervious areas that are less than 8000m^2 but may be designed to manage runoff from larger areas too.

Sand filters are similar to bio-retention areas and other bio-retention systems, with the only difference being that stormwater runoff passes through a linear filter medium without vegetation (Armitage *et al.* 2013). The primary objective for sand filters is water quality improvement and they are particularly effective in the removal of hydrocarbons. They are also used extensively to remove sediment and other particulate pollutants from the first flush (Armitage *et al.* 2013).

Sand filters can be expensive to construct and often require regular maintenace, making them a less cost-effective option. They are highly efficient at removing suspended solids and pollutants. They remove approximately 80-90% of TSS, 50-80% of hydrocarbons, 50-80% of total phosphorous, 25-40% of total nitrogen, 40-50% of E.coli and 50-80% of heavy metals from stormwater runoff (Armitage *et al.* 2013).

Advantages	Limitations
Particularly effective in removing suspended solids (TSS)	Generally ineffective in controlling stormwater peak discharges
Efficient stormwater management technologies in areas with limited space as they can be implemented	Limited potential for the removal of fine sediments and dissolved pollutants
beneath impervious surfaces	Premature clogging is likely to occur in sand filters if they receive excessive sediment carrying runoff, especially from construction sites and areas with open soil patches
They manage stormwater runoff effectively on relatively flat terrains with high ground water tables where bio-retention systems are inappropriate	Large sand filters are not generally attractive, especially if they are not covered with grass or other vegetation
The filtered effluent can be reused for most non-potable domestic water uses including: toilet flushing, dish washing and garden watering; and	Sand filters are expensive to implement and maintain relative to most options technologies
May be retrofitted with relative ease into existing impervious developments, constrained urban locations or in series with conventional stormwater management systems	If designed and/or implemented incorrectly, they may fail, resulting in standing pools of water which have the potential to attract nuisances such as mosquitoes and midges.

Advantages	Limitations
Reduces runoff volumes and rates, and attenuates flood peaks effectively	Not suited to areas where the water table is shallower than 1.8m
Flexible application means these areas are easily incorporated into a wide variety of landscapes	Requires frequent landscaping and maintenance to remain aesthetically pleasing
Very effective at the removal of most stormwater runoff pollutants	Susceptible to clogging if surrounding landscape is not managed
Well-suited for installation in highly impervious areas, provided the system is well-engineered and adequate space is made available	Not suitable for areas with steep slope
Good retrofit capability	Construction costs can be high
Aesthetically pleasing	

A5.2.9 Bio-retention areas

Bio-retention areas, sometimes referred to as ‘rain gardens’ are landscaped depressions which are typically under drained and rely on engineered soils, enhanced vegetation and filtration to remove pollution and reduce runoff downstream (Armitage *et al.* 2013). They are usually employed to manage the runoff from the first 25mm of rainfall by passing runoff through a number of natural processes such as filtration, absorption, biological uptake, sedimentation, infiltration and detention. These areas tend to include a number of different smaller stormwater interventions such as filter strips, temporary pond areas, sand beds, mulch layers and a wide variety of vegetation (Armitage *et al.* 2013). They are particularly effective at managing stormwater runoff from minor and more frequent rainfall events.

Bio-retention areas can manage stormwater runoff on a number of sites, such as between residential plots, alongside parking lots, adjoining roadways and within large landscaped impervious areas. The engineered soil media and the different varieties of vegetation are managed to capture and treat a specified water quality volume of stormwater runoff and in doing so they reduce runoff quantities and rates whilst improving the quality of stormwater entering watercourses further downstream (Armitage *et al.* 2013).

Routine inspections and maintenance are required to ensure that bio-retention areas function effectively. The design life of these areas, as with most interventions, is directly related to the quality and frequency in maintenance (Armitage *et al.* 2013). Maintenance includes regular inspections, litter and debris removal, replacement of mulch areas, vegetation management and sediment removal.

Bio-retention areas can have high initial construction costs, making them less cost-effective in terms of cost per unit reduction of runoff volumes and pollutant loads. They remove approximately 50-80% of TSS, 5-80% of hydrocarbons, 50-60% of total phosphorous, 40-50% total nitrogen and 50-90% of heavy metals (Armitage *et al.* 2013). Their amenity potential is good.

Advantages	Limitations
Able to temporarily store large volumes of stormwater thus attenuating downstream flood peaks	Not very good at removing dissolved pollutants and fine material
Relatively inexpensive to construct and easy to maintain	Generally not as effective in removing pathogens as constructed wetlands
Serve multiple purposes during drier seasons, particularly as sports fields, play parks or commons	Siltation can be a problem and the floors of detention ponds can become swampy for some time after major rainfall
If managed regularly, they can add aesthetic value to adjoining residential properties as well as presenting fewer safety hazards than wet ponds due to the absence of a permanent pool of water.	Not very suitable in areas with a relatively high water table, or where the soil is very coarse and there is a risk of groundwater contamination

A5.2.10 Detention basins

Detention basins or detention ponds are temporary storage facilities that are usually dry but are designed so that they are able to store stormwater runoff for short periods after high rainfall events (Armitage *et al.* 2013). The captured stormwater either infiltrates into the underlying soil layers or is drained into the downstream watercourse at a predetermined rate. Therefore they are effective at regulating the flow in downstream watercourses. Generally detention basins are designed to temporarily store as much water as possible for 24 – 72 hours whilst aiming to provide a safe and secure public environment (Armitage *et al.* 2013).

Detention basins are typically lined with grass and are designed to be multifunctional in that they provide access to recreational area when dry. They are surface storage basins that provide flow control through the attenuation of stormwater runoff and also facilitate some settling of particular pollutants. Detention basins tend to be located towards the end of the stormwater management train so are used if the extended treatment of runoff is required. The pollutant removal capability of a detention basin can be improved through the construction of a sediment trap at the entrance to the basin (Armitage *et al.* 2013).

The hydraulic and pollution removal performance of detention basins depends on good maintenance. Regular inspections are needed to check if the clearing of accumulated sediment is necessary, especially if the basin is being used as a field or common (Armitage *et al.* 2013). Other maintenance includes the management of vegetation, inspections after high rainfall events, and possible de-silting.

Detention basins are relatively inexpensive to construct and have low maintenance costs, making them cost-effective options for control runoff. Detention basins remove approximately 45-90% of suspended solids, 30-60% of hydrocarbons, 20-70% total phosphorous, 20-60% total nitrogen, 50-70% E.coli and 40-90% of heavy metals (Armitage *et al.* 2013).

The strategic positioning of such storage areas in urban areas can enrich the urban environment and facilitate maintenance operations. In fact, such areas, given their dimensions, can be easily used as social and recreation areas, such as play grounds or football fields, or for agriculture. There is a good example of this in San Paolo, Brazil, where floodplain storage has been applied to mitigate the flood risk from the Tamanduateí River, as shown in Error! Reference source not found.b (Giugni *et al.* 2012).

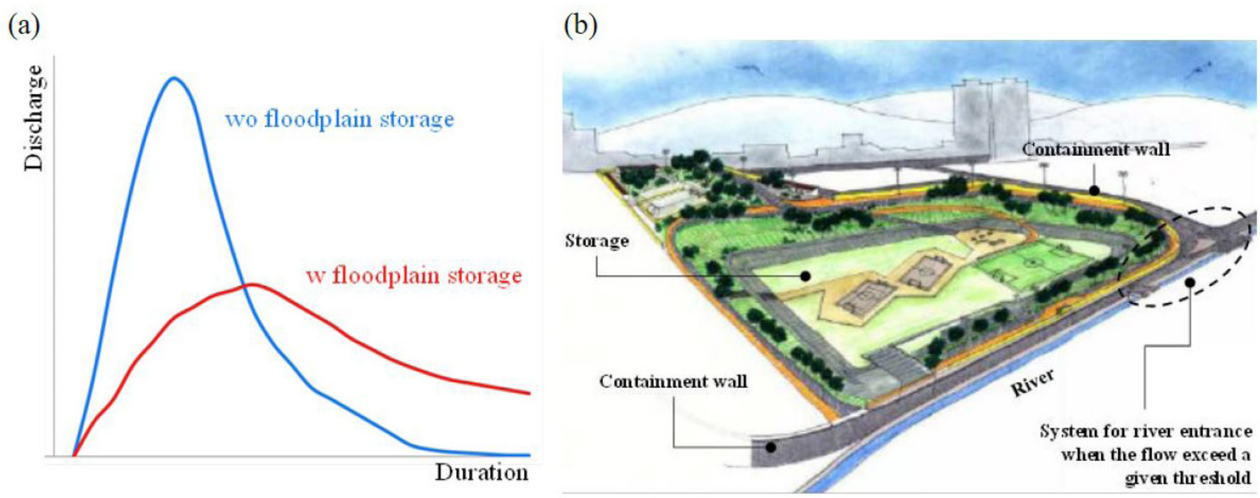

Figure A5.10 (a) Lamination effect due to the flood plain storage and (b) Example of flood plain storage in San Paulo, Brazil
Source: Giugni *et al.* 2012

A5.2.11 Constructed treatment wetlands

Wetlands are generally marshy areas of shallow water that are either partially or completely covered in aquatic vegetation. Wetlands provide habitat for a wide variety of fauna and flora and provide aesthetic appeal, especially in urban areas where green open space is limited. Constructed wetlands are man-made systems that are designed to mimic the natural wetland systems in areas where they were not previously found (Armitage *et al.* 2013).

They are able to serve larger catchment areas and are very useful at removing nutrients and suspended solids from stormwater runoff from residential areas. The most common stormwater pollutant treatment processes that wetlands provide are sedimentation, fine particulate filtration and biological nutrient and pathogen removal (Armitage *et al.* 2013). The percentage removal of pathogens and nutrients depends largely on the pollution concentration of the inflow, the rate at which the water is flowing through the wetland, the pollution saturation level of the wetland and the degree to which the nutrients and pathogens adhere to other particles and sediments (Armitage *et al.* 2013).

Constructed wetlands usually include four distinct zones (Armitage *et al.* 2013):

- The inlet zone which includes a sediment forebay for the removal of the more coarse sediments and litter entering the system;
- The macrophyte zone which is usually shallow and heavily vegetated and facilitates the removal of finer particles and the uptake of soluble nutrients such as nitrogen and phosphorous;
- The macrophyte outlet zone which channels cleaner stormwater runoff downstream; and
- The high flow bypass channel which protects the inlet, outlet and vegetative zones from damage and scour during abnormally high flow events.

Other considerations include litter traps or trash racks at the inlet to the wetland which prevents litter, debris, course sediment and other pollutants from entering the macrophyte zone and from being carried further downstream. The selection of the vegetation to be used in the wetland is important and a number of selection criteria should be considered, such as the speed at which the vegetation establishes itself and grows, the disease or weed risk associated with vegetation, the suitability of the vegetation for the local climate, the tolerance of vegetation to becoming water-logged and the pollutant removal capacity of the various vegetation types (Armitage *et al.* 2013).

Advantages	Limitations
Highly efficient at removing pollutants from stormwater runoff	Wetlands could potentially attract mosquitos and birds whose faeces can increase the amount of phosphorous in the water
May attenuate peak stormwater flows depending on location and design of wetland	Limited to relatively flat land
Good community acceptability and provides amenity value in urban environments	Limited depth range for flow attenuation and little reduction in run volume
	Flooding of the wetland may result in water logging of the plants which may result in die off and a loss in treatment efficiency

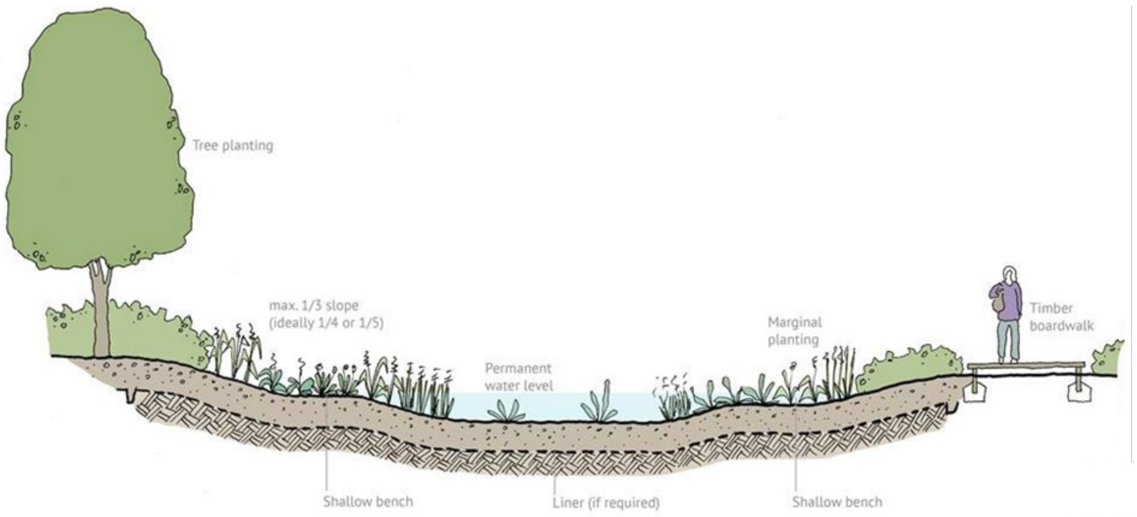

Figure A5.11 Constructed treatment wetlands are man-made systems designed to mimic natural wetland systems
Source: susdrain, www.susdrain.org

Inspection and maintenance of constructed wetlands can be frequent and costly, however can be reduced through effective pre-treatment such as litter traps, trash racks and sediment forebays at the inlet to the wetland (Armitage *et al.* 2013). Maintaining healthy vegetation and adequate flow conditions is essential to the efficient functioning of the constructed wetland and this requires harvesting of the vegetation, such as papyrus or reeds. Once harvested the vegetation can be composted and re-used.

Wetland construction costs can be high when compared to other interventions, however their ability and efficiency in removing nutrients and pollutants makes them relatively cost-effective. They also have the added benefit of providing amenity value. Construction costs per hectare of wetland are exponential, meaning the cost per hectare decreases the larger the wetland. Constructed wetlands are estimated to remove approximately 80-90% of suspended solids, 50-80% of hydrocarbons, 30-40% of total phosphorous, 30-60% total nitrogen, 50-70% E.coli and 50-60% of heavy metals (Armitage *et al.* 2013).

A5.3 Non-structural interventions

Non-structural measures do not involve physical construction but use knowledge, practice or agreement to reduce risks and impacts, in particular through policies and laws, public awareness raising, training and education (Kundzewicz 2002). These include flood warning systems, land use regulations such as development setbacks which identify where development can and cannot occur, or to what elevation structures should locate their lowest habitable floor to; flood proofing and retrofitting of buildings may increase the strength against flood actions; elevation of buildings may avoid completely the inundation. Flood insurance and relocations also belong to this typology of measure. Some of these measures are described in more detail below.

A5.3.1 Sweeping and solid waste management

Interventions such as street sweeping and proper removal and disposal of solid waste help to reduced sediment (and hence pollution) loads entering the drainage system, and help to prevent solid waste from blocking culverts and reducing the efficiency of the conveyance system.

A5.3.2 River cleaning and stewardship

One approach to keeping rivers clear of litter and debris and maintaining a healthy river system is to involve communities that live alongside rivers and streams. Community involvement projects can have multi-sectoral impacts as they generate employment opportunities, provide awareness, safeguard communities and provide city-wide services such as functioning river systems that are clean and clear of litter. Sections of rivers or streams are maintained by cooperatives which are responsible for removing alien vegetation, rubble and any solid waste blocking the free flow of water down the stream or river. They are also responsible for maintaining the grass and other vegetation along the banks of the waterway. The cooperatives generally consist of members of the community that are unemployed and vulnerable and the project focuses on raising awareness and generating employment. Two examples of such projects include the Mlalakua River Restoration Project in Dar es Salaam and the Sihlanzimvelo Stream Cleaning Project in Durban:

- In Dar es Salaam, the **Mlalakua River Restoration Project** was initiated in 2012 and is a multi-stakeholder partnership that has focused on implementing measures that enhance healthy living conditions of the riverine communities, and prevent further pollution on a sustained basis. The Mlalakua River originates from the Mzinga and Kizinga Rivers and drains into Msasani Bay in Kinondoni Municipality. The restoration project forms part of the International Water Stewardship Programme (IWaSP), an international programme for water security managed by the Deutsche Gesellschaft fur Internationale Zusammenarbeit (GIZ). Project activities include physical clean-up of the Mlalakua River, the establishment of sustainable solid waste and wastewater management systems, such as introducing private waste collectors and developing new recycling centres, building capacity of service providers, raising awareness in communities, improving household sanitation, and implementing effective law enforcement measures. Project partners include the Wami River Basin Water Board (WRBWB), National Environment Management Council (NEMC), the local Kinondoni Municipal Council (KMC), Coca-Cola Kwanza, Nabaki Africa, Nipe Fagio, the Bremen Overseas Research and Development Association (BORDA), and GIZ. Donor funding for the initial phase of the project was approximately EUR 400 000. In April 2016 the multi-stakeholder project came to an end with the project being handed over to the Mlalakua Community Change groups which will continue on with improving the health of the river.

- In Durban, the **Sihlanzimvelo Stream Cleaning Project** has been very successful in areas of the municipality where a number of rivers were considered critical in terms of health and functioning. Approximately 470km of degraded river systems were identified and pilot study areas were initiated. Residents of the four communities formed part of the initial pilot study. They were employed to clean and maintain sections of the river adjacent to where they live. This includes unblocking of culverts and the removal of litter and alien vegetation. Grass and vegetation along the riverbed is maintained to a certain height. The results have been impressive and rivers have become cleaner, the risk of flooding has reduced through the removal of litter and debris and the communities feel safer as the areas became more accessible and crime has decreased. Through the project, residents have become more aware of the benefits that are derived from healthy river systems and have an incentive to keep it clean. The Sihlanzimvelo Stream Cleaning Project is funded by the eThekwini Municipality and the South African government's Expanded Public Works Programme (EPWP) and includes a contractor development component. The budget for the project is R45 million (approximately US$3 million). Over the course of the project a total of 732 job opportunities have since been created.

A5.3.3 Riparian buffers

A riparian buffer is a vegetated area, or buffer strip, that is located adjacent to a stream or river channel and is usually forested, which helps to shade and partially protect the waterway from the impacts of adjacent land uses. Riparian buffers play an important role in improving water quality as well as providing stormwater infiltration benefits and conservation value. Riparian buffers are similar to filter strips but differ in that they are generally forested and always occur adjacent to river channels. Filter strips tend to be located in urban areas adjacent to development.

Riparian buffers reduce excess amounts of sediments, organic material, nutrients and pesticides in surface runoff and reduce excess nutrients and other chemicals in shallow ground water flow (Waidler *et al.* 2009). They are also known to reduce pesticide drift entering the water body. With the use of suitable indigenous vegetation, riparian buffers have the potential to provide a habitat corridor for wildlife (Armitage *et al.* 2013).

Advantages	Limitations
Relatively low costs involved in planting and establishing buffer zones	Relatively limited potential for the removal dissolved nutrients
Significantly improve water quality of streams and rivers	
Infiltration of stormwater runoff helps to attenuate flood peaks	
Natural intervention that provides amenity and conservation value.	

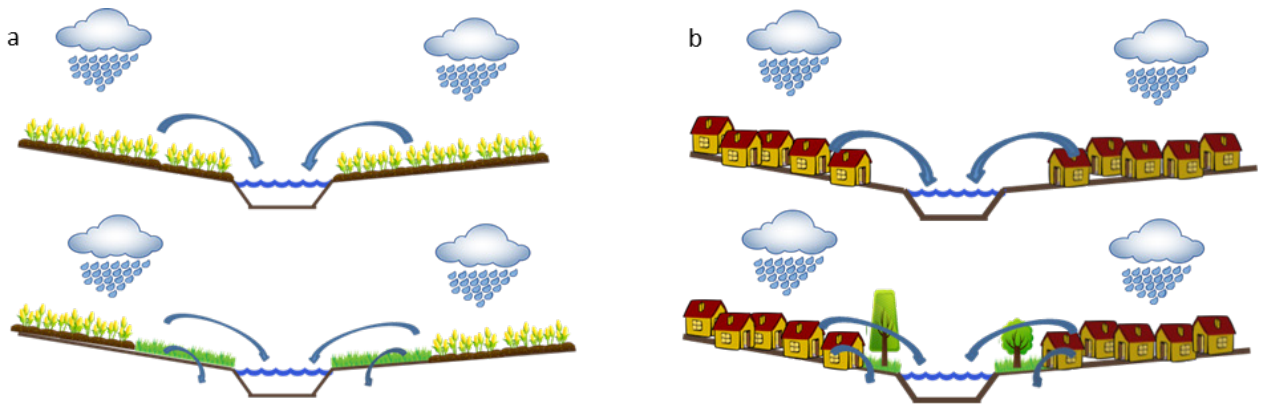

Figure A5.12 Riparian buffers are located adjacent to streams and river channels. They can either be made up of grasses and smaller plants as in picture (a) or they can be densely vegetated with trees and bushes as in picture (b). They provide a buffer between adjacent land uses such as agriculture and residential areas and waterways.

Riparian buffers can be cost-effective in that they require no major engineering or construction. The costs are associated with the purchasing of seedlings and the labour required to plant them. Riparian buffers are efficient at removing suspended solids, hydrocarbons and other pollutants. They are less effective at removing dissolved nutrients such as nitrogen and phosphorus. They contribute to the infiltration of stormwater runoff and therefore attenuate flood peaks.

A5.3.4 Catchment reforestation

Catchment reforestation is an important intervention that does not differ much from the riparian buffer intervention. Catchment reforestation focuses on planting indigenous trees and shrubs within the greater catchment area, in particular in areas that were previously forested. By increasing the number of larger trees and shrubs in the catchment the amount of runoff entering streams and rivers in reduced through trapping and infiltration. Forested areas are well known for their ability to reduce runoff as well as reduce nutrient and pollutant loads entering waterways. Reforestation in the catchment also increases conservation value and amenity value.

The capital costs involved in catchment reforestation are relatively low when compared to other interventions. This is because the intervention involves no engineering or construction work and is based solely on the planting of trees and shrubs. Costs include the buying of seedlings and the labour involved in planting them. Catchment reforestation provides numerous benefits such as amenity and conservation value as well as contributes to providing clean water.

Advantages	Limitations
Relatively low costs involved in planting and re-establishing forested areas	Relatively limited potential for the removal dissolved nutrients
Significantly improve water quality of streams and rivers	
Infiltration of stormwater runoff helps to attenuate flood peaks	
Natural intervention that provides amenity and conservation value.	

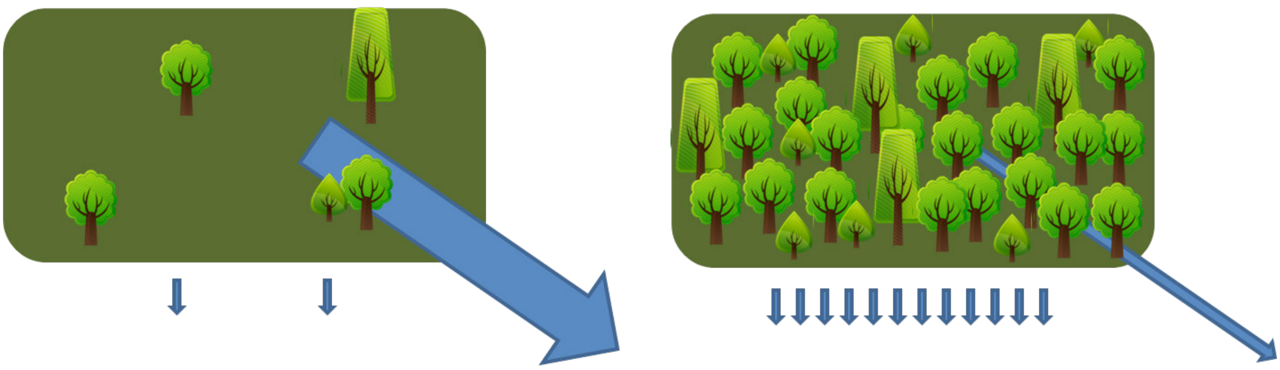

Figure A5.13 Catchment reforestation will aid in runoff infiltration reducing the overall amount of stormwater reaching rivers and streams. Reforestation will also aid in removing sediments and nutrients.

Trees absorb rainfall, slow down flow velocity, disperse surface runoff, offset water discharge, filter pollutants, and reduce excess nutrient and sediment loads into the rivers and streams (Rutherford *et al.* 2006, Ouyang *et al.* 2013, Opperman 2014). Therefore land cover change, such as deforestation, increases nutrient and sediment loads entering waterways, alters infiltration rates, elevates greenhouse gas emissions and leads to changes in regional and local hydrological cycles (Ouyang *et al.* 2013). The latter results in a significant reduction in floodwater retention and an associated loss of flood control (Ouyang *et al.* 2013). Therefore reforestation and the development of forested floodplain buffers in a catchment can reduce the water discharge and sediment load into the rivers and streams and enhance flood attenuation based on catchment characteristics (Ouyang *et al.* 2013). Vegetation can have numerous impacts on the amount of rainfall that becomes runoff and can generally affect flooding in three specific ways: by affecting the size and shape of the stream channel (geomorphology), by altering the amount of water that reaches the stream channel (hydrology), and by altering the resistance to flow (hydraulics) (Rutherford *et al.* 2006, Opperman 2014).

River channels that are forested have a higher roughness which means that the flood arrives later and that the peak flow is attenuated when compared to channels cleared of vegetation. The response to larger floods generally differs from smaller floods with smaller attenuation of the peak observed in the case of the small flood (Rutherford *et al.* 2006). Revegetating the riparian zone in the Murrumbidgee catchment in Australia had a considerable effect on the size and timing of the flood peak reaching different outlets (Error! Reference source not found.; Rutherford *et al.* 2006). At the upstream site (C) the peak is attenuated y 18% and at the larger outlet (A) the peak is attenuated by 29% (Error! Reference source not found.).

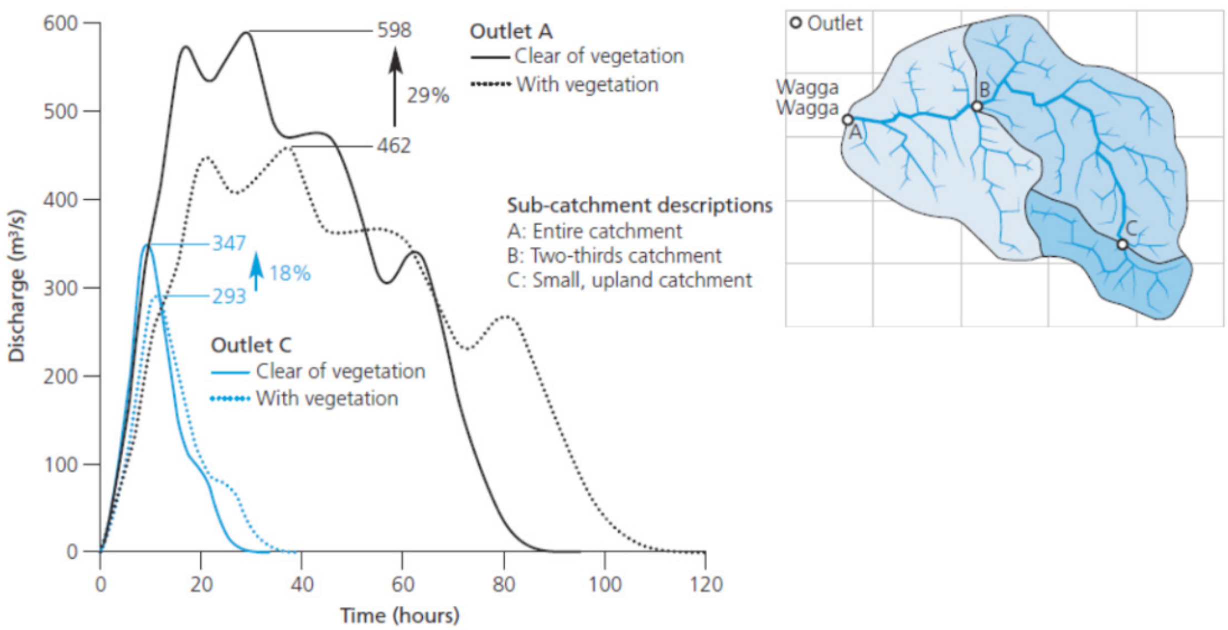

Figure A5.14 The effect of revegetation on discharge upstream and downstream of the Murrumbidgee in Australia
Source: Rutherford *et al.* 2006

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APPENDIX VI. COST ESTIMATES FOR SELECTED GUD INTERVENTIONS

Table A6.1 Unit cost estimates for GUD interventions extracted from stormwater management literature and updated to 2015 US$ costs

Intervention	Unit Cost	Unit	2015 cost	2015 cost US$	Source
Grassed swales	15	£ per m^2	20	31	CIRIA 2007
	12	£ per m^2	16	24	EA 2007
	4.5	Aus$ per m^2	8	6	Fletcher *et al.* 2003
	9.5	Aus$ per m^2	17	13	Fletcher *et al.* 2003
	10	Aus$ per m^2	17	13	URS 2003
	18	Aus$ per m^2	31	23	URS 2003
	18	Aus$ per m^2	31	23	URS 2003
	8	£ per m^2	8.5	13	Paths for all, Scotland 2014
	9	Can$ per m^2	9.5	7	Toronto & Region Conservation Authority 2013
	8	£ per m^2	8	12	Severn Trent Water 2015
	305	R per m^2 (2010)	417	33	Armitage et al 2013
	12	£ per m^2	12	18	Hull City Council 2015
	15	Euro per m^2	15	17	Morales Torres *et al.* 2015
				18	
Detention Basin	18	£ per m^3	24	37	CIRIA 2007
per m^3 stored volume	45	£ per m^3	59	90	Stovin and Swan 2007
	18	£ per m^3	24	37	SNIFFER 2007
	20	£ per m^3	20	31	Hull City Council 2015
	22	Euro per m^3	22	24	Morales Torres *et al.* 2015
	50	Euro per m^3	51	57	Natural Water Retention Measures Project 2013
				46	
Retention pond (wet)	45	Euro per m^3	45	50	Morales Torres *et al.* 2015
per m^3	25	£ per m^3	33	50	CIRIA 2007
	27	US$ per m^3	39	39	US EPA 1999
				46	
Constructed Wetland	40	Euro per m^3	40	44	Morales Torres *et al.* 2015
per m^3 treated volume	28	£ per m^3	37	57	CIRIA 2007
	40	US$ per m^3	46	46	UN-Habitat 2008
				49	
Floodplain restoration (gardens)	109	Rand per m^3	149	11.7	Armitage *et al.* 2013
per m^3	8.6	US$ per m^3	8.6	8.6	Tanzania National Construction Council (from DeRisi report)
(excavation costs)	102	Rand per m^3	140	11.04	Department of Co-operative governance and Traditional Affairs (DoCGTA). (2010).
				10.5	

Table A6.1 Unit cost estimates for GUD interventions extracted from stormwater management literature and updated to 2015 US$ costs (continued)

Intervention	Unit Cost	Unit	2015 cost	2015 cost US$	Source
Riparian Buffers	3627	US$ per ha (lower bound)	4008	4008	Michie 2010
per hectare	4906	US$ per ha (upper bound)	5421	5421	Michie 2010
	793	US$ per ha (lower bound)	873	873	Dep. Environmental Protection 2010
	1911	US$ per ha (upper bound)	2103	2103	Dep. Environmental Protection 2010
	640	US$ per ha (lower bound)	802	802	NRCS Illinois 2005
	836	US$ per ha (upper bound)	1047	1047	NRCS Illinois 2005
		UPPER bound		2857	
		LOWER bound		1894	
		AVG		2376	
Catchment reforestation	917	US$ per ha	917	917	TNC 2015.
per hectare	1048	US$ per ha	1158	1158	FAO 2011
	1195	US$ per ha	1195	1195	http://www.greentoscale.net/en/green2scale-ratkaisut/afforestation-and-reforestation (2016)
				1090	

APPENDIX VII. COST ESTIMATE FOR DETENTION BASIN

This appendix focuses on the costs of construction, such as the land purchase, earthwork, etc. The values reported below present the information collected from the Tanzania National Construction Council and from the study of different ongoing projects in Dar es Salaam.

The transport to the waste treatment plant of the removed soil/derbies is assumed having a percentage of 10% of the total earthwork cost.

Additional costs, that are a percentage of the total work costs, are generally added to the above costs. Table A7.4 below lists all the additional costs (as percentage of the total civil works cost) to add to the final value.

Table A7.1 Unit costs for basic construction work item

Work item	Description	Unit cost
Purchase of land		1000 \$/ha
Earthwork	Excavation	8.6 $\$/m^3$
	Embankment	12.8 $\$/m^3$
Concrete work		255 $\$/m^3$

Table A7.2 Unit costs for basic construction materials

Work item	Description	Unit cost
Gasoline	Liter	0.69
Diesel	Liter	0.67
Portland cement	1000 kg	98.62
Reinforcement bar	1000 kg	495.62
Fine aggregate	m3	10.39
Coarse Aggregate	m3	21.82
Plywood	m2	23.85
Timber	m3	286.15
Wooden pile	m	7.95
Wood	m3	238.46

Table A7.3 Unit costs for basic construction materials

Labor	Unit cost
Foreman	8.48
Skilled labor	4.43
Common labor	3.64
Unskilled labor	2.91
Operator for heavy equipment	8.02
Driver for light vehicle	7.64
Carpenter	6.75
Welder	9.35
Mechanic	9.70
Electrician	10.39

Table A7.4 Additional costs to consider as percentage of the total civil work cost

Labor	Percentage respect to the total cost of the civil works
Preparation works	7%
Contractor’s indirect costs	10%
Engineering service	7%
Contingency	10%
Government administration cost	1%
Carpenter	6.75
Welder	9.35
Mechanic	9.70
Electrician	10.39

APPENDIX VIII: INUNDATION RESULTS RELATED TO SCENARIO 2

First sub-domain

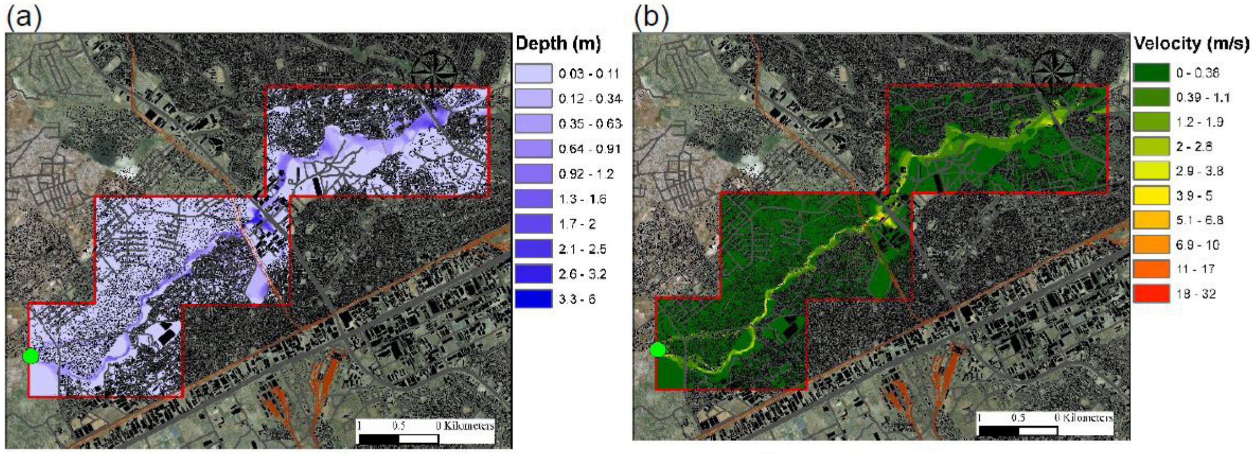

Figure A8. 1. Inundation results for the first sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

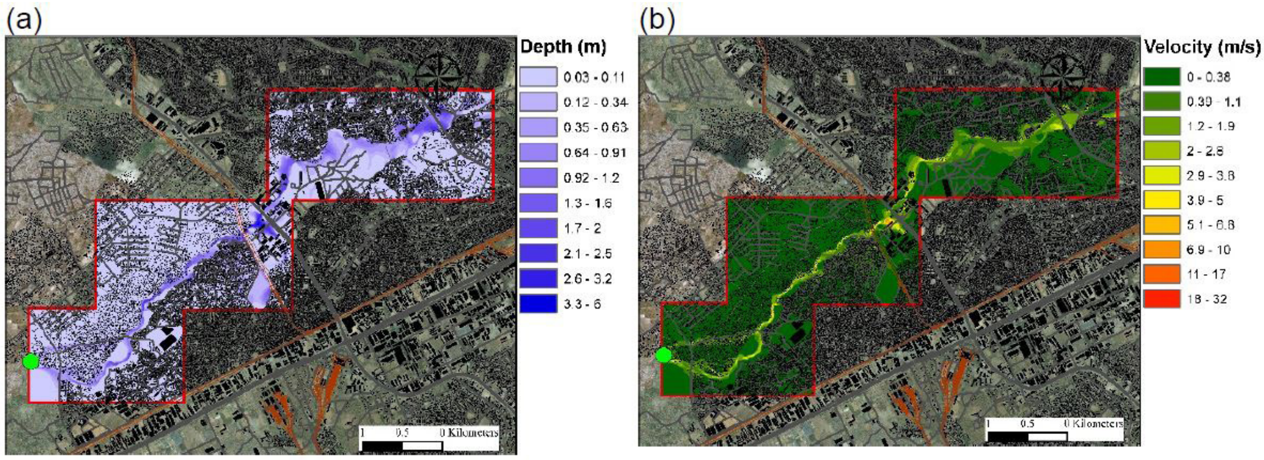

Figure A8. 2. Inundation results for the first sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

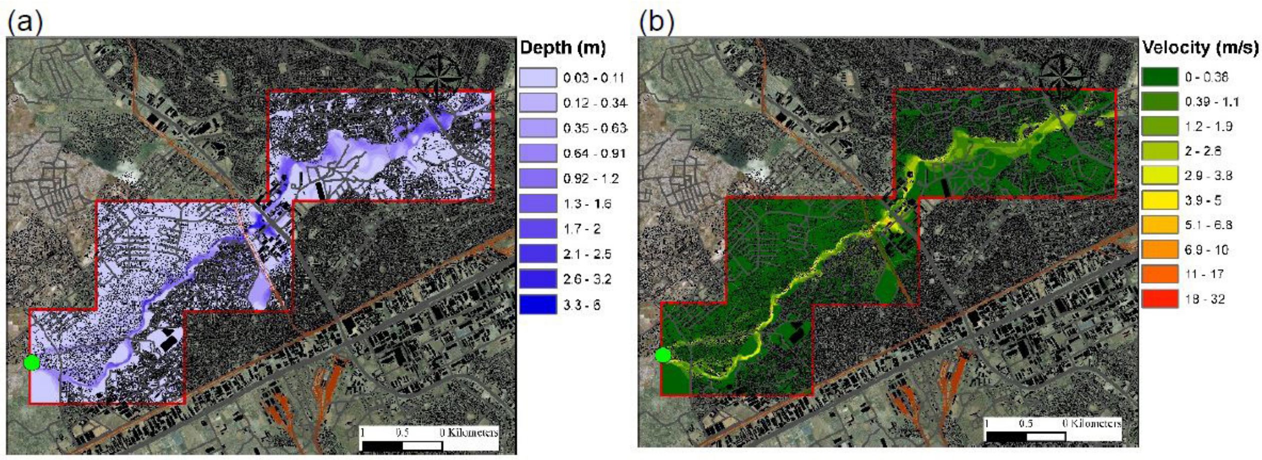

Figure A8. 3. Inundation results for the first sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

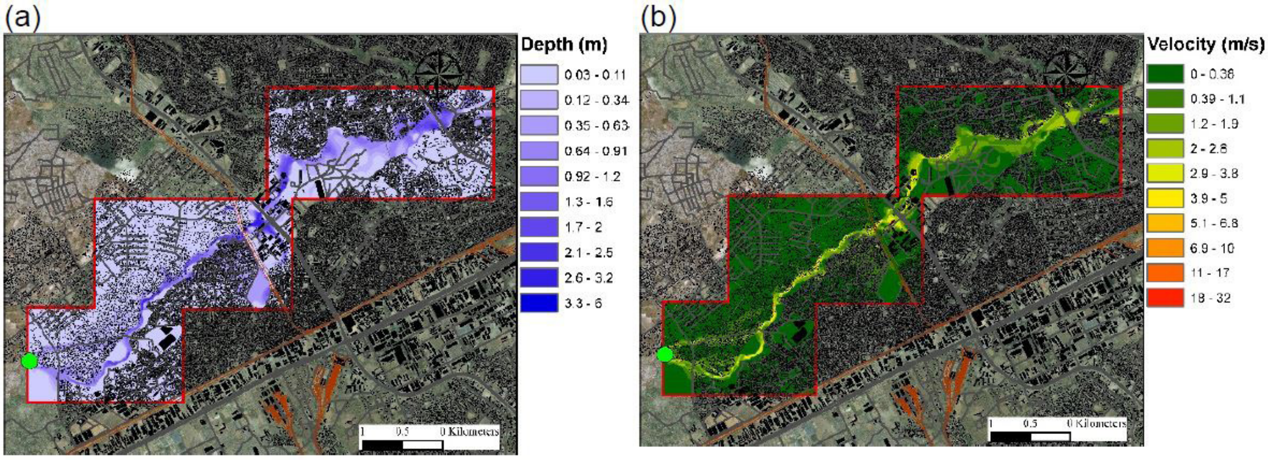

Figure A8. 4. Inundation results for the first sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

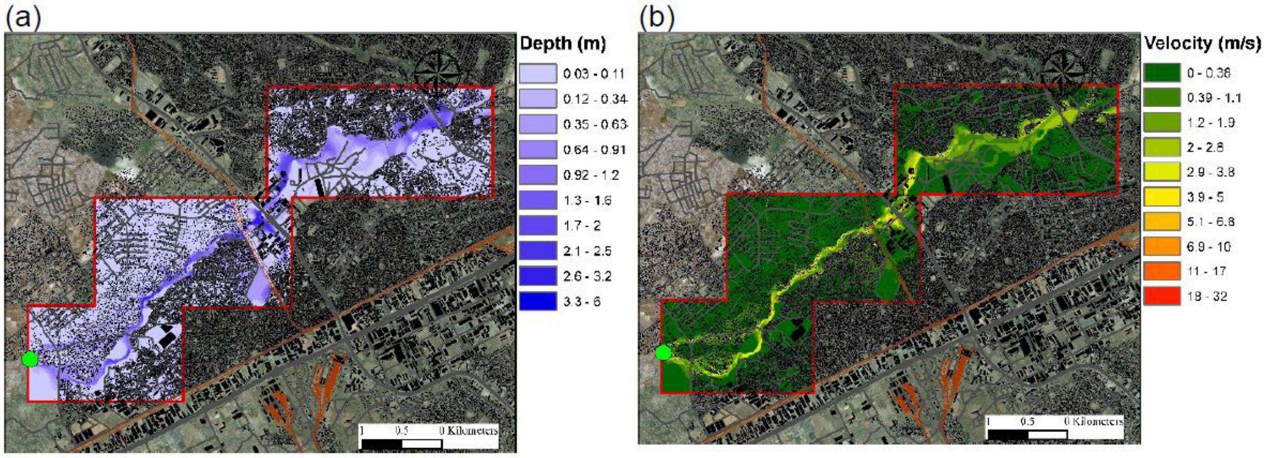

Figure A8. 5. Inundation results for the first sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

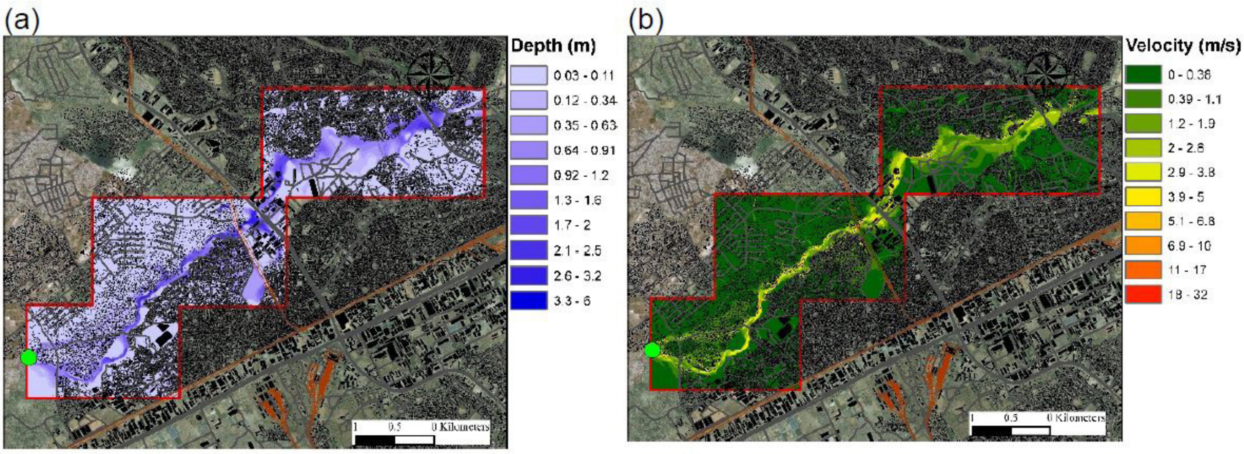

Figure A8. 6. Inundation results for the first sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

Second sub-domain

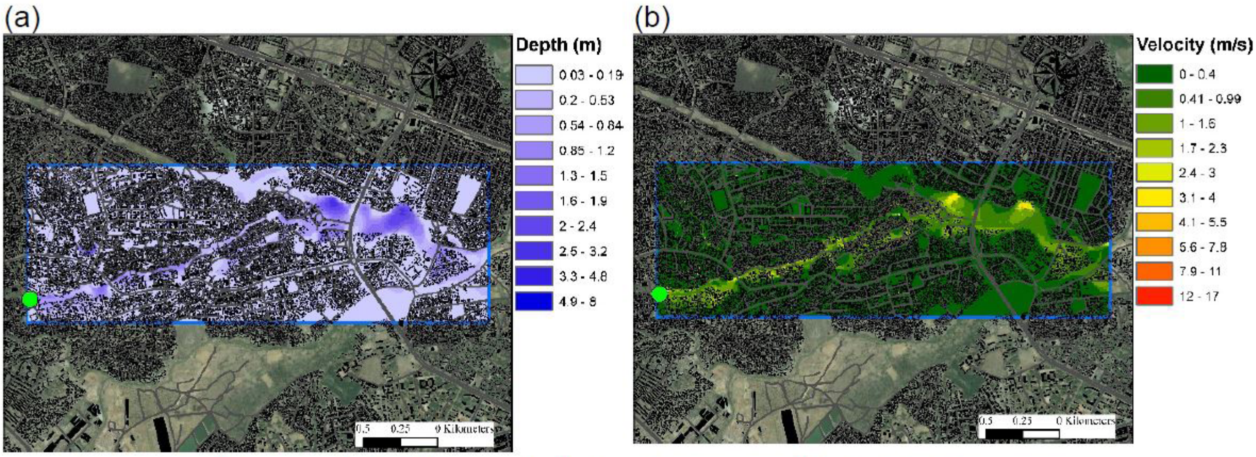

Figure A8. 7. Inundation results for the second sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

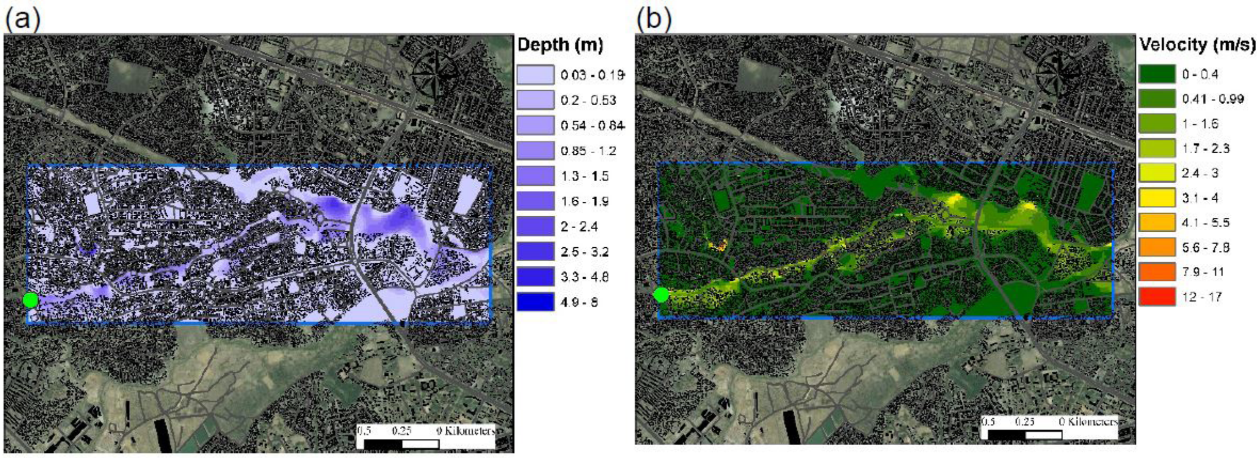

Figure A8. 8. Inundation results for the second sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

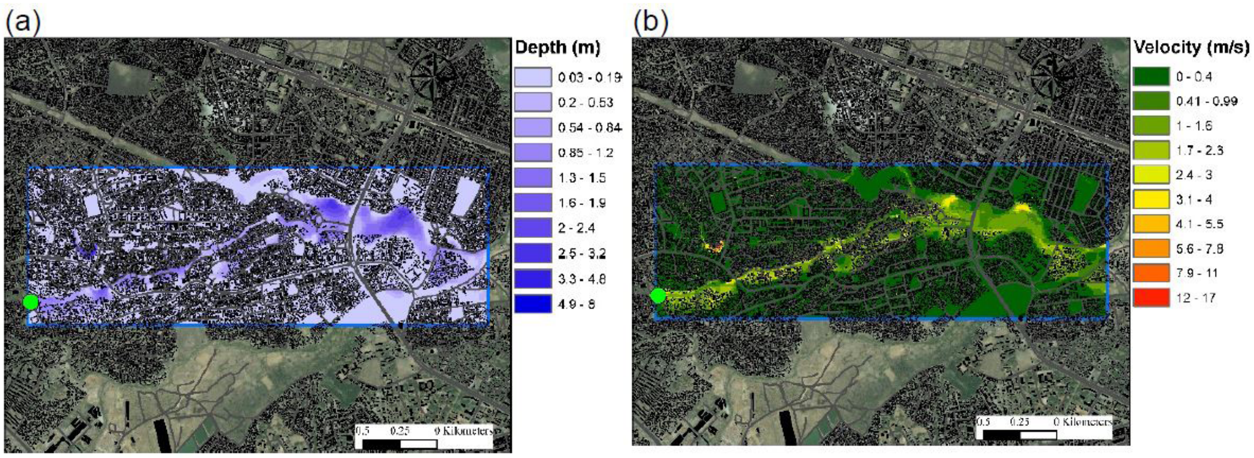

Figure A8. 9. Inundation results for the second sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

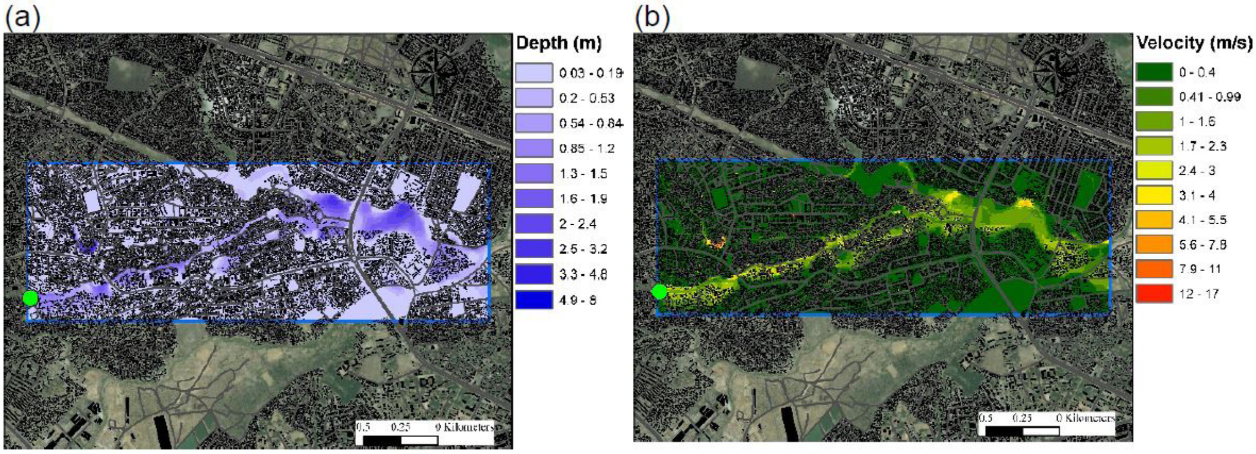

Figure A8. 10. Inundation results for the second sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

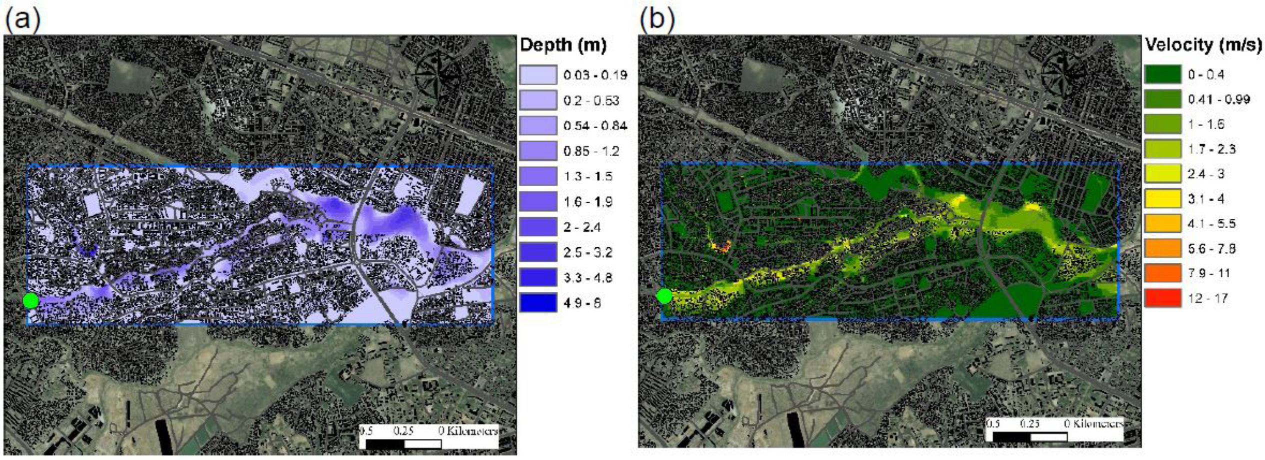

Figure A8. 11. Inundation results for the second sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

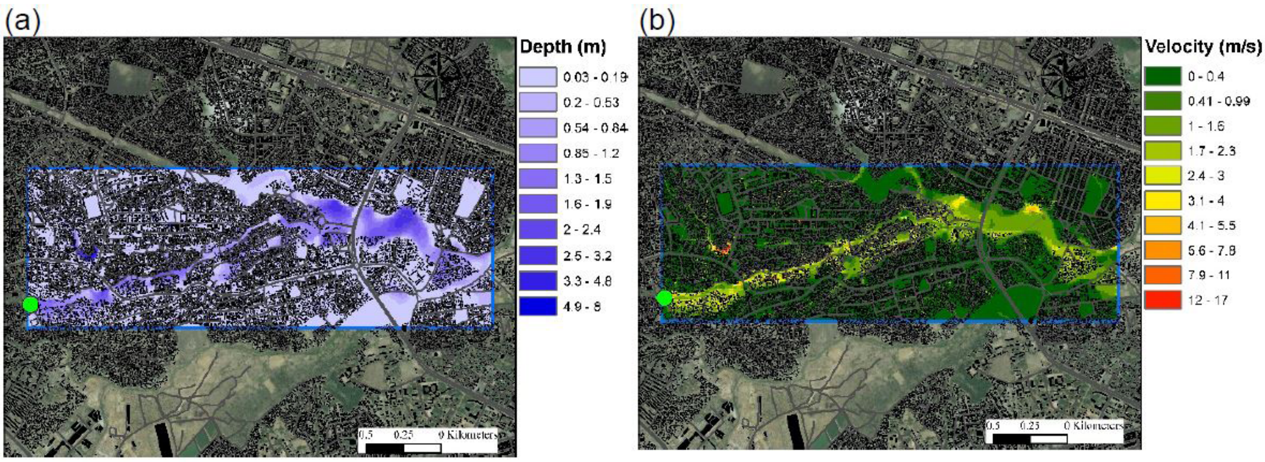

Figure A8. 12. Inundation results for the second sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Third sub-domain

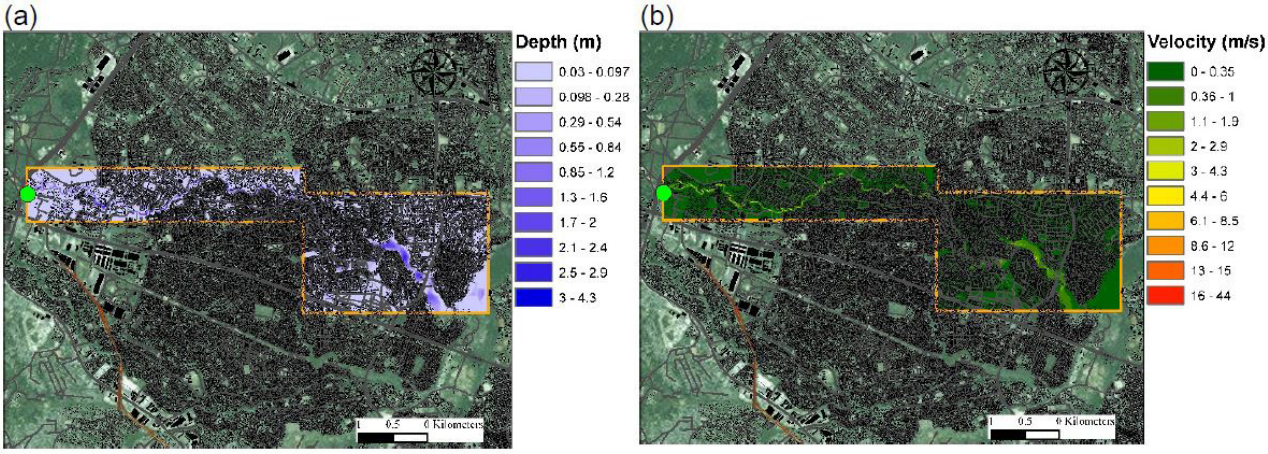

Figure A8. 13. Inundation results for the third sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

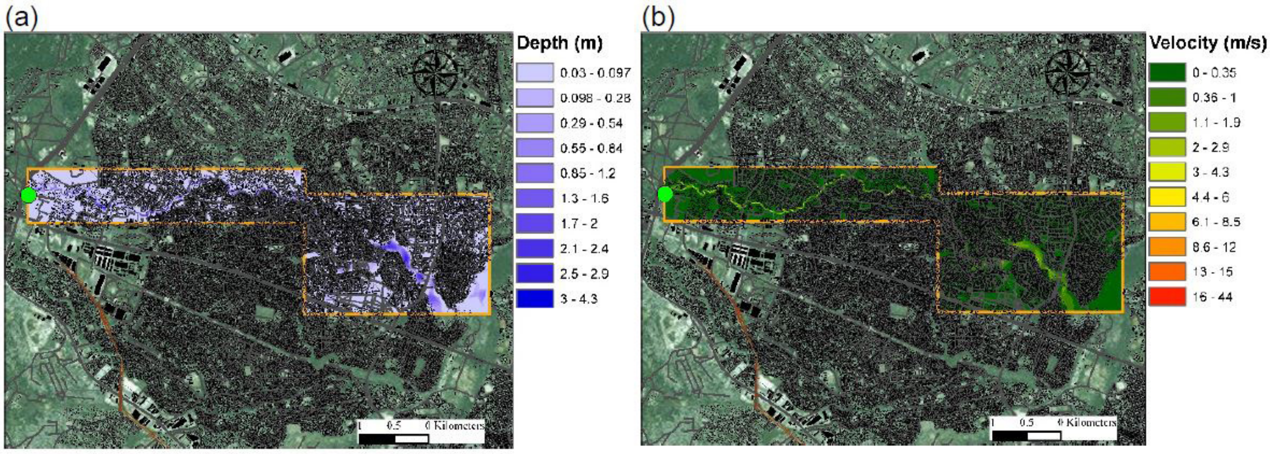

Figure A8. 14. Inundation results for the third sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

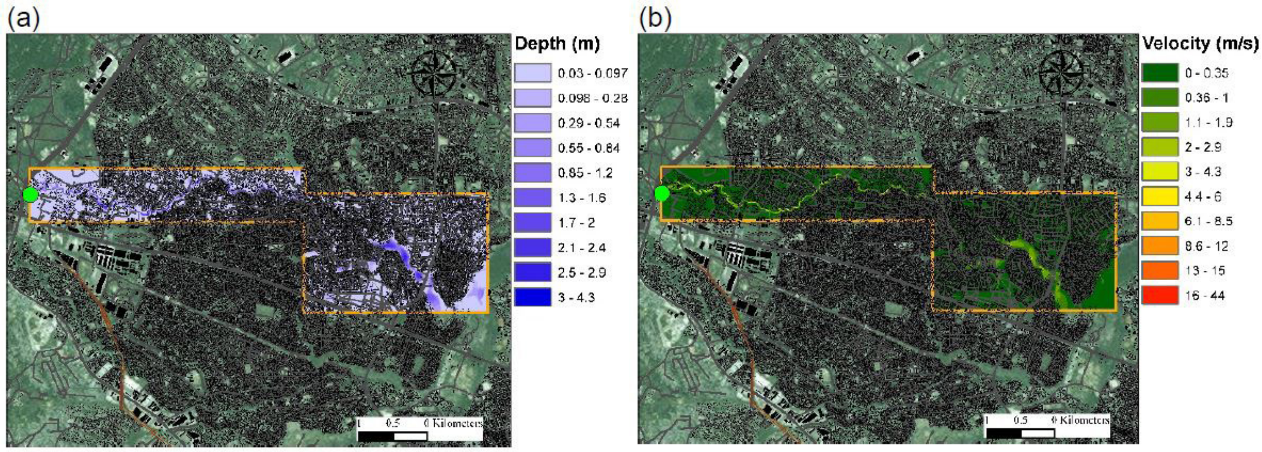

Figure A8. 15. Inundation results for the third sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

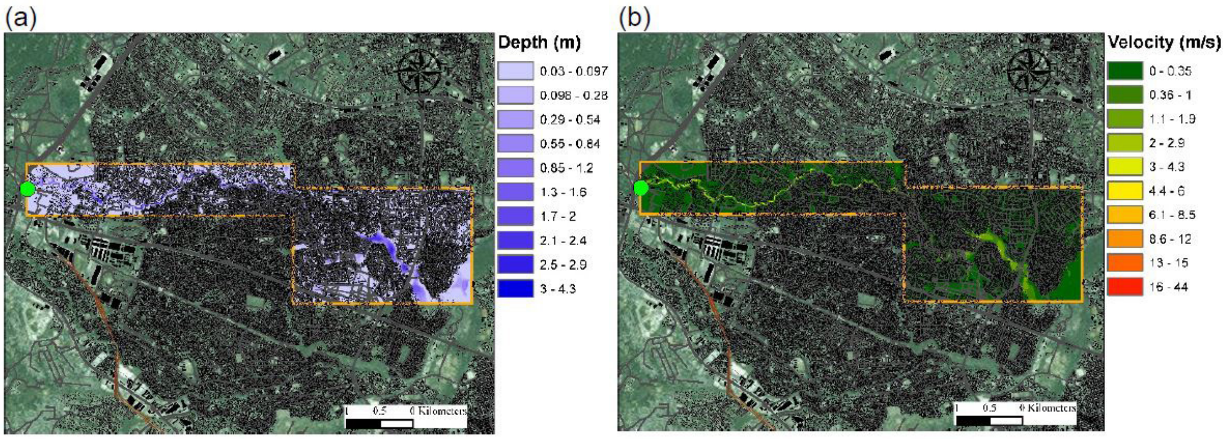

Figure A8. 16. Inundation results for the third sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

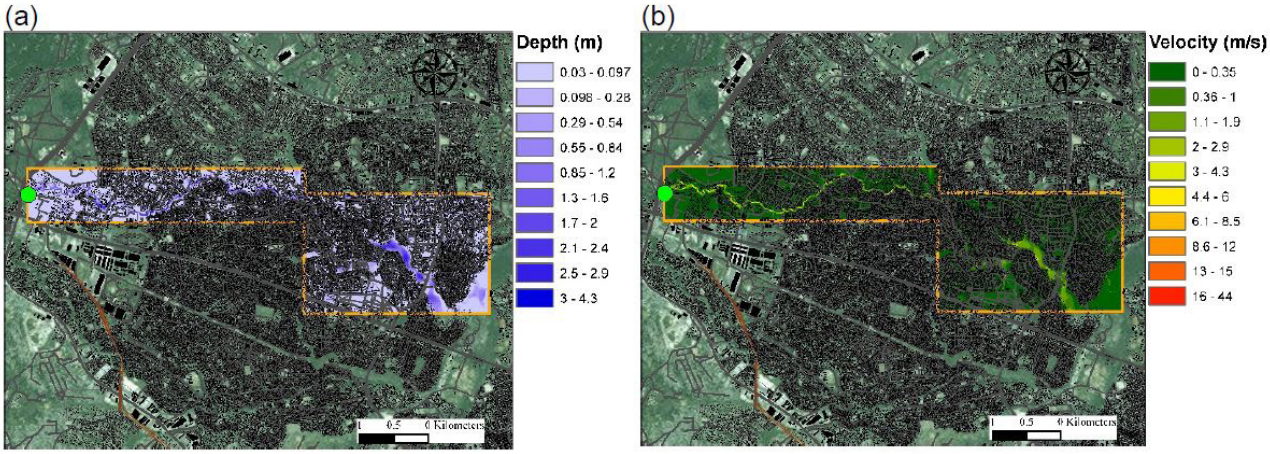

Figure A8. 17. Inundation results for the third sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

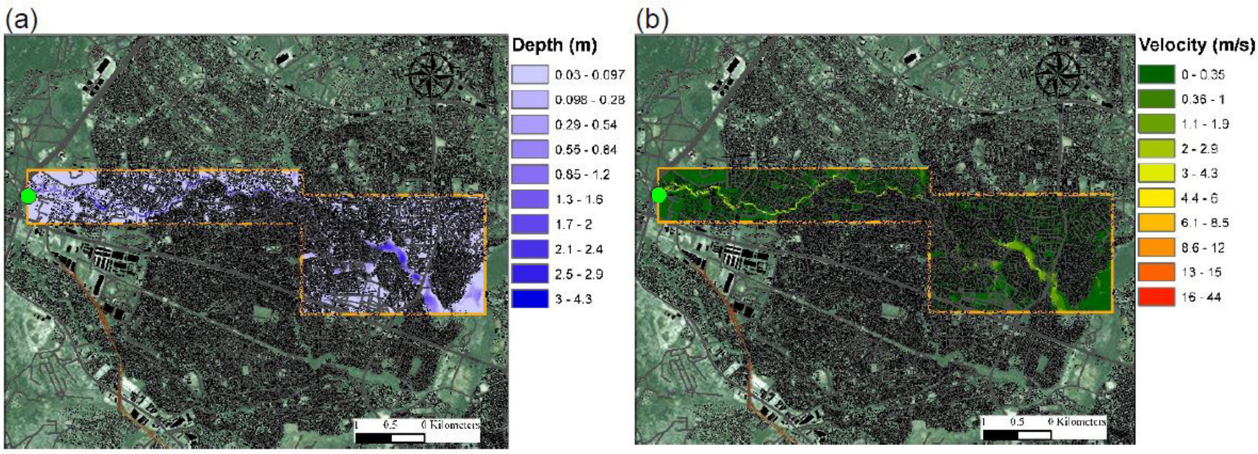

Figure A8. 18. Inundation results for the third sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Fourth sub-domain

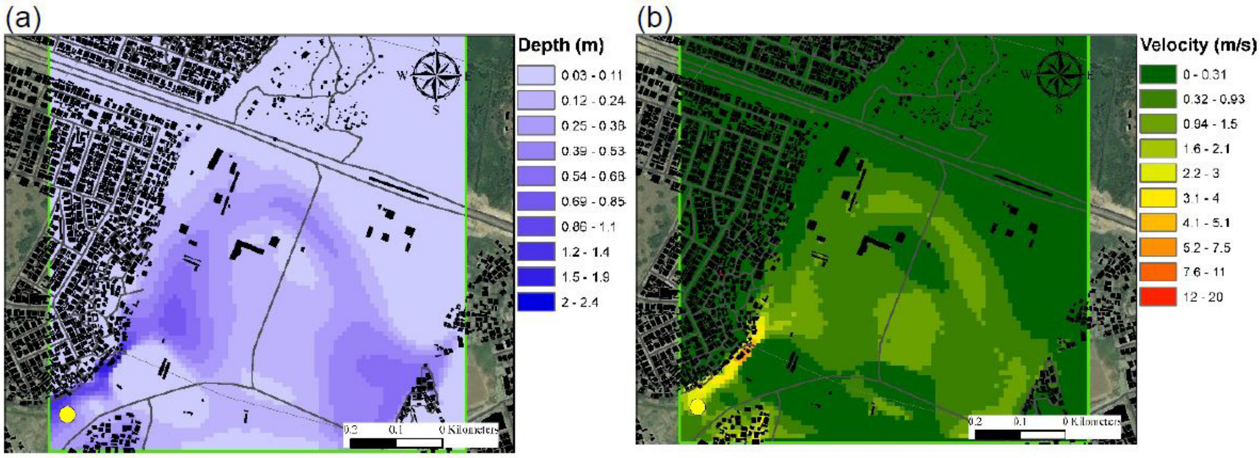

Figure A8. 19. Inundation results for the fourth sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

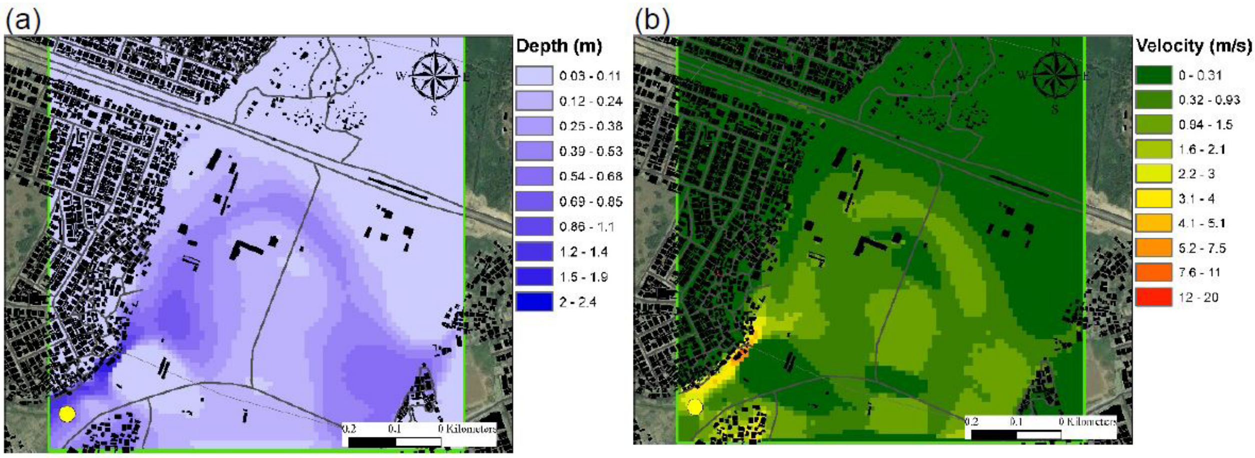

Figure A8. 20. Inundation results for the fourth sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

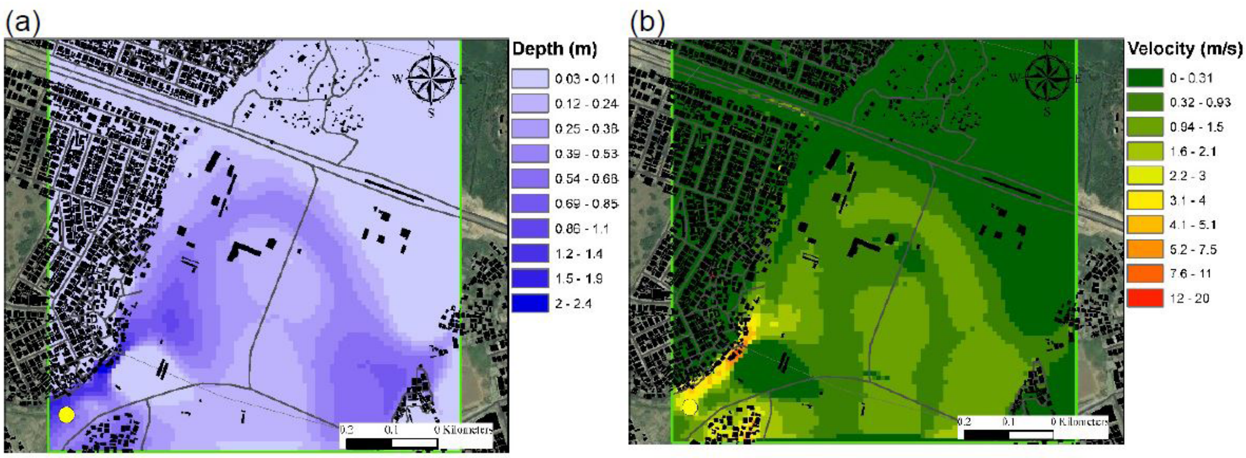

Figure A8. 21. Inundation results for the fourth sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

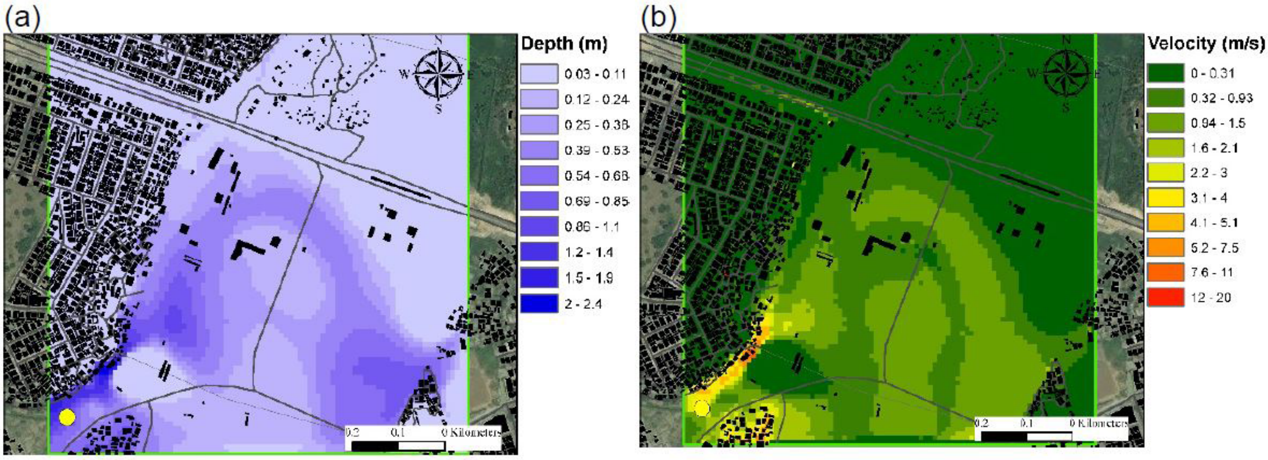

Figure A8. 22. Inundation results for the fourth sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

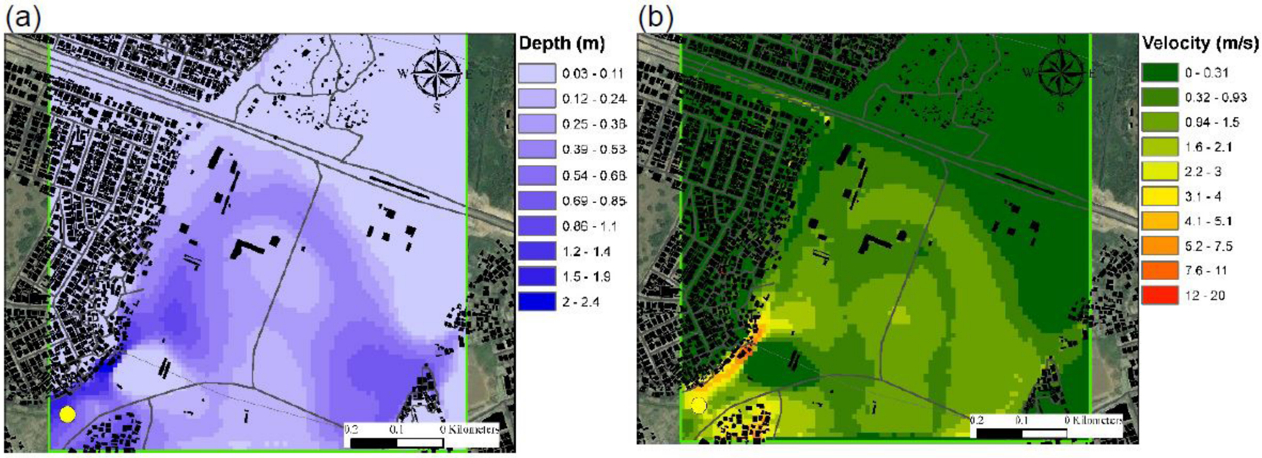

Figure A8. 23. Inundation results for the fourth sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

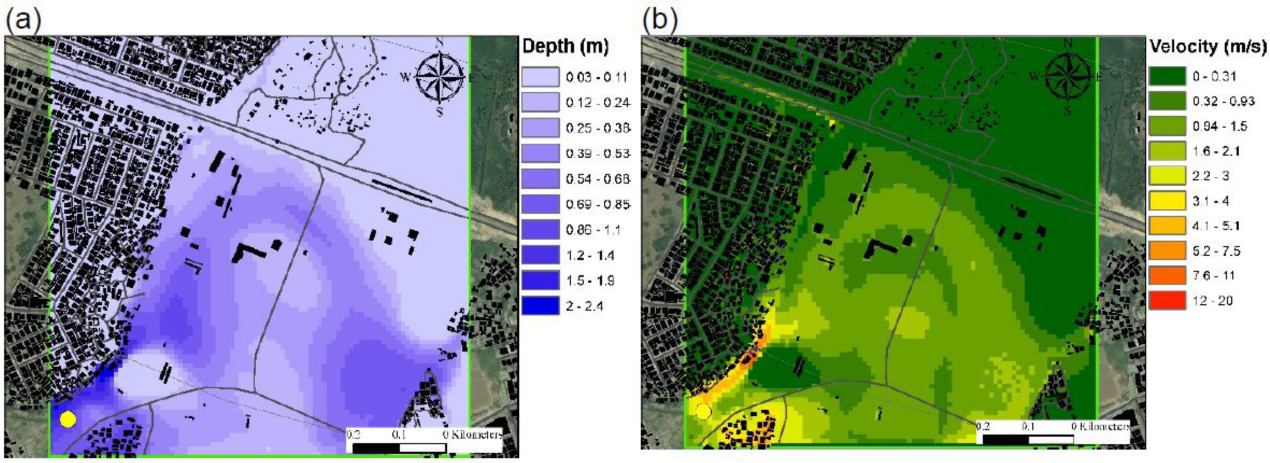

Figure A8. 24. Inundation results for the fourth sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Fifth sub-domain

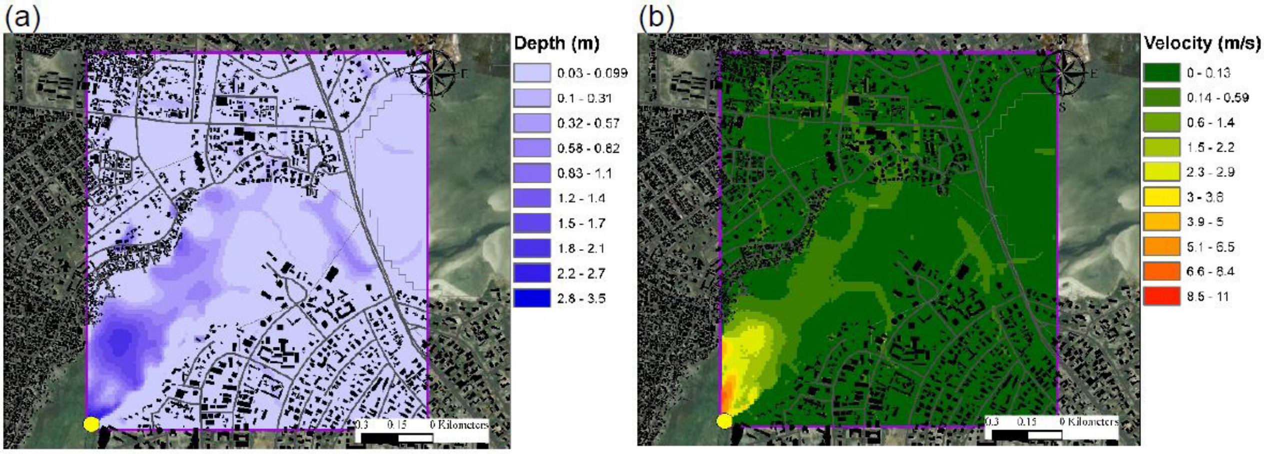

Figure A8. 28. Inundation results for the fifth sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

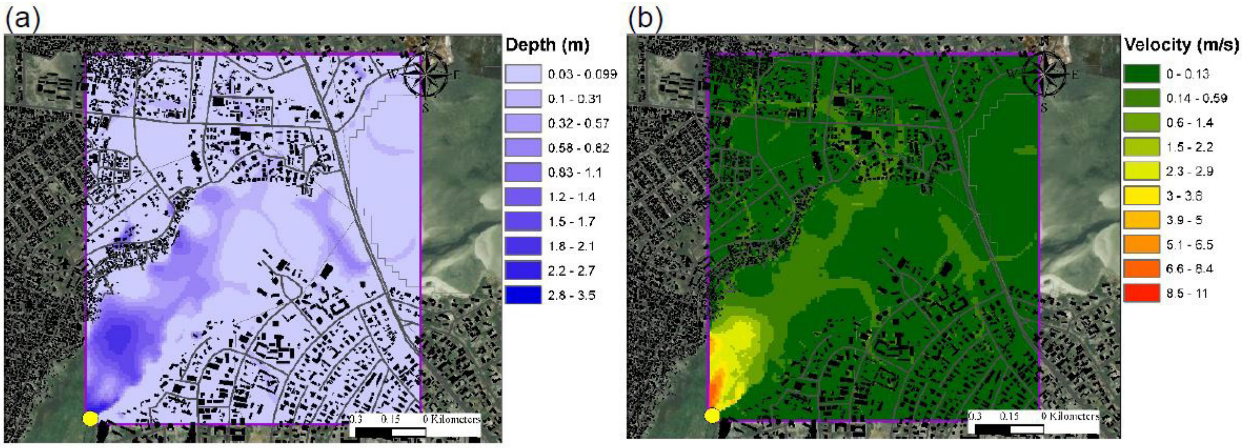

Figure A8. 29. Inundation results for the fifth sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

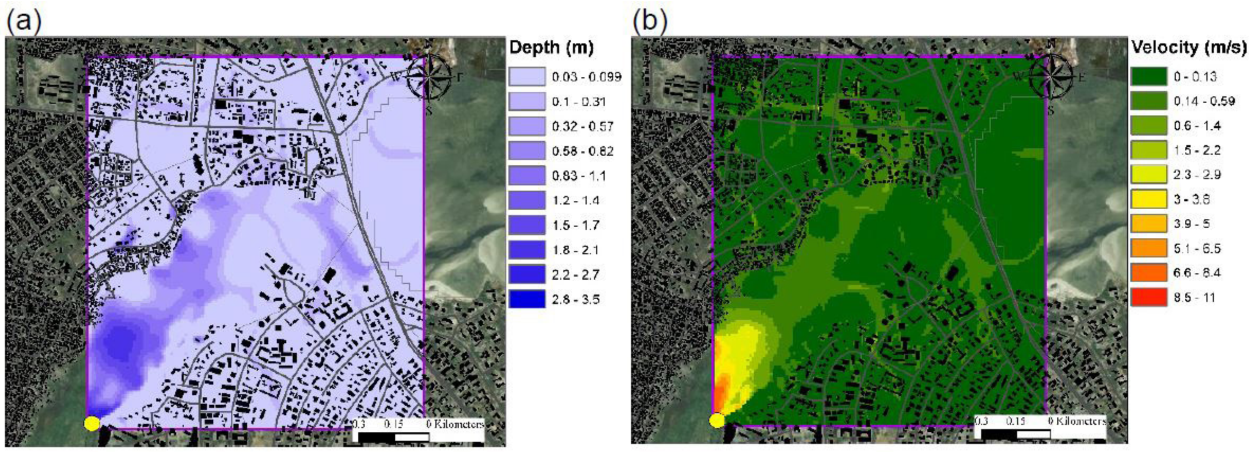

Figure A8. 30. Inundation results for the fifth sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

The hazard curves

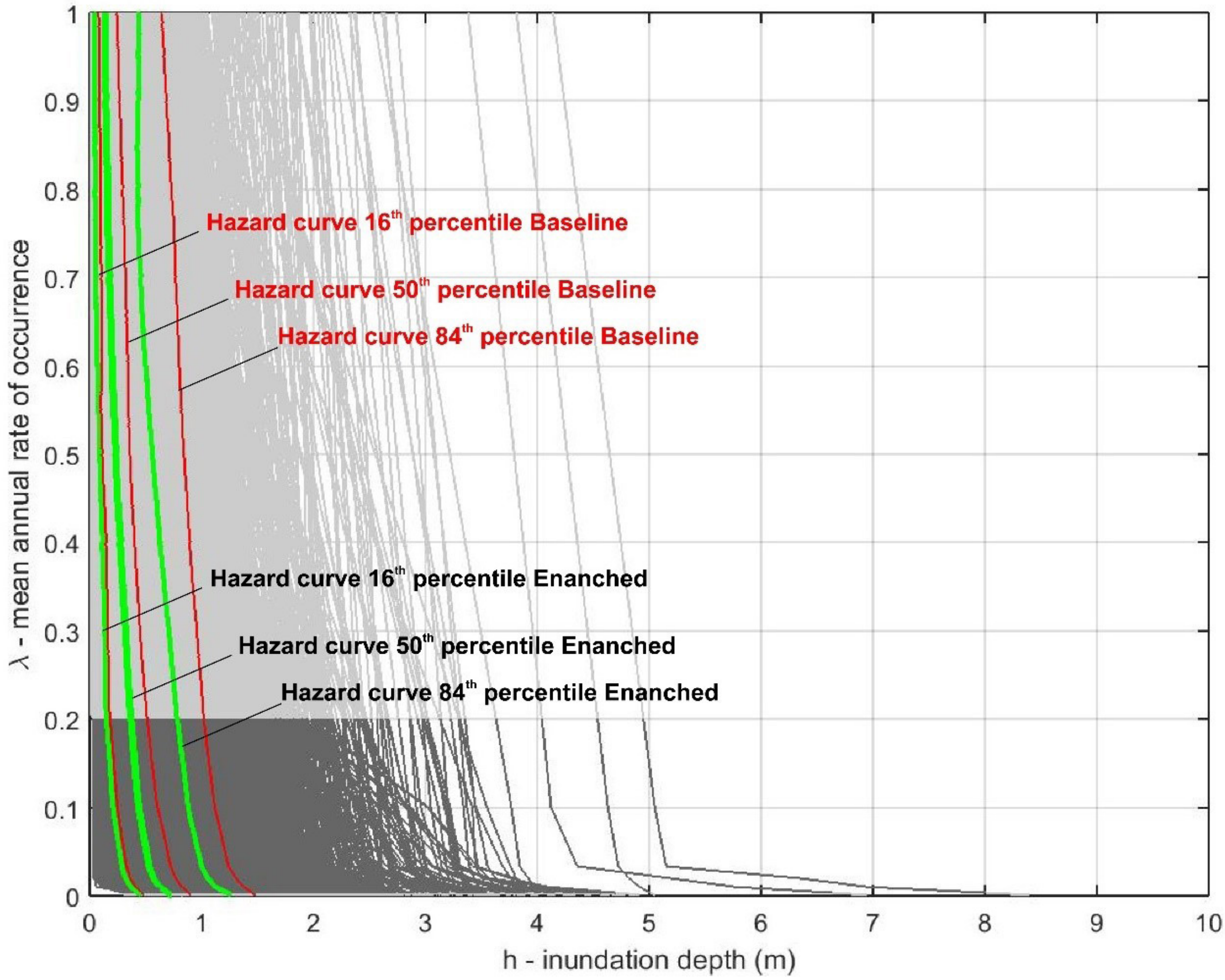

Figure A8.31 Hazard curves calculated for the mitigation strategy 2

APPENDIX IX: INUNDATION RESULTS RELATED TO SCENARIO 4

First sub-domain

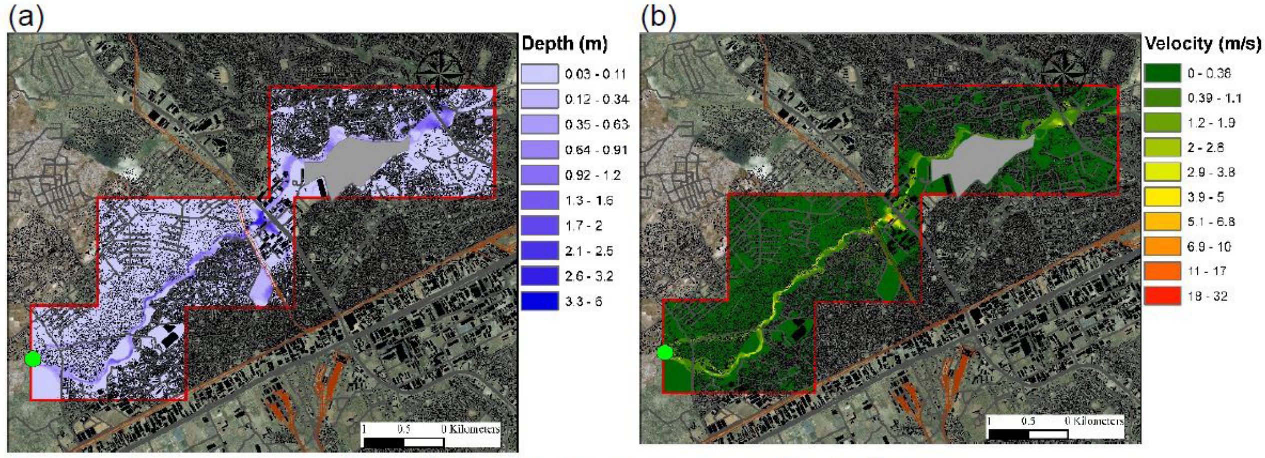

Figure A9. 1. Inundation results for the first sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

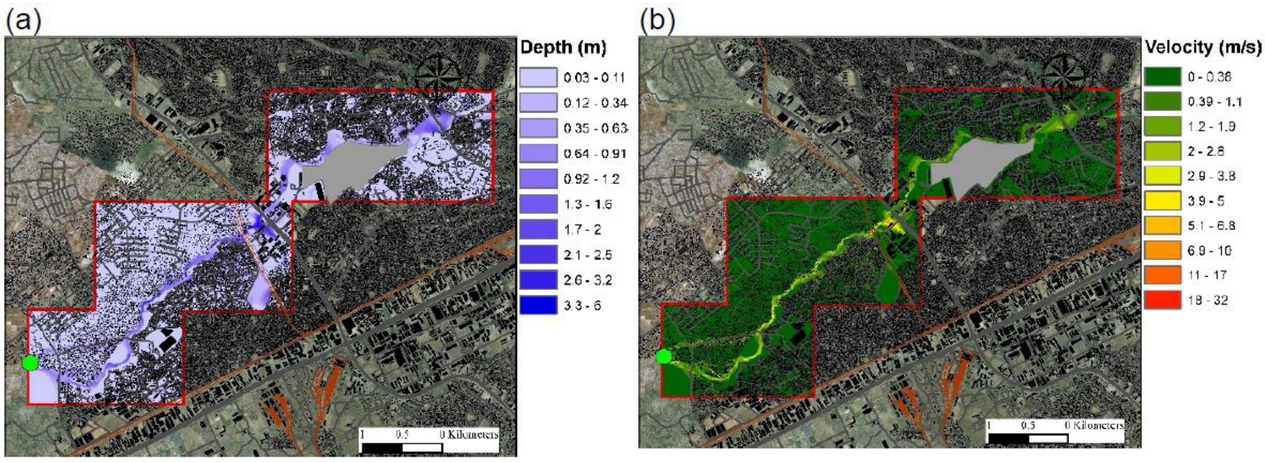

Figure A9. 2. Inundation results for the first sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

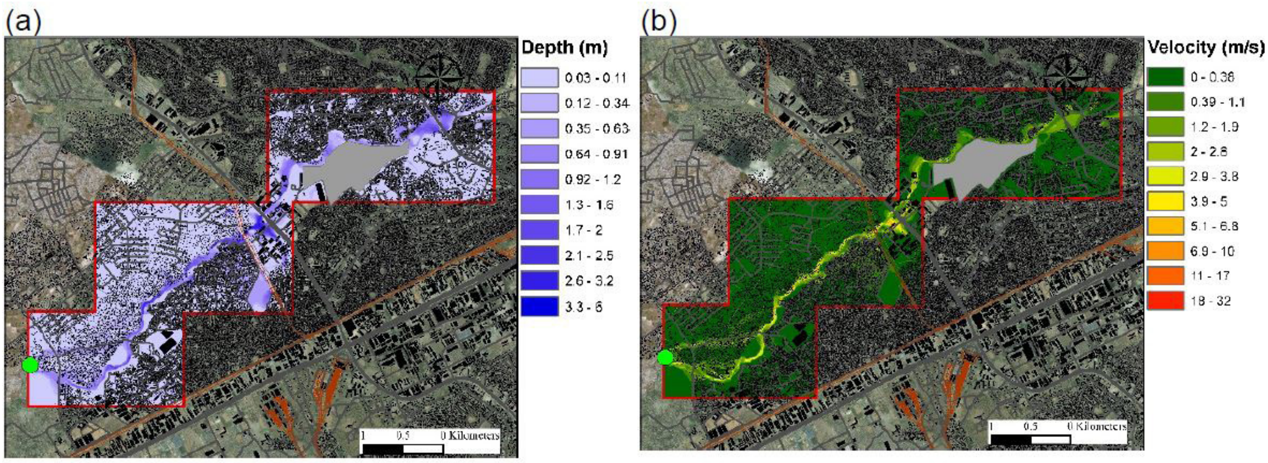

Figure A9. 3. Inundation results for the first sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

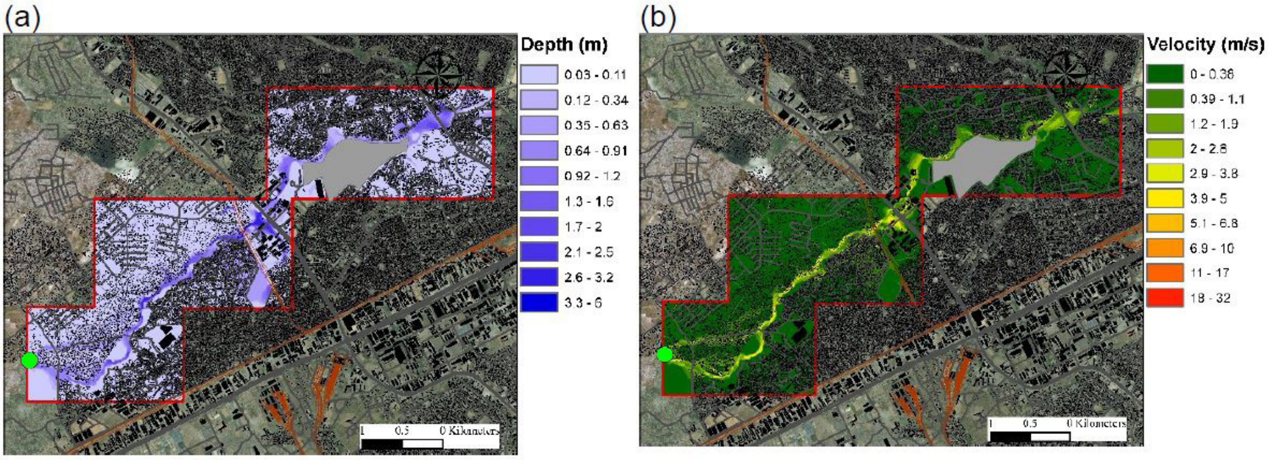

Figure A9. 4. Inundation results for the first sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

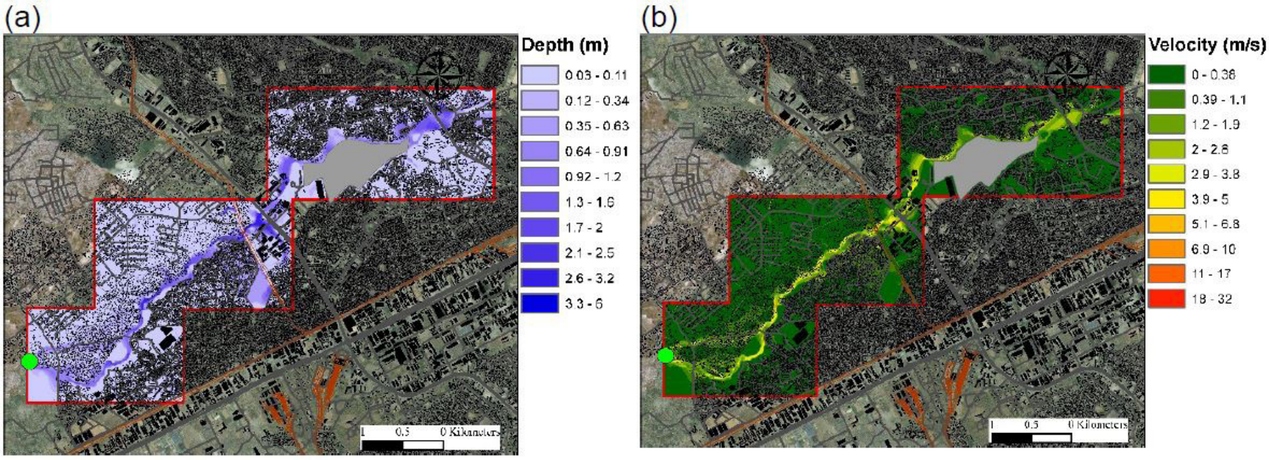

Figure A9. 5. Inundation results for the first sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

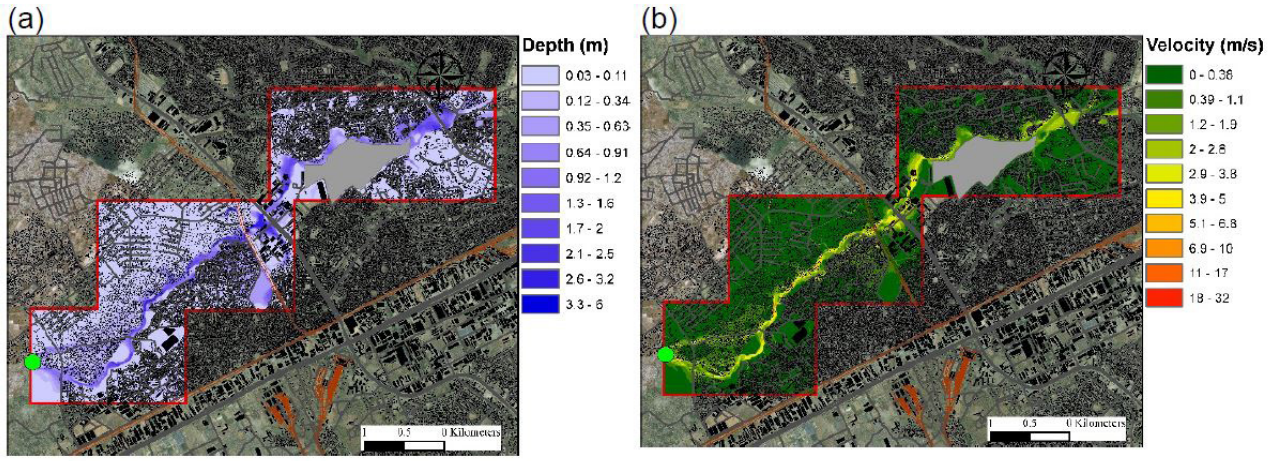

Figure A9. 6. Inundation results for the first sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

Fourth sub-domain

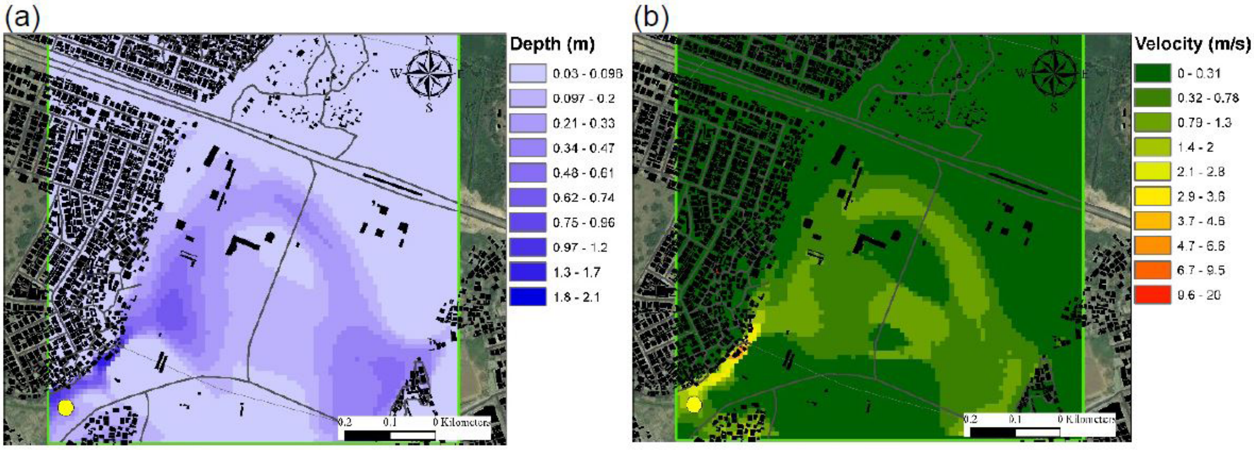

Figure A9. 7. Inundation results for the fourth sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

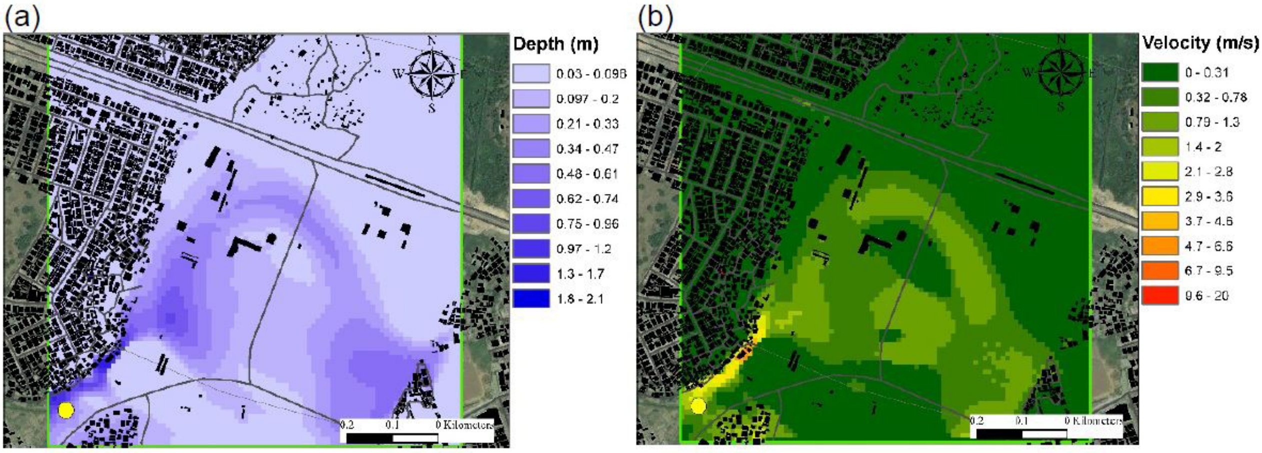

Figure A9. 8. Inundation results for the fourth sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

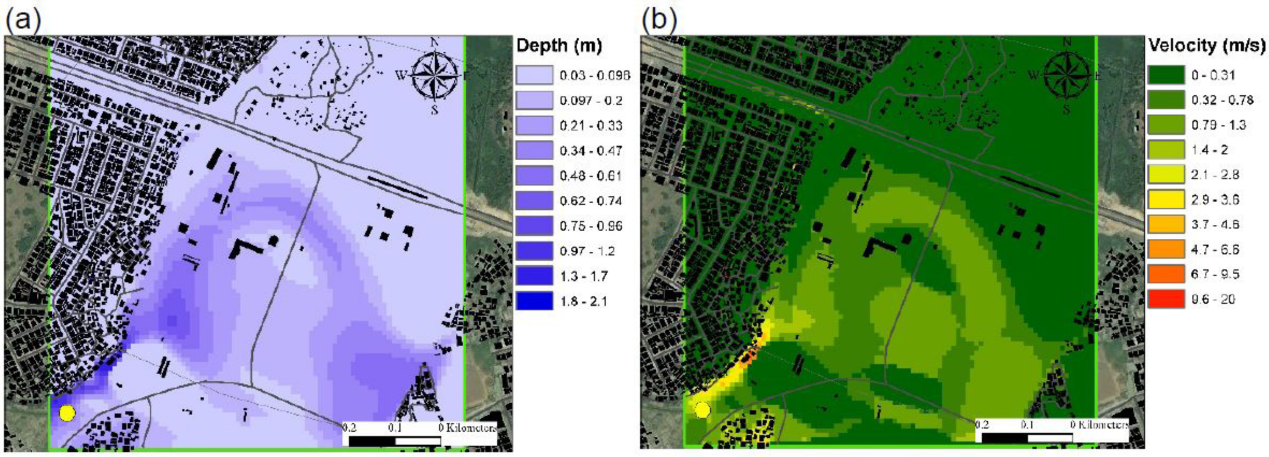

Figure A9. 9. Inundation results for the fourth sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

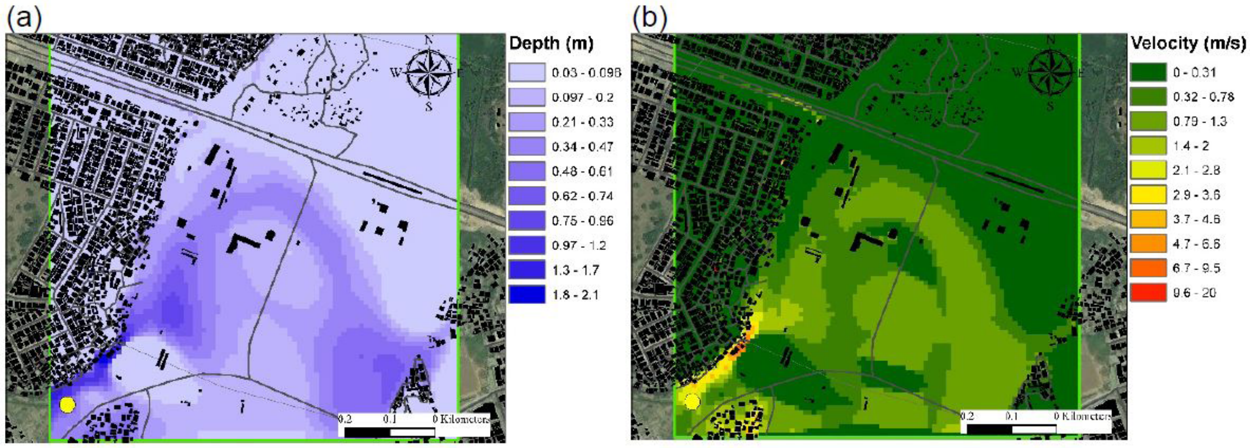

Figure A9. 10. Inundation results for the fourth sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

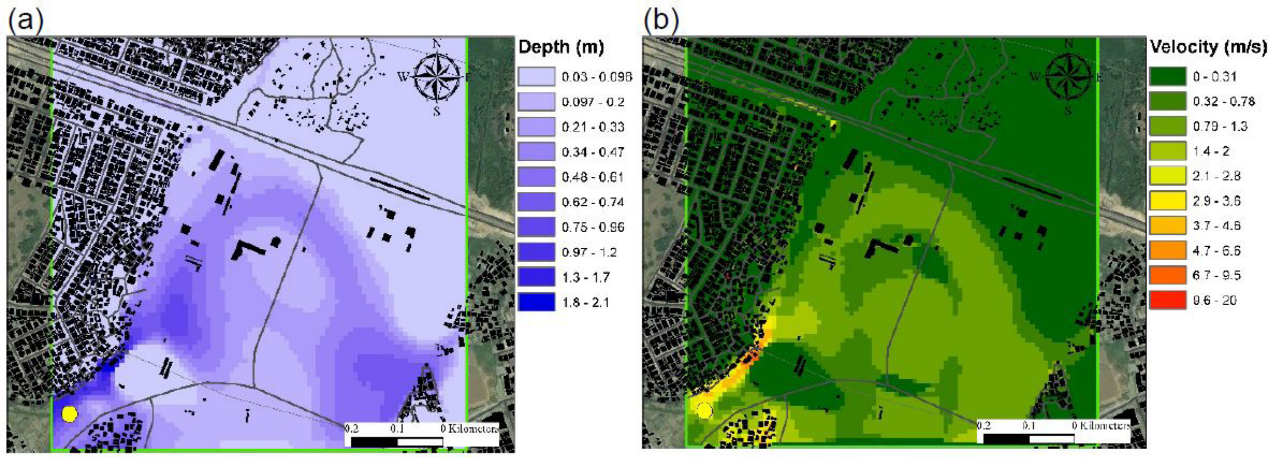

Figure A9. 11. Inundation results for the fourth sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

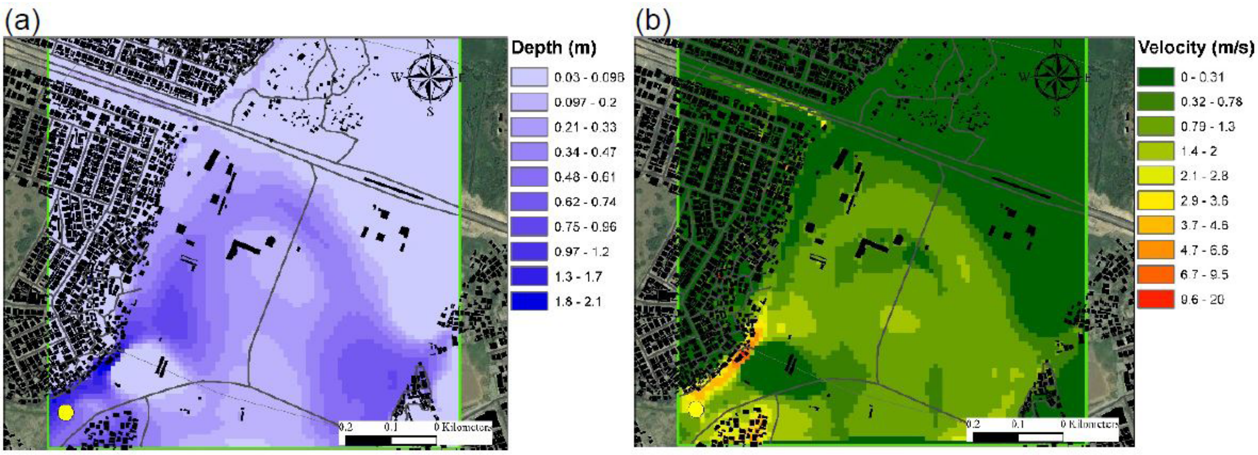

Figure A9. 12. Inundation results for the fourth sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

Fifth sub-domain A9.4

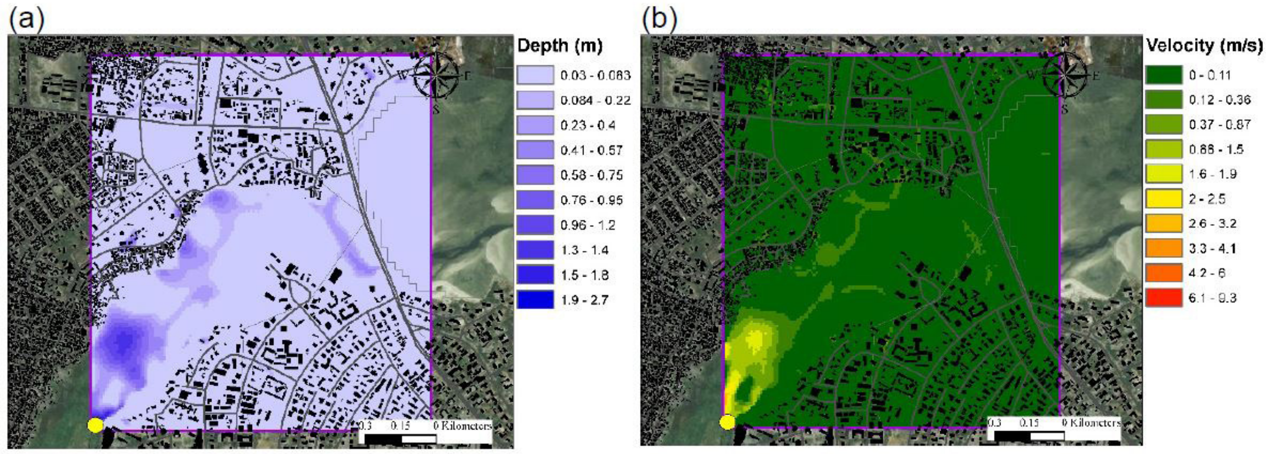

Figure A9. 13. Inundation results for the fifth sub-domain corresponding to TR = 5 years. (a) Inundation depth, (b) Flow velocity.

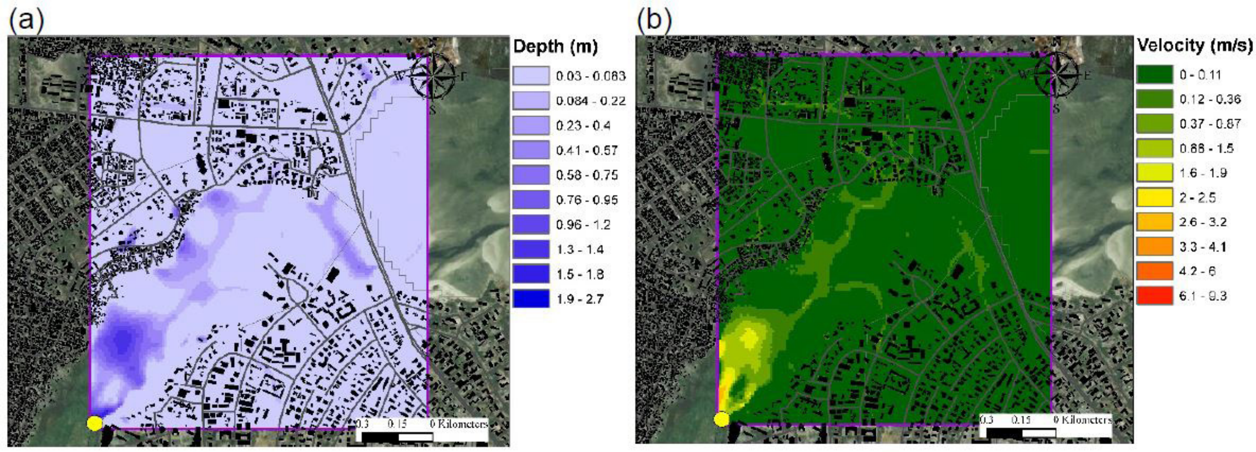

Figure A9. 14. Inundation results for the fifth sub-domain corresponding to TR = 10 years. (a) Inundation depth, (b) Flow velocity.

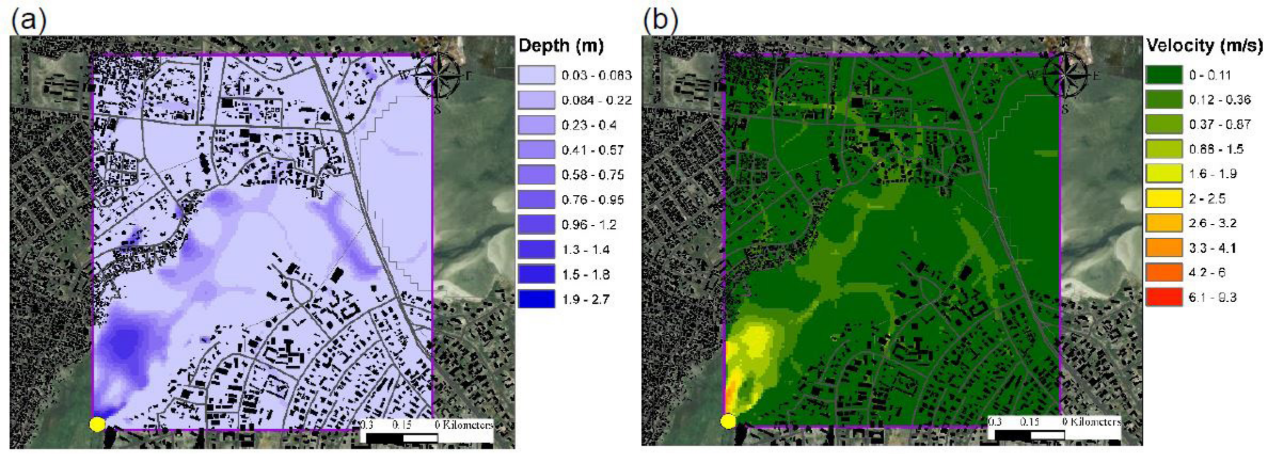

Figure A9. 15. Inundation results for the fifth sub-domain corresponding to TR = 30 years. (a) Inundation depth, (b) Flow velocity.

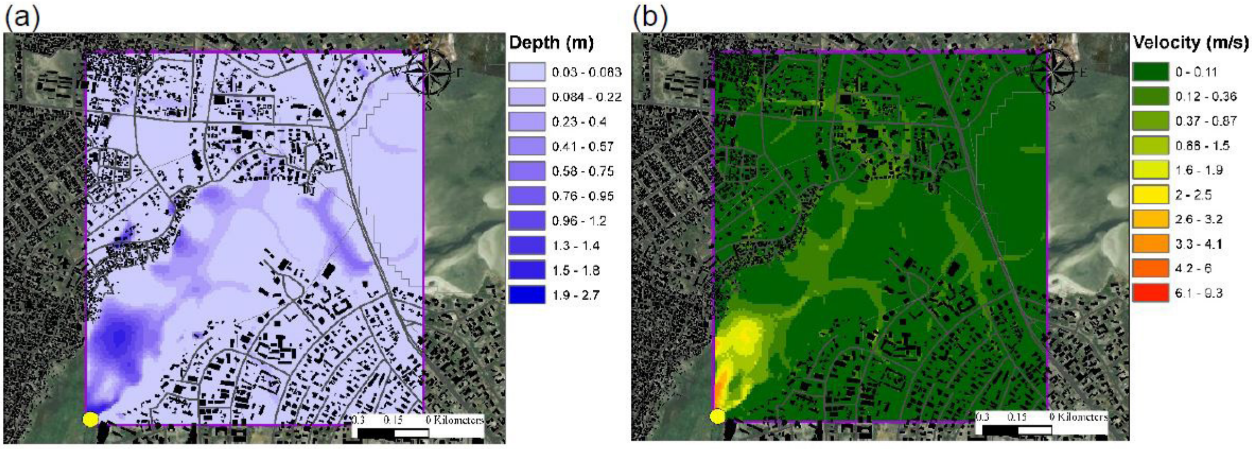

Figure A9. 16. Inundation results for the fifth sub-domain corresponding to TR = 50 years. (a) Inundation depth, (b) Flow velocity.

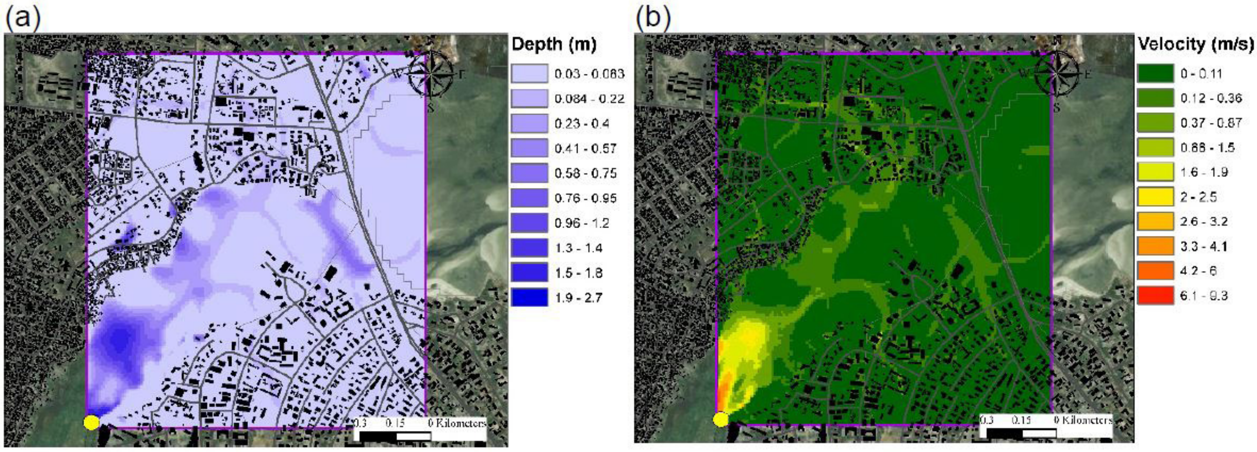

Figure A9. 17. Inundation results for the fifth sub-domain corresponding to TR = 100 years. (a) Inundation depth, (b) Flow velocity.

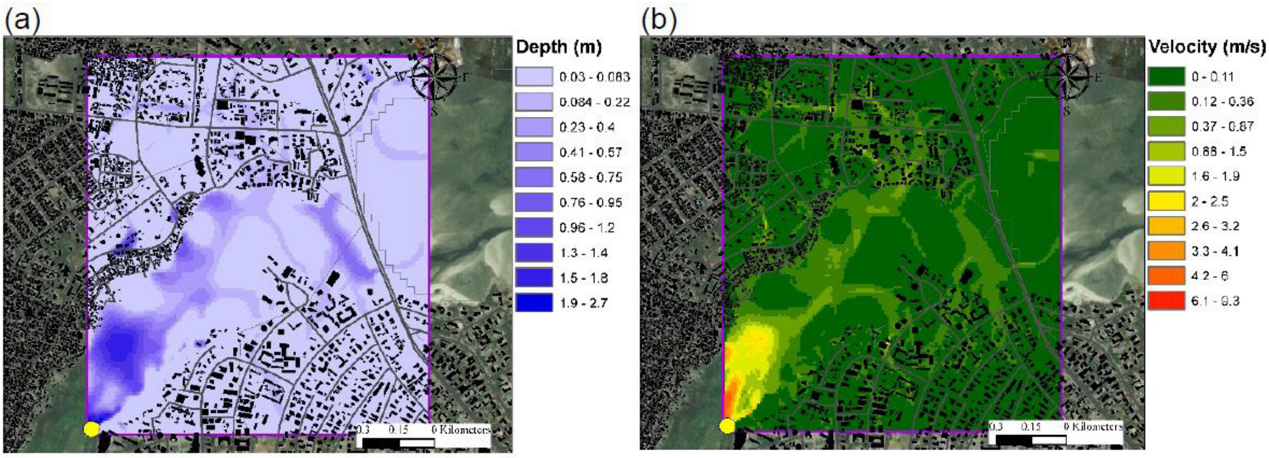

Figure A9. 18. Inundation results for the fifth sub-domain corresponding to TR = 300 years. (a) Inundation depth, (b) Flow velocity.

The hazard curves

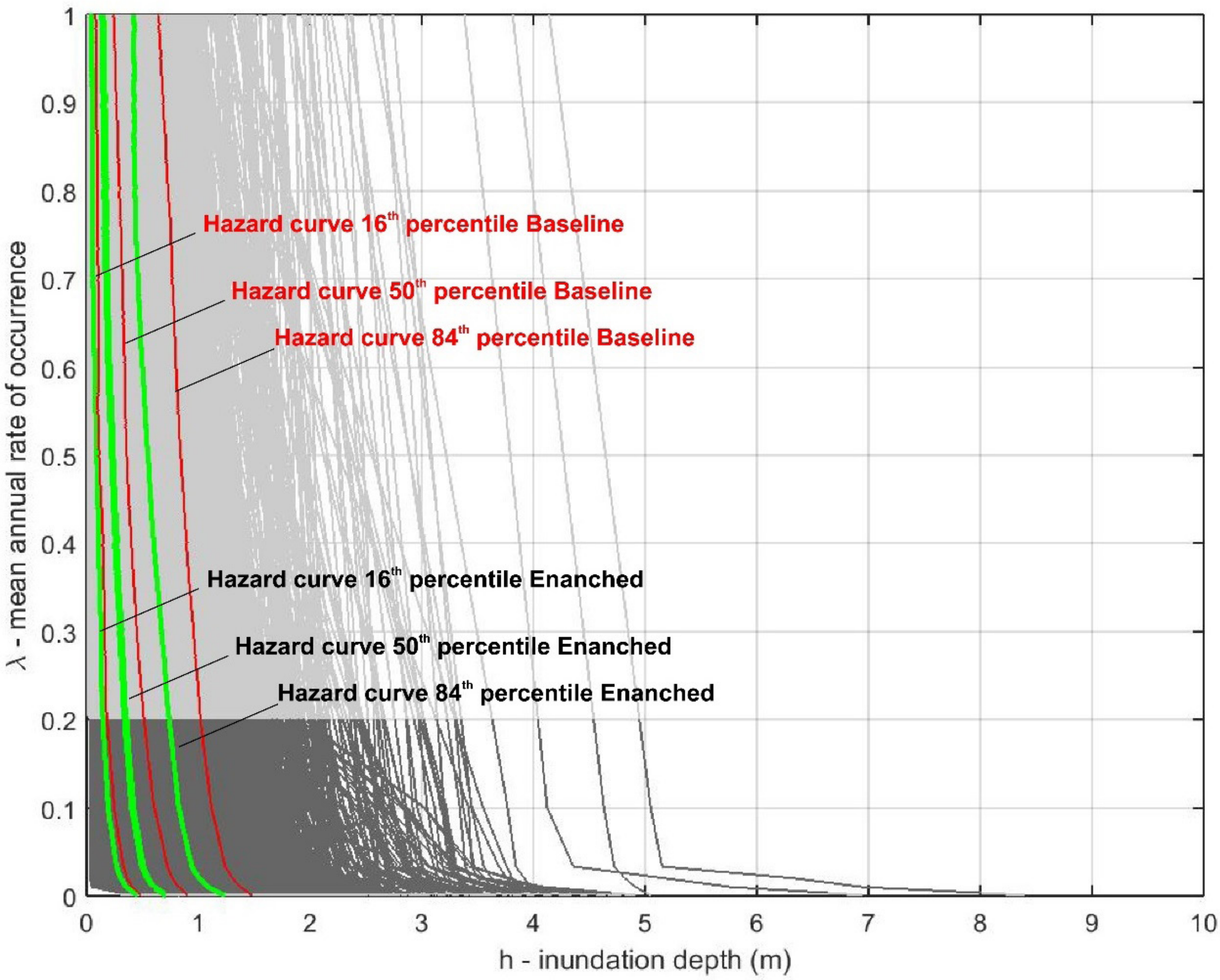

Figure A9.19 Hazard curves calculated for the mitigation strategies 4

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