Design With Terrain and Gravels: Nature-Based Drainage Solutions for Sustainable Stormwater Management of Urban Areas

(The Case of Jemo- Hurbu Watershed of the Little Akaki River Catchment in Addis Ababa, Ethiopia)

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This is to certify that the thesis prepared by Alazar Assefa Wondim, entitled with: Design with Terrain and Gravels: Nature-Based Drainage Solutions for Sustainable Stormwater Management of Urban Areas submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy in Environmental Planning complies with the regulations of the University and meets the accepted standards with respect to originality and quality

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Declaration

I, the undersigned, declare that this Dissertation is my own original work and has not been presented for a degree in any other University. All sources of material used for the dissertation have been duly acknowledged, following the scientific guidelines of Addis Ababa University

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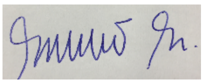
Signature: 

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Acronyms

AACA: Addis Ababa City Administration

AACRA: Addis Ababa City Roads Authority

ASCE: American Society of Civil Engineers

BMPs: Best Management Practices

CIRIA: Construction Industry Research and Information Association

CLUVA: Climate change and Urban Vulnerability in Africa

CSIRO: Commonwealth Scientific and Industrial Research Organization, Australia

CSIS: Center for Strategic and International Studies

DANIDA: Danish International Development Agency

DTM: Digital Terrain Model

EDRB: Elevated Detention Retention Basin

FDRE: Federal Democratic Republic of Ethiopia

EEA: European Environment Agency

ERA: Economic Report on Africa

GDP: Gross Domestic Product

GIS: Geographic Information System

IBTP: Infiltration Bumper with Tree Planter

IDF: Intensity-Duration-Frequency

ICLEI: International Council for Local Environmental Initiatives

IUCN: International Union for Conservation of Nature

MoHURD: Ministry of Housing and Rural-Urban Development (

MUDC: Ministry of Urban Development and Construction

NGOs: Non-governmental organizations

NMA: National Meteorological Agency

SDG: Sustainable Development Goal

SuDS: Sustainable Drainage Systems

UHI: Urban Heat Island

UN: United Nations

UNDP: United Nations Development Program

UNHSC: University of New Hampshire Stormwater Center

US EPA: United States Environmental Protection Agency

WGA: Water Resilient Green Cities Africa

WESS: World Economic and Social Survey

WSUD: Water Sensitive Urban Design

Design with Terrain and Gravels: Nature-based Drainage Solutions for Sustainable Stormwater Management of Urban Areas

The Case of Jemo- Hurbu Watershed of the Little Akaki River Catchment of

Addis Ababa, Ethiopia

'While floods are acts of God, flood losses are largely acts of man' American geographer Gilbert F. White, in his book Human Adjustments to floods, 1942

Abstract

Rapid urban growth and global climatic variability result in frequent flooding in urban areas and pose unprecedented stress on the existing drainage infrastructures. In developed nations, a shift in urban stormwater management from relying exclusively on gray, pipe-based drainage infrastructures towards green, nature-based approaches referred to as Sustainable Drainage Systems (SuDS), among others, is currently taking place. In cities of developing countries, the existing gray infrastructures are not well developed, prompting an opportunity of performing a technical leapfrogging towards SuDS. Through vigilant adoption of this increasingly-practiced nature-based drainage solution, municipalities can provide better drainage and flood control and create a fertile ground for more co-benefits to local residents in terms of livelihood and livability.

This Ph.D. thesis identifies options to improve the drainage challenge of settlements developed over higher slope terrains and low lying plains of urban areas in developing countries with the high rate of urban growth and drainage infrastructure deficit, through terrain modifications and introduction of gravel-based drainage design solutions as a nature-based drainage option to control flooding and provide co-benefits.

The study is presented in three parts based on two empirical studies from case sites, both developed in the south-western fringe of Addis Ababa, Ethiopia, and one desktop study building upon one of the empirical studies. The case studies present the design of novel drainage and stormwater harvesting solutions constructed by using locally available materials and terrain modifications. The first design is for drainage of cobblestone streets in hilly areas. The design is referred to as Infiltration Bumper with Tree Planter (IBTP) and targets flood prevention, groundwater recharges and city greening simultaneously. The second design is for the management of stormwater in low lying residential areas. The design is referred to as Elevated Retention and Detention Basin (ERDB), and targets waterlogging prevention, stormwater harvesting, and green area improvements. The first solution (IBTP) is developed and tested to control stormwater runoff generated from the local cobblestone streets within the designated case study catchments for a 2-year storm event corresponding to 40 mm over 2 hours. The second solution (ERDB) is developed and tested to control 100% stormwater runoff generated from the Jemo condominium (the multistory residential neighborhood in Addis Ababa) within the designated case study catchments for the same storm event. The desktop-study resulted in a GIS-based planning tool for upscaling of the IBTP to a city-wide solution.

The results of the study indicate that the design outputs are applicable to newly planned urban areas as well as retrofitting in already developed urban areas with similar land uses and geophysical situations. Moreover, by applying the nature-based drainage solution into a wider spatial scale, the systems ensure flood control with more co-benefits to human settlement frequently vulnerable to flooding and drought as compared to conventional methods. If considering the local context of cities in developing countries, the suggested designs can enhance the green infrastructure and contribute to the movement towards urban resilience. Future research should focus on implementation in municipal policies and guidelines, as well as full-scale pilots for refinement of the design. Citywide implementation of the solutions additionally calls for research on the institutional transition to support the technological transformation from relying only on gray to greener and sustainable drainage systems.

1. Introduction

1.1. General

The principal aim of this Ph.D. study was to investigate options for the nature-based drainage design solutions by dealing with terrains and naturally abundant materials like crushed stone gravel, sand, native soils, and vegetation in order to prevent settlements from flooding and associated environmental problems. The main focus was to contribute to nature-based solutions to reduce the negative impact of urbanization on flood-prone lands which are typically susceptible to flooding due to their terrain characteristics either developed on steep or flat terrains. Due to inconsiderate land use planning practices, urbanization still continues on those land features of cities and towns in different parts of the world. In cities of developing countries, the situation is more complicated due to underdeveloped drainage infrastructure to manage stormwater runoff generated in these often environmentally sensitive lands. In the era of climate change, conventional and engineering-based stormwater management options increasingly fail to solve the drainage problem sufficiently. Moreover, the well-known and widely practiced nature-based drainage solutions in cites of the developed world such as permeable paving, rain gardens, and vegetated swale may not be sufficiently efficient due to terrain characteristics, soil texture, and hydrology of areas. In this case, some additional context-specific and innovative nature-based design considerations may be needed in order to fit into such environmentally sensitive urban lands.

In general, the concept of nature-based solution embedded in the wider discussions on climate change adaptation, ecosystem services and green infrastructure (Kabisch et al. 2017). The concept defined by IUCN (2016) as "actions to protect, sustainably manage, and restore natural or modified ecosystems that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits". In urban settings, the natural system significantly modified by the development of buildings, streets and other infrastructure development activities. The nature-based solutions are able to restore and revitalize the natural system with the provision of multiple environmental benefits for urban communities if implemented properly as a blue-green infrastructure. According to the European Commission, blue-green infrastructure defined as "a strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services. It incorporates green spaces, blue or aquatic ecosystems and other physical features in terrestrial including coastal and marine areas.

Globally, cities and towns have been facing significant environmental challenges over recent years including extreme weather events, drought, and flooding (Coutts et al. 2012). Hydro-meteorological hazards have been the dominant hazard types, affecting Asia, mostly, with tropical cyclones and floods, Africa with drought, and Europe with extreme temperature changes and heatwaves (Thomas et al. 2013). Worldwide flooding is the number one cause of losses from natural catastrophic events, and even though the spatial impact is mostly local, regional or sometimes national, the consequences are all over the world (Taubenbock et al. 2011).

Urban areas by their distinctive nature concentrate people and their resources, thereby increasing risk and vulnerability. The 2018 Revision of World Urbanization Prospects estimated that recently 55% of the world's population of 4.3 billion people live in urban areas, a proportion that is expected to increase to 68% by 2050. Different researchers working at the global scale are emphasizing the challenge of flooding mainly posed by a combination of both global climate change and rapid urban development (Mcgranahan et al. 2007, Douglas et al. 2008 & Huong and Pathirana 2013). The adverse impact of rapid and uncontrolled urbanization over the natural landscape coupled with local and global climatic variability increase the risk of flooding together with the associated environmental crisis in different parts of the world.

In cities of developed countries, specifically, in Western Europe, North American and Australia, there is already a great range of measures in place to ensure that urban areas can endure extreme weather events. Well-developed engineering drainage infrastructure in the past together with the recent knowledge and practices on nature-based drainage solutions seems to lead those cities into climate-resilient cities of the future. In addition to the existing infrastructure, the emerging nature-based solutions such as green roofs, rain gardens, and bio-swales have been shown to reduce local flooding, economic loss, and discomfort caused by storm events with medium or frequent return periods (Kabisch et al. 2017). As the same author mentioned, there has been a rapidly increasing research on the efficiency and function of individual installations into multiple spatial scales to adapt to the changing precipitation dynamics to address the extreme events. In the case of cities in developed countries, particularly in the United States, the research and application of the nature-based drainage solutions increasingly considers water quality as an important factor in order to gain control of diffused pollution by implementing Best Management Practices (BMPs) in addition to stormwater runoff quantity issues (Castro-Fresno et al. 2013). When it comes to cities of developing countries, not least African cities, which are likewise increasingly exposed to both water scarcity and intense flooding due to extreme changes in weather patterns across the globe (CSIS 2018), the rapid rate of urbanization combined with neither conventional drainage infrastructures nor nature-based alternatives being in place at all. In this situation the quantitative control of urban stormwater is limited and the quality of stormwater drainage is still further off (Tucci 2007). Even when measures are taken to control stormwater runoff the first choice is typically conventional approaches to the modern infrastructure idea (Mguni 2015), leaving the nature-based solutions behind as a missed opportunity. The applicability of the nature-based drainage solution in developing countries possibly benefits their cities leading towards a resilient future to urban flooding and stormwater management. In the absence or with a deficit of basic drainage facilities, the solutions will dress more sustainable stormwater management options by targeting both quality and quantity.

1.2. Global climatic change and flooding

Recent scientific outputs suggest that climate change is likely to cause shifts in the global pattern and intensity of flood events, in some regions increasing the exposure of populations to severe flooding (Few 2003) and frequent drought in other regions intermittently. Climate change has the potential to severely challenge society in a number of ways including from the sea in form of higher sea levels and storm surges, from glacial lake outburst, which is a problem in countries such as Nepal (Horstmann 2004), and from precipitation where heavier rainfall may cause flooding and prolonged drought may cause water scarcity (Trenberth 2008). For instance, in the last two decades, European cities and towns were experiencing extreme flooding and drought across the continent. The summer of 2002 in Europe brought widespread floods but was followed a year later in 2003 by record-breaking heatwaves and drought (Trenberth 2011). Moreover, in the summer of 2007, extensive flooding in central England was accompanied by drought and heatwaves in southeast Europe creating an unprecedented climatic challenge (Trenberth 2011).

Developing countries are vulnerable to extremes of normal climatic variability, and climate change is likely to increase the frequency and magnitude of some extreme weather events and disasters (Mirza 2003). In Africa, increases in droughts, floods, and other extreme events will add to stress on water resources, food security, human health, and infrastructure, leading to a constrained development in Africa, likely to worsen the economic gap between the developed world having more resources to cope with climate challenges and thus be less affected. In the case of urban areas, global climate change is likely to affect built-up areas and infrastructure through sea-level rise and increased frequency of extreme events (Suarez et al. 2005). The combination of future changes in rainfall, land use, and drainage design will render most large urban areas increasingly vulnerable to extreme rainfall and pluvial flooding (Willems et al. 2012).

In the case of Addis Ababa, which serve as case city in this PhD-study, climate change analysis shows that there has been no significant change in the seasonality of rainfall, but an increase in rainfall from March to May is projected (CLUVA 2013). Further, the intensity of extreme rainfall events may increase. In the case of the substantial increase in rain intensity, additional challenges in stormwater management will follow. As the city is located at the bottom of the mountains, the impact of climatic variabilities together with anthropogenic factors manifested in the form of physical damage on manmade and natural structures, hazard on people and animals, loss of biodiversity, potable water scarcity, increase in water-borne disease, etc. These biophysical phenomena directly or indirectly affect the socio-economic situation of the community along and from the vicinity of the city to the river banks, to increasingly become a burden to the municipality.

1.3. Anthropogenic factors contribute to the flooding of urban areas

Flooding in urban areas is not just related to heavy rainfall and extreme climatic events; it is also related to changes in the built-up areas themselves (Douglas et al. 2008). Heavy rainfall is the most common cause of floods and the magnitude, speed of onset and duration of the flood will then be influenced by factors such as topography, vegetation and soils, river alteration, land use and urbanization (Few 2003). The recent increase in flood risk is highly intensified by land-use changes for urban expansion by altering the natural landscape and hydrologic cycle through a variety of human interventions. The most common human actions are sealing of natural land by impervious surfaces, terrain leveling, removal of vegetation cover, and draining the wetlands in the low-lying plains, all leading to elevated flood risk of cities (Arnold & Gibbons 1996, Dadson et al. 2017, & Gunnell et al. 2019).

Large areas of land are converted into impervious with buildings, roads, paved walkways, roofs, and parking areas, the area in which rainfall can infiltrate into the soil is reduced and flooding will be a common scene if adequate drainage systems are not in place. Distinctive nature of impervious surfaces is the productions of runoff during even relatively minor storm events with surfaces leveled and sealed which have limited depression storage to store and retain water (Barnes et al. 2015) Impervious surfaces can be defined as any material that prevents the infiltration of water into the soil and their coverage is a quantifiable land-use indicator that correlates closely with the adverse impacts of stormwater runoff (Arnold and Gibbons 1996). Runoff generated from these surfaces may be collected and diverted through a series of culverts and concrete channels which are impervious by themselves, and which cannot adjust to changes in the frequency of heavy rain, as natural streams do (Douglas et al. 2008). Estimating the contribution fraction of stormwater runoff generated from impervious surfaces and its impact on streams and other water bodies of urbanized and suburban areas is still under research by different scholars (Boyd et al. 1994; Arnold & Gibbons 1996; & Sabin et al. 2005).

Terrain modification and leveling of natural land may reduce the conveyance and storage capacity of the natural landscape and contribute to increments in stormwater runoff. Changes to stream channels during urban development can limit their capacity to convey floodwaters (Konrad 2003). Moreover, grading and leveling of natural depressions or blue spots can reduce the stormwater storage capacity of the landscape. Without natural depressions in the landscape, surface runoff volume increases. This could happen as a result of leveling from human activities and accumulation of sediments from erosion decreasing the stormwater storage capacity of the blue spots (Temme et al. 2005) resulting in flash flooding.

Removal of the natural vegetation cover of a landscape contributes significantly to the problem of flooding. Explicitly, vegetation cover loss in areas with higher slope gradient increases runoff and soil erosion and contributes to downstream flooding and even landslide in some geologically sensitive areas (U.S. EPA 2014, Giordan et al. 2017 & Piacentini et al. 2018). Surface runoff and river discharge generally increase when natural vegetation is cleared both for urban and agricultural development over the natural landscape (Sahin & Hall 1996, Costa et al. 2003 & Foley et al. 2005). By intercepting and retaining or slowing the flow of precipitation reaching the ground, trees (in conjunction with soils) can play an important role in urban hydrologic processes (Nowak and Dwyer 2007). In this regard, the importance of green vegetation cover in controlling stormwater runoff and associated soil erosion is enabled by intercepting and diverting stormwater runoff into the ground. In the short term, vegetation influences erosion mainly by intercepting rainfall and protecting the soil surface against the impact of rainfall drops; and in the long term, influences the fluxes of water and sediments by increasing the soil-aggregate stability and cohesion eventually improve infiltration (Zuazo & Pleguezuelo 2008). With the loss of vegetation, the fern layer is reduced and thus the macro soil fauna – especially earthworms are reduced and thus the bio-pores they construct, dry up the upper soil and thus the water storage capacity of the soil is reduced (Blanchart et al. 2004).

The other anthropogenic factor that increases the stormwater runoff and flooding in urban areas is occupying the low-lying plains along river banks and coastal areas. Developing mobility infrastructures and buildings significantly contribute to waterlogging and associated negative impacts on the water bodies and the entire urban environment. Many major towns and cities are located adjacent to rivers and there are continuing economic pressures to build in river floodplains (Wheater 2006). The development occurs formally through inconsiderate land development practices and informally by the encroachment of the floodplains, mainly in the case of cities of developing countries. These areas are normally categorized as high-risk areas in terms of flooding, and the existing development in the area must be prioritized for protection, retrofitting, or in worst case managed retreat and preventive resettlement (Wilby & Keenan 2012). Occupation of those lands increases the risk of flooding towards settlements developed over the flood plains as well as downstream communities. Obliviously, floodplains have the function indicated by their name; rivers can be expected naturally to overtop their banks every few years (Wheater 2006).

1.3.1. Contribution of human activities to flooding and associated challenges in Addis Ababa

In the case of Addis Ababa, a recent study has confirmed, the densely developed portion of the city to be more prone to flooding due to lower storage and more runoff compared to other areas, and that urban growth is a major contributor to an increase in runoff over time. As far as the increment of hard surface continues, flooding is imminent at the lower and mid catchment of the city. Since the 1980s, riverine flooding contributes to severe damage to peoples' life and property. The problem is more pronounced on informally developed settlements near to the banks of major streams and low-lying plains (Kefyalew 2003). Recently, the damage expanded to settlements and major infrastructures in downstream areas of the city due to more occupation and modification of the natural landscape along the river banks and hilly areas over the upstream. The loss of vegetation over such landscape with the capacity to reduce the negative impact of flooding contributes to the damage to the river ecosystem of the city. In this regards, flood plain, wetlands, and riparian vegetation along the river banks significantly reduced that able to contribute to the stormwater quality and quantity control at their natural status.

1.3.2. Current stormwater management and structural interventions towards flooding and associated environmental challenges in Addis Ababa

A study conducted by Kefyalew (2003) on the flood risks and control measures taken after the year 2000, shows the structural solutions developed along the rivers and streams over 15 years were mainly developed to contain stormwater within the natural banks of the major streams and rivers. Physical structures like terraces, retaining walls and gabions constructed in the upper and mid catchment of major rivers and other small rivers by different actors. The city also tried to mitigate the negative impact of flooding by planting of trees, shrubs, herbs, and grasses along the river banks in different parts of the city. However, the land degradation and hazard due to flooding continued throughout the city, except in some areas with adequate riparian vegetation rehabilitation carried out. In this regards, it will be difficult to control the negative impact of stormwater runoff in large and complex urban areas like Addis Ababa through piecemeal and single objective structural measures. Rather, coherent measures of stormwater management in reestablishing of the green cover through nature-based solution as a green infrastructure are needed.

Green spaces in urban and peri-urban areas of Addis Ababa are under threat from overuse for urban construction (CLUVA 2013) which substantially reduces the amount of natural land cover which stabilizes the flow of stormwater. Stormwater management in the city depend on technical drainage infrastructures (Backhaus et al. 2017), which are typically underground pipe or surface water channels, single-purpose by their nature and dislocating urban stormwater abruptly from the built environment into rivers. Such type of conventional practice for stormwater management concentrating runoff and carrying it away from the site as quickly as possible through storm sewers causes various problems including erosion, downstream flooding, and pollution loading of surface waters, and reduced groundwater recharge. To cope up with these environmental challenges, there are possibilities to reduce the amount of stormwater where it falls as precipitation by using green spaces, vegetation, and soil (WGA, 2013) as green infrastructure development. By weaving natural processes into the built environment, green infrastructure provides not only stormwater management but also flood mitigation, water purification, air quality management and much more co-benefits. Contextual nature-based drainage design solutions can be designed with key parameters to provide co-benefits consists of water supply for domestic use, irrigating green spaces, and groundwater recharging. Moreover, the nature-based drainage design solutions can be linked to the establishment of street trees network with better water supply from the solutions to provide shadowing and evaporative cooling.

1.4. Identified research gaps

Managing stormwater runoff from large urban/suburban landscapes is a complex task. It requires consideration of numerous factors, including site conditions, source areas (catchments), space limitations and cost-effective technological practices (US EPA, 2009). To come up with a convincing outcome in managing urban stormwater runoff through nature-based drainage design solutions, more research, and innovation is required in addressing various site conditions with different geophysical situations and materializing the ideas of co-benefits.

Unlike pipe-based systems that can be used irrespective of most geophysical conditions, various types of solutions are needed when it comes to the nature-based solutions. Virtually, there are several well-known nature-based drainage design solutions available which are developed and tested in different parts of the world. However, the applicability of those solutions is limited to specific geophysical conditions. For instance, nature-based infiltration elements like permeable pavements and rain gardens are more applicable on highly permeable soils and gently rolling terrains (Ballard et al. 2007).

In the case of steep terrains, the available nature-based solution are not effectively manages stormwater runoff through infiltration, retention or detention process due to the higher stormwater runoff speed. In this regards, we need solutions that calms the speed of stormwater runoff and facilitate more infiltration and retention which can operate based on the use of locally available natural or recycled materials and plant species. In the case of low- lying plains with waterlogging problems, the available solutions are not that much effective for infiltration due to saturated soils condition from the rise of ground water table and flat terrain. In this regards, creating more space for retention and detention with some terrain modification and using abundant natural or recycled material together with native plant species will be a good solution. There is very limited literature regarding the nature-based drainage solutions that are applicable in an urban setting with high slope terrains or on the low-lying plains with wet soils.

Globally, the available literature on improving the situations are mainly focused in rural or peri-urban settings with largescale engineering interventions such as increasing hillside vegetation and riverbank terrain modifications to minimize the risk of land slide and waterlogging respectively (Islam & Islam 2018). Large scale engineering interventions on the natural landscapes will harm the intervention area and usually transfers flooding problem to the downstream. The available literatures in the context of Ethiopia are mainly focused on soil and water conservation in rural settings (Sultan et al. 2018, Tebebu et al. 2015 & Mekuriaw et al. 2018) with particular emphasis on the natural resource management and livelihood improvement of farming communities rather than on the design, development and performance of the available landscape based drainage solutions. In this regards, there are published literatures on landscape based stormwater runoff management in the uphill areas for soil and water conservations, biodiversity improvement, food security and income generation for the communities participated in the project.

The problem of occupying flood prone areas for human settlement is more visible in cities of developing countries with continued land development practices over floodplains and encroachments of environmentally sensitive lands (Jha et al. 2012) however, the issue is also the concern of municipalities in developed countries (Löschner et al. 2016). In the case of Addis Ababa, flooding is prevalent because of the topography with steep mountains and low-lying flood plains with recurrent heavy rainfall (Backhaus et al. 2017) coupled with densely developed formal and informal urban expansion over naturally flood-prone areas. With the development of two innovative nature-based drainage solutions, this research aims to contribute to control urban flooding from settlements developed on those flood-prone land features and eventually enhance the green infrastructure of urban centers. Moreover, the design and development process of the nature- based urban drainage solutions documented together with runoff reduction performances of the solutions in the context of Addis Ababa, Ethiopia within subtropical highland climate.

In recent years, different studies have been conducted on the performances of well-practiced nature-based solutions for urban stormwater management and green infrastructure improvement (Davis & Naumann 2017). To improve the drainage conditions of areas with difficult terrain characteristics this study suggested two design solutions and one planning tool, thereby addressing the following issues relating to nature-based urban drainage design solutions:

- Practicality and capacity of nature-based systems for flood and erosion control under different geophysical condition, where critical design parameters include level of imperviousness, topography, hydrology, soil, and geology.
- Ability of nature-based systems to ensure co-benefits for the local community through multifunctional design solutions, enabling e.g. gardening, urban agriculture, water harvesting, and local climate improvement.

- Flexibility of nature-based system in terms of suitability for upscaling into the larger spatial unit and thus testing the flood control capacity of these system against conventional pipe based drainage infrastructures, e.g. in terms of implementation and operation costs.

The two novel and multi-functional nature based drainage design solutions have not been developed and tested before anywhere in the world with similar deign to solve specific type of drainage challenges. The IBTP system designed to operate through infiltration process and differs from the conventional infiltration trenches for its application under paved surfaces for space saving and to retain more water for tree growth within the tree pit. The ERDB system is also designed differently from the conventional wet ponds or gravel-bed constructed wetlands for its capacity to manage stormwater runoff without consuming open space as multi-functional green infrastructure. The system operates through retention and detention of runoff on surface system and within gravel media during rain event. Ultimately, the surface of the system free from any water and ready for human activities after the design two years rain events. Moreover, the system also operate effectively during extreme rain events by the provision of additional storage facilities for water harvesting of extra volume out of the system. Regarding to upscaling strategy, the use and application Arc GIS for the watershed level application of the IBTP system is original and new due to the nature of the system which is applicable on street profile.

1.5. Objectives

1.5.1. The general objective of the study

According to the research gaps identified above, the main research question addressed in this thesis is: ‘How can nature-based drainage solutions be integrated in roads and settlements developed over flood-prone areas with difficult geophysical land features to apply well-practiced and multifunctional nature-based drainage solutions?

The main objective of the research is to reduce the drainage challenge of settlements developed over relatively higher slope terrains as well as low lying plains of urban areas in developing countries, with high rate of urban growth and drainage infrastructure deficit through the introduction of gravel-based drainage and storage as a nature-based option to control flooding driven by rapid urbanization.

1.5.2. Specific objectives of the study

- To contribute to the development of nature-based solutions for drainage of local cobblestone streets in undulating urban terrain by proposing and subsequently testing a system for street drainage that can be implemented as a stand-alone solution with a capacity comparable to a conventional pipe-based street drainage system, and simultaneously contribute to groundwater recharging and greening of the city.
- To demonstrate how Arc GIS can be used as a planning tool for city-wide road drainage, returning not only the adequate spacing of nature-based drainage elements in response to road slope but also the number of construction materials needed and the associated benefits in terms of groundwater recharging.
- To develop a space-efficient nature-based retention and detention element for flood control in settlements developed on flood-prone plains of cities in developing countries, additionally providing multiple services including flood control, stormwater storage, stormwater treatment, and groundwater recharging, and allowing for use of the area in between events.

This study mainly focused on the potentials of nature-based drainage design solutions in urban stormwater management in the context of developing countries by taking special emphasis on settlements developed on flood-prone areas with high terrain and low-lying plains. However, the proposed nature-based drainage solutions can be applicable even in cities of the developed nations as a retrofitting for settlements within similar land features. Consequentially, the study aimed to work on identifying a more efficient nature-based solution that can replace the traditional pipe based drainage infrastructure depending on the respective context of climatic, geophysical features, land uses, and other factors. As such, the proposed and tested solutions in this particular study can be seen as being part of the global initiative by filling the research gap in the context of cities of developing countries with further validation on their performances in different contexts besides the case study area.

2. Theoretical framework

This section of the thesis presents the theoretical backdrops that support the study and contextual review on the possible application of nature-based drainage solution for stormwater management and other environmental benefits in the case study city, Addis Ababa. It highlights and explains the application of nature-based drainage design solutions for stormwater management of urban areas in line with five key concepts. The first section deals with the evolution of nature-based drainage solutions from emerging urban green infrastructure approaches and landscape architecture traditions. The second deals with the multiple ecosystem services obtained from open green spaces by applying nature-based drainage solutions as an integral part of urban green infrastructure and stormwater management strategy. The third presents the technological transformation from engineering-based gray infrastructure to green and multi-functional urban stormwater management infrastructure by introducing nature-based drainage solutions. The fourth presents the potentials of nature-based drainage solutions in linking green spaces and water to the livability and livelihood in an urban context. The entire theories, concepts, and ideas presented above are coined in the fifth section, which focuses on building urban resilience to flooding.

2.1. The merging of landscape architecture and urban stormwater management

As noted by Eisenman (2013), before the environmental concerns and wildlife corridors troubled in modern time United States, Olmsted – the founding father of landscape architecture said already in 1903 that "A connected system of parks and parkways is manifestly far more complete and useful than a series of isolated parks". Olmsted's idea conceptualized and continued to influence the urban design and planning practices in line with eco-hydrological values as green infrastructure or nature-based drainage design solutions, towards sustainable urban stormwater management initiative. In this regards, both water flow and urban landscape act as mutual drivers, and at the same time values are added to the public urban space (Sörensen 2016). However, most cities in developed, as well as developing countries, are still managing their stormwater using piped drainage and a flood control system.

Green infrastructure is a new term, but it's not a new idea. It has roots in planning and conservation efforts that started a hundred and fifty years ago (US EPA, 2007b). Green infrastructure in urban settings might include backyard habitat, street trees, and set-aside buffer along rivers and streams that protect against flooding (Benedict and McMahon, 2006). Green infrastructure as products includes nature-based technologies and practices that use natural systems or engineered systems that mimic natural processes to enhance the overall environmental quality and provide utility services US EPA (2013b).

The nature-based drainage solutions use vegetation, soils and other natural materials such as gravel and rocks utilized to absorb, retain and convey stormwater either to a storage facility for reuse or discharge stormwater into the natural drainage systems be it above or belowground. The system mainly operates with natural processes through infiltration, detention, and evapotranspiration of stormwater runoff by reengineering the available open green spaces and structures. The traditional solution to the stormwater management in western cities has been 'gray' infrastructure such as piped drainage systems which are mainly single-objective oriented designs to cope up with rainwater in urban landscape (Davis and Naumann 2017). Nature-based drainage solution as a green infrastructure may achieve urban drainage objectives by utilizing a mix of natural processes and green/gray components onsite. According to Ballard et al. (2007), rainwater harvesting systems, trees, green roofs, permeable pavements, bio-retention basins, swales, and wetlands are among the most common means of controlling runoff and supporting groundwater recharge.

In urban settings, there are several landscape design factors to be considered when introducing nature-based drainage solutions like green infrastructure for stormwater management and flood preventing measures. Among these, public safety requirements and esthetic performance for improving the quality of life in urban area are the most central. To meet public safety and aesthetic requirements in the design process of nature-based drainage solution, involving designers with expertise in mainstream urban landscaping and social structures are among the important factors (Sörensen 2016). Moreover, the elements by themselves can improve the quality of life in the city by integrating with day to day landscape architecture practices. Green spaces and water are key factors for the quality of life in cities with careful design consideration and adaptation to the surrounding buildings, infrastructure, and landscapes (Mrowiec 2016).

In the case of Addis Ababa, there are no green infrastructure development practices towards stormwater management or flood control measures except some attempts in the planting of trees, shrubs, herbs and grasses along the river banks, streets and parks for city beautification and river erosion control purposes. The attempts are based on older urban landscaping traditions which are not designed and developed carefully to cope with flooding and other environmental challenges associated with the high rate of urbanization and the current global climatic variability. The city has just recently started to think along lines of sustainability and the potential of green infrastructure, thus there is still little capacity for adapting planning regimes towards this line of thinking due to the existing institutional setups and knowledge gaps in the municipality (Herslund et al. 2017). In this regards, the introduction of landscape based urban stormwater management design and technological practices by WGA project by developing full scale demonstration site for water quality improvement and runoff reduction (Adugna 2018 & Yeshitela et al. 2017) is a good opportunity for the citywide application of the nature- based drainage systems.

2.2. Ecosystem services

Landscapes differ in their capacities to provide ecosystem goods and services, which are the benefits humans obtain from nature (Burkhart et al., 2009). These include supporting, provisioning, regulating and cultural services. Preserving and linking of natural areas as green infrastructure help to protect and restore naturally functioning ecosystems and provide a framework for future development (Benedict and Mc Mahon, 2001). Moreover, recognizing the ecological functioning within the boundaries of urban complexes has several benefits obtained through exploiting urban ecological functioning to process wastes, slow the flow of water, mitigate climate, and promote health and human wellbeing, quality of life in cities and quality of environment downstream can both be enhanced (Pickett et al., 2010).

Urban stormwater management, particularly flooding and water pollution have become a critical issue in academia and practices of developed countries since the 1970s (Fletcher et al. 2014). Urban green does play a crucial role in the regulation of the stormwater by reducing flooding and filtering wastewater and using the landscape for stormwater management can also offer synergies such as an enhanced urban green infrastructure (Ahern, 2008). However, planners and designers will be challenged to find new ways to provide for sustainable ecosystem services in the increasingly limited spaces within compact cities (Ahern 2012). In this regards, multifunctional and innovative nature-based drainage solution on the available open spaces, streets and other urban areas offers good opportunity to maximize the ecological benefits of urban areas from green infrastructure within space shortage situation.

The ecosystem services of nature-based drainage solutions are beyond the stormwater regulating services. The solutions have the potential to improve water quality, mitigate flooding, replenish groundwater resources and enhance green infrastructure. Eventually, the green infrastructure developed as a nature-based drainage solution reduce the risks of climate change, such as heat island effect and flash floods, while simultaneously providing greater health and well-being for urban residents (Luise Blau et al. 2018). However, the value of urban ecosystem services remains highly uncertain, especially across the diverse social, ecological and technological contexts represented in cities around the world (Keeler et al. 2019). The value of nature-based drainage solutions as green infrastructure actions is calculated by comparison to the cost of conventional gray infrastructure alternatives, the value of avoided damages, or market preferences that enhance value (Foster et.al 2011). There is a perception that green infrastructure is not as cost-effective as gray infrastructure however, green infrastructure can be shown to provide more value than gray infrastructure at comparable cost (US EPA 2013). The indirect benefits such as low maintenance cost and another environmental quality improvement in addition to stormwater management services will pay even the higher cost of development initially encore.

In the case of Addis Ababa, the benefits of incorporating nature-based drainage solutions as green infrastructure will be much effective instead of concentrating only on expanding gray drainage infrastructures to reduce the risk of flooding form densely developed upper catchment of the city landscape. Recently, the flood risk is exacerbated by uphill deforestation, urban land use change with increased impervious surface cover and the scarcity and clogging of formal drainage systems in the city

(Backhaus et al. 2017). Natural landscapes and green spaces in urban and peri-urban areas of Addis Ababa are substantially reduced to the level of elimination (Yeshitela et al. 2016) except in the Northern and North- Eastern mountain ranges of the city with intact forest cover like Entoto. At natural state, those green elements of the city landscape can stabilize the flow of stormwater from the uphill areas to the downstream and densely developed parts of the city. There are no visible attempts made from the local government to apply the nature-based drainage solutions or maximizing the capacity of natural landscape within the city, neither for regulating stormwater runoff except some riverbank or for hillside greening.

2.3. Technological transformations

The traditional solution to cope with excess stormwater in western cities has been piped drainage systems that often no longer have the capacity to keep pace with on-going urbanization and the impacts of climate change, and frequently involves high construction, maintenance, and repair costs (Davis and Naumann 2017). Such type of conventional practice for stormwater management concentrating runoff and carrying it off a site as quickly as possible through storm sewers causes various environmental problems, including erosion, downstream flooding, and pollution loading of receiving surface waters, and reduced groundwater recharge (CSIRO 2006). As Fletcher et al. (2014) noted, the trend in Europe, North America and Oceania is to move away from conventional drainage systems or at least complement drainage infrastructure with different nature-based drainage approaches, called Sustainable Urban Drainage Systems (SuDS), low impact development (LID) or Water Sensitive Urban Design (WSUD), among others.

The primary goal of sustainable urban stormwater management is to generate no additional runoff from the existing site or urban area compared with pre-development conditions. Accordingly, urban stormwater management should emphasize the restoration or protection of natural hydrologic processes at small scales, to restore natural flow regimes at larger spatial scales at the downstream (Burns et al. 2012) to achieve the entire urban water management objectives. Nature-based solutions and similar concepts such as urban green infrastructure are often described as approaches aimed at promoting sustainable urban development (van der Jagt 2017). It is a type of an integrated nature-based drainage design and planning approach that minimizes generation of stormwater runoff and "mimics" the natural water cycle.

According to CSIRO (2006), the approach limits runoff and potential pollutants from leaving the site. This can be achieved through the following ways and steps.

- An integrated design approach that involves configuring the location and placement of impervious surfaces.
- Establishing structural landscape based practices for stormwater infiltration, detention, and treatment.
- Providing appropriate stormwater pollutant removal devices where significant pollutant sources occur.

The system integrates open green spaces with ponds and constructed wetlands utilized for stormwater regulation and water filtration (Benedict and McMahon, 2001). Moreover, vegetated fields and natural landscapes with some terrain modifications used to absorb, harvest and convey stormwater either to a storage facility for use or discharge it into natural drainage systems in the downstream area after the rain events. These include rain/ gardens, infiltration trenches, grass swales, and others. Moreover, permeable pavements made from porous materials, such as permeable asphalt, permeable concrete, permeable interlocking concrete pavements, concrete grid pavers and plastic reinforcement grid pavers with a layer of soil underneath (sub-soiling) are also utilized to enhance infiltration (Scholz & Grabowiecki 2007).

In the case of Addis Ababa, the existing man-made and conventional drainage systems are strained by high surface runoff generated from the emerging built-up areas and pollutants from illegally connected sewer systems. However, the city has given little attention to reducing the impact of flooding through nature-based or as gray drainage infrastructure, creating a serious challenge to the city's built structure at downstream areas. As a result of the poor performing drainage system of the city, the rivers of Addis Ababa serve as the main drains for stormwater and are also used as the disposal of domestic and industrial wastewater, whilst the rivers are crucial for the water supply of the city (Tamiru 2001 & Adugna et al. 2018). Recently, the riverside landscape is documented to be the most exposed sites for flooding and landslide disasters, attracting a lot of attention from the city government and various NGOs (Cherenet 2015).

To cope with the challenge associated with flooding, the nature-based drainage solutions together with other green infrastructure provisions can replace or compensate the existing gray infrastructure. In this regards, the recent attempt to convert all muddy local roads of the city into cobblestone pavement is a good initiative as a start for transition from gray to nature-based and green drainage infrastructure in urban stormwater management. Cobblestone pavements by their nature partially infiltrate the stormwater runoff into the ground rather than paving with asphalt which is completely sealed the natural ground. The excessive runoff generated from the cobblestone pavements typically managed with the provision of gray drainage infrastructure. However, several drainage problems occurred after the implementation of cobblestone streets and created unexpected flooding and erosion on the surface of the pavements in different parts of the city. To improve the runoff control capacity of the cobblestone street to the highest level, nature-based drainage solutions can be installed to supplement or to replace the existing gray drainage provisions depending the local context. Specifically, in those areas with difficult geophysical features consisting of high gradient and poorly drained native soils, the infiltration performance of the cobblestone is usually lower and an additional nature-based solution to improve the drainage problems is needed.

2.4. Linking livability and livelihood to green spaces and water

In an urban setting, green spaces serve as a recreational place for the inhabitants, particularly kids and the elders spend more time on the outdoor green spaces. In the case of areas with low-level socio-economic status green open spaces serve as a local meeting place (Hadavi et al. 2015). To ensure the supply of green spaces, future urban design, and planning practices could ambitiously look at the potentials of underutilized or unutilized urban open spaces and structures (Mesimäki et al. 2017) for more recreational and other socio-economic benefits. In the case of densely developed cities, rooftops, fences, playfields and parking lots can be designed as a green infrastructure by incorporating the nature-based drainage solutions. In this regards, the inclusion of man-made ecosystems in urban areas like green roofs could be considered as the creation of socially and ecologically complementary habitats for experiencing urban nature in the absence or shortage of open green spaces (Mesimäki et al. 2017).

High level of livability can be experienced even in densely developed urban areas through linking the community to greener nature by the use of the blue-green system over the available spaces and structures. Increasing evidence has shown that design with nature can achieve multiple benefits through multifunctional landscapes by considering the role that nature plays to the quality of life in urban settings (Yang et al. 2013). Green spaces and water bodies in cities improve the quality of life from valuable contributions such as local climate regulation, air quality, and flood control (Ruth & Franklin 2013). In this regards, the inclusion of nature-based solutions into the available open spaces and structures provides opportunities for increased amenity value and place-making in addition to stormwater management solutions to reduce flood risk and attenuate surface water runoff (Vernon & Tiwari 2009).

In the context of cities of the developed world, nature-based drainage solution offers multiple contributions to the livability, sustainability, and resilience of cities by supporting urban agricultural and urban gardening practices through delivering water for irrigation. The most obvious benefits of urban agriculture are related to the production of fresh fruits, vegetables, and other foods for urban residents nearby (Lovell 2010). In Addition to local food production, urban agriculture provides a place for recreation, social interaction and community engagement and more ecological benefits to the community (Lin et al. 2017).

As a multifunctional landscape, urban agriculture should be seen as a beneficial tool for urban planning not only because of its ability to function as a nature-based stormwater management strategy but also due to the multiple social and environmental benefits it provides. As the world urbanizes, greater local food self-reliance, using nutrients accumulating in our cities, must be regarded as an important aspect of sustainable urban development. In fact, in cities of developed nations especially in the US, incorporating appropriate types of urban agriculture practice into the urban environment has been found to improve the overall sustainability (Rogers & Hiner 2016) and green infrastructure for stormwater management and climate change adaptation measures in particular.

In cities of developing countries, urban food growing is certainly one of the options for low-income people to create livelihoods for themselves. In general, urban agriculture is present throughout the world in a diversity of farming systems, and it is estimated that 25-30% of urban dwellers are involved worldwide in the food production (Orsini et al. 2013). By considering the local hydrologic factors, stormwater generated from buildings' rooftops & other impermeable surfaces can be used for irrigation through water harvesting schemes of nature-based drainage solutions for self-sufficiency in urban farms.

In the case of Addis Ababa, the nature-based drainage solutions are not practiced deliberately for improving the livability of urban centers or livelihood improvements of the dwellers. However, the livelihood study in Jemo river catchments of little Akaki river has shown that the local green spaces and water bodies provide a livelihood to a considerable number of households and the available green spaces used for recreation, socializing and to mitigate temperature increase (Yeshitela et al. 2017). Moreover, there are opportunities for building water-resilient livelihoods within specific local situations through managing water resources and green spaces (Workalemahu et al. 2018) sustainably through multi-functional and nature-based drainage design solutions.

There are more irrigation potentials from the nature-based water harvesting schemes for farming communities along the river banks and gardening opportunities for the residents within the residential areas in the downstream areas of little Akaki river. In other words, effective planning and implementation of nature-based drainage solutions will improve the livelihood of local farmers working along the little Akaki river bank and contribute to improving the livability of the housing areas through provision of water for irrigation to improve agricultural productivity and enhancing the local green space quality. Specifically, the nature-based drainage solutions will provide additional water for the irrigation from the systematic rooftop and paved street surfaces harvesting schemes in addition to the customary riverine irrigation practices in the area.

2.5. Building urban resilience

According to Holling (1996), the emerging theory of resilience or resilience thinking is based on several key concepts and ideas, including thresholds or tipping points, alternate stable states or regimes, regime shifts, complex adaptive systems, adaptive cycles, panarchy, and transformability. Zevenbergen (2016) defined and presented flood resilience into two specific categories. The first one is more traditional and applied in engineering and conceptualized as the ability of a system to resist or absorb disturbances and to remain functional under a wide range of flood wave or rainfall intensities. In the second category, Zevenbergen defines flood resilience as a broader concept of socio-ecological resilience and is typically defined from a holistic system's perspective. Recently, nature-based drainage solutions are becoming a potent tool to improve the quality of urban spaces in addition to urban resilience by improving the capacity of populations to cope with stressors in general and, therefore, to extreme events such as flooding.

In an era of climate change, water scarcity, extreme heat and coastal, river and rainwater related flooding events that directly or indirectly through e.g. reduced food yields in peri-urban areas affect urban areas and their inhabitants in industrializing and industrialized countries (Satterthwaite et al. 2010). The negative impacts of flooding and other climate change hazards threatens the economic resilience of cities and heighten their vulnerabilities in particular to developing countries and some industrialized nations (WESS 2013). Vulnerable human settlements in megacities and agglomerations of developing countries highlight the urgency for cities to improve and maintain their existing gray drainage infrastructure. In this regards, cities have to start perceiving those challenges as opportunities of investment and building cities resilience to serve as the main pillars for a sustainable world (WESS 2013) to look into greener and more nature-based solutions. With a shift in perception and creative planning and design, cities can eventually improve flood-control infrastructure and live with floods by retrofitting the built environment and adding redundancy, diversity, and flexibility into every subsystem (Liao 2012). Adapting to climate change and improving urban resilience to extreme weather events and natural hazards are crucial strategic goals for towns, cities, and metropolises all over the world through nature-based solutions depending on the local and regional context (ICLEI 2017). Accordingly, cities should rely on a mix of gray, green and blue infrastructure solutions, which balance traditionally built infrastructures with more nature-based solutions and thus improve the management of urban water, heat, and other climate-driven threats (Depietri & McPhearson 2017).

In the context of Addis Ababa, besides technical provisions, there are possibilities to manage the stormwater where it falls as precipitation by using green spaces, vegetation, and soil as a nature-based drainage solution (WGA, 2018), and reducing the amount of water send off to further management downstream. The existing man-made and conventional drainage systems of the city are underdeveloped and strained by high surface runoff generated from the emerging built-up areas and pollutants from illegally connected sewer systems. However, the city has given little attention to the flooding, which is creating a serious challenge to the city natural landscape and the built environment. The city administration has given more emphases on providing safe water and sewerage system to households which necessitate immediate action rather than investing in drainage infrastructure.

According to CLUVA (2013), nearly 50% of the land cover of Addis Ababa as a whole can be grouped as impervious and the trend in the conversion of natural landscape continued. As a result, even small amounts of increment in impervious cover can have large effects on stormwater flow pattern and eventually on stream ecosystems of the entire city and the downstream rural lands. In this regards, considering nature-based drainage solutions for stormwater management as well as in day to day urban development activities as green infrastructure, vulnerable human settlements in the city will be made more resilient to flooding and associated environmental challenges.

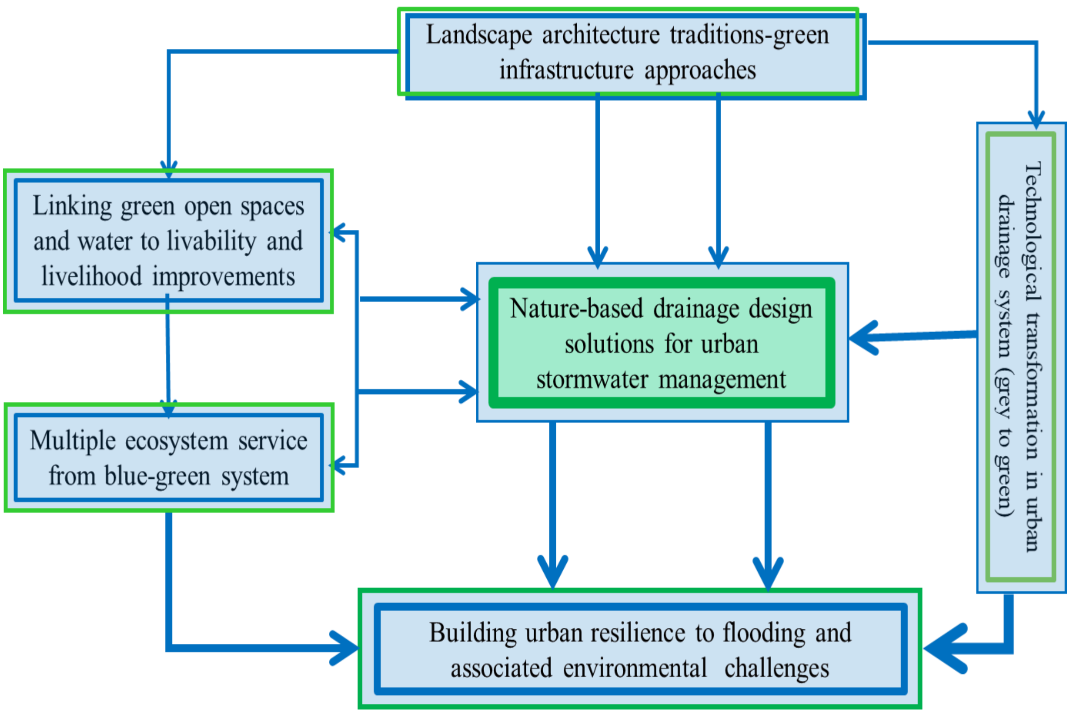

Figure 1: Diagrammatic representation of the conceptual framework of the research, reflecting how urban resilience based more on nature need to follow both a technical and social-economic track

3. Methodology

3.1. Description of the case study area

Addis Ababa is the capital city of the Federal Democratic Republic of Ethiopia (FDRE). The city lies at an altitude of 2,300 meters, located at 9°1′48″N 38°44′24″E Coordinates at the foot of Mount Entoto and forms part of the watershed to the Awash Basin. From its lowest point, around Akaki, at 2,100 meters above sea level in the southern periphery, the city rises to over 3,000 meters in the Entoto Mountains to the north. The form of the terrain varies with the city structure classified into different slop categories of flat (0-5%), gently rolling (5.1-10%), hilly (10.1-15%), and mountainous areas (more than 15%). As a result of the significant variation in terrain characteristics within a city; several prominent landscape features are visible in the form of cliffs, canyons, mountain peaks, ranges of hills, plateaus and others characteristics landscape features.

According to Koppen climate classification, Addis Ababa has a subtropical highland climate with complex mix of highland climate zones. According to the National Meteorology Agency (NMA) of Ethiopia the long wet season is from June to mid-September; it is the major rainy season of the country. Addis Ababa gets an average of 1089 mm of rainfall per year with the driest period is in November with an average of 9 mm of rainfall and the wettest month is in August with an average of 269 mm of rainfall. There are seven big rivers, six medium sized, seventy five small rivers forming a network in the city of Addis Ababa (AACA, 2011). The entire river system of the city drained into two major river systems, greater Akaki and little Akaki which are the tributaries of the Awash River. The rivers originate from north and north western mountains and flow to Aba Samuel Lake to the South.

3.2. Research design and methods

In the beginning, an in-depth literature review was conducted to provide foundation for the entire Ph.D. and to establish a conceptual framework of the research in line with the applicability of the nature-based drainage solution to build urban resilience towards flooding and other climate change driven environmental challenges. The reviewed pieces of literature included contemporary knowledge of nature-based drainage solutions in line with landscape architecture tradition, green infrastructure development, ecosystem services and transition from only gray to greener and sustainable drainage solutions in urban stormwater management. The research method applied in the study can be described as a mixed research approach consisting of action research with full-scale experiments for the development of specific nature-based drainage solutions in the two case study sites, followed by an analytical approach to data exploration through Arc GIS exercise. The two case sites employed in the study are both located within Jemo river watershed of the little Akaki river system of Addis Ababa city.

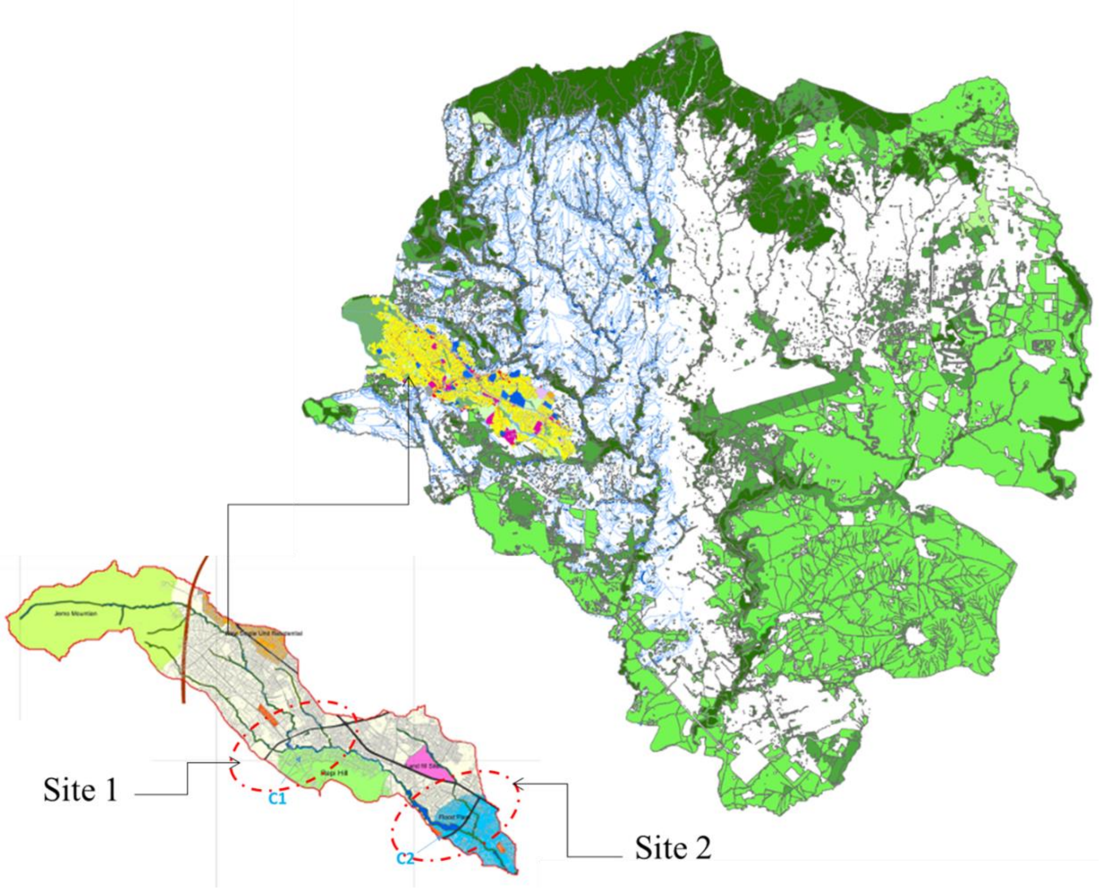

Figure 2: The map of study area Jemo watershed land use map overlaid on river and stream network of little Akaki river catchment and green cover map of Addis Ababa.

3.3. The two case studies

The study area - Jemo river watershed is located in the western fringe of the city within the little Akaki river system (Fig 1). The two case sites in the upstream and low stream of the watershed selected for their depiction in settlement pattern and terrain characteristics as well as due to the observed flooding problems. Regarding the settlement patterns, there are large scale single family residential settlements in the upstream area and residential Multi-unit (Condominiums) in the downstream selected for testing different types of nature-based design and technologies. The topography of Jemo watershed is highly diverse, ranging from steeply terrains in the upstream Repi hill area to flat terrains to the downstream areas of the Jemo condominium site. In this regard, the case sites selected to develop nature-based design solutions, particularly to address stormwater challenges on hydrological units consists of flat terrain from 0%-5% and high terrain from 15% - 20%. The two hydrological units are found in residential neighborhoods, specifically over the local streets with flooding and erosion problems and on community open spaces of Jemo condominium with the waterlogging problem. In principle, the design of the nature-based design element is based on four hydrological mechanisms consists of temporary storage, infiltration into the soil, evaporation into the atmosphere, and conveyance to the main water systems (Jensen et.al, 2013).

In general, the study used watershed selected by the WGA project team which identified for developing a landscape-based stormwater management strategy based on different criteria to test appropriate multi-functional nature-based drainage design technological practices. Among these, the most relevant criteria are listed as follows.

- Reduction of complication for validity or verification of scientific facts
- Diversification of land use and landscape features for upscale effects of the research results in different parts of the city.
- Availability of open spaces or the possibilities for conducting various tests.
- The willingness of the local government organs and the residents to work together in developing different LSM measures.
- Absence of previously recorded landscape based structural or nonstructural intervention in the area to manage the stormwater or alleviate water shortage throughout the watershed.

Among the two case study sites, the first site is selected from up-hill areas of the watershed from settlements developed around Repi hill and the second case site is selected from settlements developed on the low-lying plains on the downstream areas. In the first case site, an infiltration and retention-based drainage solution were developed and tested for the local cobblestone streets at the uphill areas of the watershed to control flooding and erosion from the surface of the cobblestone pavers. The research method applied here is exploratory research tools to identify the flooding problem in the case study based on the researcher observations, discussions with key informants from the local community, local authorities and experts' opinions from Addis Ababa City Road Authority (AACRA). Exploratory research is a methodological approach that is primarily concerned with discovery and with generating or building theory (Jupp 2006). The focus of exploratory research in this regard is on creating clear insights with the issue of flooding at the preliminary stage and to facilities for the later investigation on identifying appropriate types of nature-based drainage design solutions for the flooding and erosion control from the cobblestone paved streets.

In line with the results of exploratory research and literature review on the design principles of different types of nature-based solutions, the researcher proposed an infiltration and detention-based street drainage solution for the first case and detention and retention system for the second case. Specifically, the study designed and developed the Infiltration Bumper with Tree Planter (IBTP). Among the widely practiced nature-based solution such as curb extension and vegetated swales, the proposed system designed to be more space-efficient and multifunctional. The system designed to accommodate the main drainage unit within the road profile rather than parallel as of a conventional ditch or pipe-based drainage system. A full-scale experiment was used to test the performance of the proposed IBTP, using two comparable street sections with the same catchment area (with and without provision of the proposed system) as experimental setup on selected flood and erosion-prone street. The entire development process and the performance of the proposed drainage solution in flood control with co-benefits presented as a paper one in the fourth chapter of the thesis in title with "Groundwater recharging, erosion control, and city greening – a novel nature-based system for road drainage".

The IBTP drainage solution was only tested for higher terrain with permeable soil conditions; however, the study also demonstrated the applicability of the solution into a wider spatial scale with diverse landscape conditions with a significant impact in stormwater runoff reduction and additional benefits by the use of GIS-based upscaling tool. To consider conditions for and impacts of upscaling the suggested and tested IBTP drainage solution, the Arc GIS-based planning tool was used by adjusting the placement of the designed drainage element along with the profile of the streets throughout the watershed. In developing a GIS-based decision support system for the instrumentation of the system with an effective spacing mechanism, the main focus was the consideration of three relevant geophysical factors in the watershed, including the slope, soil texture and groundwater table of the watershed. However, the study was limited to the slope due to the absence of accurate data on the remaining factors. Quantification and cost estimate of the proposed nature-based drainage solution was conducted based on the dimensions obtained from the Arc GIS platform. The planning part of the proposed nature-based drainage solution is presented in the second paper or in the fifth chapter of the thesis in title with “City-wide planning of nature-based street drainage scheme with Arc-GIS”.

In the second case study site, retention and detention-based drainage solution were developed and tested to improve the waterlogging problem of high-density residential areas (condominiums) in the low-lying plains of downstream areas. The research method applied to identify the waterlogging and associated flooding problem is the exploratory research method. In this case, the community design workshop (design charrette) conducted for three days by Water Resilient Green Cities of Africa (WGA) project in June 2015 used to identify the key challenge of the case site regarding flooding problems and green infrastructure development. The Green Infrastructure Charrette can be created as a mini think-tank to promote multi-disciplinary problem solving with planners, researchers, architects, landscape architects, academics and "sustainable thinkers" alike (Benedict and Mahon 2006). Design charrettes are a powerful tool for bringing together diverse interests and disciplinary expertise to explore options and generate visual ideas and potential solutions (Girling et al. 2006).

In line with the wishes and interests of the local community, the researcher designed and developed Elevated Retention and Detention Basin (ERDB) over open space available in flood-prone areas of the condominiums. Moreover, the experimental set up developed to observe the performance of the proposed drainage system. The final output of the case study two is presented in paper three in chapter six of the thesis as "Above ground stormwater gravel storage for urban drainage and rainwater harvesting in low-lying plains".

Figure 3: Diagrammatic representation of the research design and methodological approach of the research. The broken line at the bottom of the diagram represents parameters for upscaling that are not fully addressed by this research and recommended for further study in order to close up the loop in the research process

4. Paper I: Groundwater recharging, erosion control and city greening – a novel nature-based system for road drainage

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Abstract

Contemporary practices of stormwater management in urbanized catchments are shifting from conventional pipe-based discharge systems towards more nature-based retention systems. We designed a road drainage system that can trap stormwater by the use of infiltration trenches placed perpendicular to runoff direction, thus preventing downstream flooding and erosion while enhancing groundwater recharging. Further, we connected the system to tree pits to support the development of green infrastructure. The design was tested on a typical, sloping cobblestone street in Addis Ababa, Ethiopia. From the analysis of drainage patterns as logged with pressure transducers over a 24-day long rainy period, we conclude that the infiltration trench received runoff not only from the road surface but also from interflow in the gravel layers serving as bedding for the cobblestones. If spaced correctly, the suggested infiltration trenches hold the promise of a future multi-beneficial drainage system that can be implemented as standalone elements constructed with gravel materials.

Keywords: infiltration trench, street tree irrigation, groundwater recharging, infiltration bumper with tree planter, climate adaptation & flood control.

4.1. Introduction

Streets are developed to provide access and facilitate mobility. To ensure this as an open ditch or an underground pipe (Zhou 2014 & Pazwash 2011). Continued urbanization and climate change have caused stormwater runoff to increase in volume, leading to problems with pluvial flooding and erosion. In response, more nature-based designs for urban drainage have emerged in cities of high-income countries as an alternative to the incremental enlargement of conventional pipe-based approaches. Rather than discharging the stormwater runoff, it is infiltrated, evapotranspired and detained locally, often as part of a larger program for urban development or retrofitting. This approach has been referred to as 'low impact development', 'green infrastructure stormwater management', 'sustainable urban drainage systems', 'sponge city concept', 'water sensitive urban design', or 'onsite stormwater control measures', among others (Fletcher et al. 2015 & MoHURD, 2014). Regarding street runoff, the contemporary nature-based approach has resulted in innovative solutions, including curb extensions and permeable pavements (Cederkvist et al. 2016). By retaining the runoff volume on-site, the approach to street drainage has the potential to contend with additional challenges, such as urban heat island by including shadow-providing trees; loss of biodiversity by creating new habitats with native species; or traffic congestion and hazards by using the drainage design to control motorized traffic and encourage pedestrians and bicyclists (Foster et al. 2011, 2012). In low-income countries, where most urbanization takes place, the path to sustainable urban development may be shortened if more sustainable drainage infrastructures are adopted directly, rather than following the path of conventional infrastructure (Mguni et al. 2016).

Addis Ababa, the capital city of Ethiopia, is an example of such a city in a low-income country. Here, the annual increase in the urban population of 3.0 %-3.8 % (UN-Habitat 2017& World Bank 2015) is accompanied by the strong economic growth of around 10 % in GDP since 2005 (Sennoga et al.2017). This growth has allowed for investments in the built infrastructure, including the conversion of soil streets into streets with the hard pavement. According to the Addis Ababa City Roads Authority, AACRA, the majority of local streets are already undergoing or will soon be converted into cobblestone streets over the coming decades (AACRA 2015). This plan will be executed with the exception of those streets already paved with asphalt, located in high-income neighborhoods and commercial districts. Often a shared cost model is adopted, whereby costs are shared among plot owners along the street and the city government (MUDC 2012).

Cobblestones represent a natural building material. Cobblestones are stones cut into cobble-size and used for paving streets, sidewalks, parking areas, etc. The construction is simple, in that the slightly pointed cobblestones are wedged into a gravel-based bedding layer, with a depth of approximately twice the height of the cobblestones. The bedding layer lies upon another leveling layer of coarser gravel materials. Due to rather large joints, a cobblestone pavement has more capacity to reduce stormwater runoff than smoother paving materials with narrower joints or no joints at all such as asphalt, bricks, and concrete pavers. According to Rim (2011), a cobblestone pavement with a joint width of 3 mm, joint area of 5% and the cobblestone area of 95% has a runoff coefficient of 0.2. Due to the semi-open character of the surface, it is ideal for permeable paving applications, provides benefits such as reduction of runoff, recharging of groundwater and reduction of pollution (Scholz & Grabowiecki 2007).

Despite the advantages of cobblestone, newly constructed cobblestone streets in Addis Ababa often appear to deteriorate within a short period of time after construction. During heavy rain, particularly in steep streets, surface runoff results in erosion and fragmentation of the cobblestone pavement. Further, since the cobblestone streets are equipped with an open drainage channel running parallel to the street, downstream pluvial flooding and sewer overflow are common occurrences during rainy seasons. These issues are illustrated in Figure 4. If a nature-based drainage scheme can be implemented, the problems of both flooding and erosion may be diminished. Additionally, with an infiltration-based solution, the aquifer supplying the Akaki well field, providing freshwater to the increasing residential and industrial establishments of Addis Ababa, can be replenished, and help release the pressure on the Addis Ababa water supply sources.

The potential of the Akaki aquifer was identified in 1991, and the production wells were completed in 1995 to supply an additional 125,000 m3/day of water to Addis Ababa (Sime1998). The projected potable water demand estimated to increase to 1,105,000 m3/day of water by the year 2020 (Sime1998) and the Akaki aquifer potential will contribute 11.3% of the total projected demand. It should also be noted that infiltration-based stormwater management schemes may improve the water status of urban soils and thus the resilience of street trees and other vegetation to withstand drought. Reestablishing green infrastructure, i.e. reversing the ongoing unidirectional land-use changes towards more built surfaces, is considered a high priority by the city administration, and this goal might be easier to realize if the green infrastructure is linked to other infrastructures, like urban drainage and transportation (CLUVA 2013).

4.2. Objective

The aim of this study was to contribute to the development of nature-based solutions for drainage of local cobblestone streets in urban areas. The specific objectives were to propose and subsequently test a system for street drainage that could be implemented as a stand-alone solution with the same capacity as a conventional pipe-based drainage system, and simultaneously contribute to groundwater recharging and greening of the city.

4.3. Method and materials

This study was conducted using the cobblestone street program of the city of Addis Ababa, Ethiopia as a case.

First, a stormwater drainage design for a typical cobblestone street (Fig.4) was sketched based on input from contemporary practices for nature-based stormwater management, e.g. as explained in the CIRIA manual (Ballard et al. 2007). The goals here were to ensure drainage of the street up to rain events with a two-year return period (T = 2 years), to improve the growth conditions of street trees by improving water availability, and to recharge groundwater aquifers by means of infiltration of stormwater rather than discharge. Intensity-duration-frequency curves (IDF curves) based on rainfall data from the Bole International Airport Addis Ababa weather station, located 8.5 km from the experimental site, were obtained from the Addis Ababa City Roads Authority (AACRA 2003) and used to estimate the precipitation event corresponding to T = 2 years, and thus to estimate the runoff volume to be captured.

Second, the proposed design was tested in a full-scale field experiment employing a typical cobblestone street of 10 m width, located in the Repi Hill residential area within the Jemo River watershed in the southwestern fringe of Addis Ababa, and thus within the Akaki well field. The test street had no street trees or other vegetation (Fig. 4).

Figure 4: The case site, a typical cobblestone street found in residential areas of Addis Ababa.

As illustrated above in fig 4, the road area is 10 m wide; the paved area is 7 m wide. Despite a low runoff coefficient and the presence of drainage channels in both sides, erosion and pavement damage take place (inserted photo lower right). Conveyance of water contributes to downstream flooding (inserted photo upper left) and the piles of soil stem from the implementation of the new system. The street was paved with cobblestones in 2012 following a conventional construction process consisting of 0.10m thick sand bedding layer and 0.2 m thick of gravel mix with clay and sand soil below a layer of cobblestone cubes (0.10 x 0.10 x 0.12 m). A geotechnical survey conducted in December 2015 revealed that the soil consists of weathered basaltic bedrock with moderate to good hydraulic conductivity. The bedrock is found 1 m below the ground level. The topsoil was found to consist of layered clayey loam with relatively low hydraulic conductivity. The depth to the groundwater table is significant and was found to exceed 2 m during the rainy seasons according to the geotechnical investigation conducted.

As illustrated in figure 5, the novel drainage design with infiltration trench was tested in Area 2, while Area 1 served as a comparison area. Monitoring wells were equipped with automatic water level loggers. The water flow direction, indicated by the blue arrows, follows the street slop and ends to diversion bumper indicated by the bold blue line. The experimental street section was ca. 48 m long and had a slope of 15%. It was subdivided into two comparable sections, both representing an area of ca, 160 m2, referred to as Area 1 and Area 2 (Fig. 5). Hydraulic drainage boundaries were obtained by means of three shallow street gutters, placed in front of a street bumper (Fig. 5). Thus, to prevent any upstream surface runoff from entering the experimental street section, a speed bumper with gutter was established that would divert runoff to the existing drainage canal. Another speed bumper with gutter separated Area 1 from Area 2, and diverted surface runoff from Area 1 to monitoring well (well 1) designed for later use as tree pit. Likewise, a third speed bumper with gutter diverted surface runoff from Area 2 to monitoring well (well 2) also designed as a tree pit, but from the tree pit, the runoff could enter the infiltration trench constituting the key element of the novel design for on-site control of stormwater runoff as described in Results. The bumps were placed at an oblique angle to the street so as to ensure that all surface runoff water would be diverted to the monitoring wells. To compare runoff patterns from the two experimental areas, a pressure transducer (HOBO U20 Water Level Logger) was placed in each of the monitoring wells, and the water level was recorded at 5-minute intervals.

A third pressure transducer was used to measure atmospheric pressure for the calibration of the monitoring transducers. The monitoring wells were constructed so that they could later be converted into real tree planting pits. The construction of the experimental site was completed in June 2016, just prior to the July-September rainy season. The system was initialized in July and August, and data was subsequently collected during four monitoring campaigns. Data was transferred from the HOBO loggers to Excel spreadsheets for data analysis and graphical representation. To convert water levels recorded with the loggers from kPa into m a conversion factor of 1 kPa equal to 101.971 mm $H2O$ at 4 °C was used. The initial reading from the empty well was 78.6 kPa which is equal to 7.95 m at both monitoring wells.

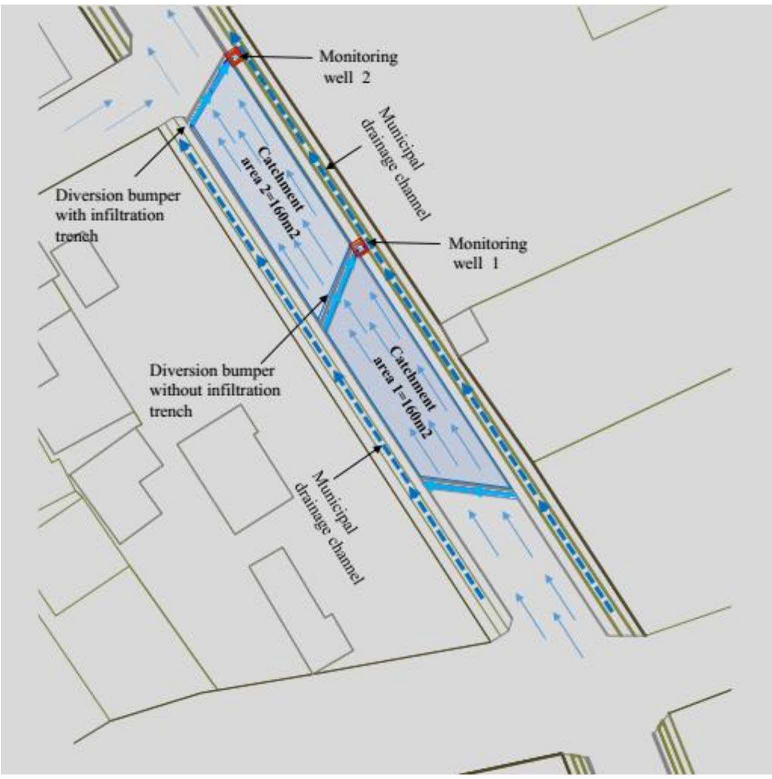

Figure 5: Plan view of experimental site layout.

4.4. Results and discussion

In order for the drainage of cobble-stone streets to facilitate on-site retention of stormwater runoff, and thus minimize erosion, reduce risk of downstream flooding, improve groundwater recharging, and potentially ensure a better water status for green infrastructure in the city, we proposed as the basic unit an infiltration trench combined with a tree planter, and positioned oblique to the natural down-hill flow direction, as illustrated in Figure 6. Locating the trench directly in the street profile rather than along the street, avoids the consumption of neighboring land area, thus making the solution more space-efficient. Further, we proposed combining the basic unit with a speed-regulating street bumper, together with a shallow gutter on the upstream side that would improve control of water conveyance (Fig.6). We have named the newly proposed design concept ‘Infiltration Bumper with Tree Planter’.

Figure 6: 3D-Illustration of the proposed design for on-site management of stormwater runoff from cobblestone streets, referred to as ‘Infiltration Bumper with Tree Planter’

The speed bumper is shown as the elevated concrete ridge, with the trapezoidal gutter running in parallel in front of it. The cobblestone pavement consisting of cobblestones placed in a bedding layer of gravel on top of a coarser gravel leveling layer can be seen in longitudinal cross-section. The belowground infiltration trench filled with crushed stone can be seen alongside the local soil in the perpendicular cross-section. The tree planter is shown with red bricks. The inflow orifice connecting the gutter to the tree planter is marked with blue. From the tree planter, the water can flow into the stone trench. The overflow orifice on the opposite wall of the tree planter placed 0.2 m above the gutter base, is not visible. Upper left corner, inserted: Illustration of suggested design including a street tree. Lower right corner, inserted: Photo of the test site, showing the bumper and gutter and the tree planter (White Square) in the back.

With reference to Figure 6, the anticipated functioning of the design is as follows: Stormwater not directly infiltrating the soil below the cobblestone pavement will form runoff and flow along the surface, following the slope of the street. This water will be trapped in the gutter in front of the speed bump and start to pond. As the ponding reaches approximately 0.05 m of depth, water escapes through the inflow orifice in the tree planter wall. Here, the growth substrate in the tree planter will soak up the water, until the substrate's capillary forces are offset, whereupon the water will start to pond inside the tree planter, and from there seep into and rapidly disperse throughout the neighboring gravel trench. From the gravel, trench water can infiltrate into the surrounding soil, and into the bedrock, with which contact should be reached. The water levels in the tree planter and in the trench will be equal. In case of overflow, water is diverted into the area next to the street through an overflow orifice in the tree planter wall opposite the street. Bypassing the water through the substrate in the tree planter, the risk of clogging of the exposed soil surfaces of the infiltration trench is expected to be negligible since suspended solids in the runoff will be filtered out by straining in the substrate, similar to processes in filter soil (Cederkvist et al. 2016). Some of the trapped water may disappear through evapotranspiration from the substrate and vegetation in the tree planter.

For the sake of functioning as a monitoring well, the two tree planters were not filled with the substrate or planted with a tree until after completion of the test. The infiltration trench was dimensioned for a 2-year storm event corresponding to 40 mm over 2 hours (AACRA 2003), which accumulates to a runoff volume of 3.2 m3 from 160 m2 when a conservative runoff coefficient of 0.5 is assumed for the cobblestone pavement (corresponding to 50 % direct infiltration and 50 % surface runoff). The oblique trench was 1 m deep (ensuring contact to the weathered bedrock), 0.5 m wide and 7.8 m long, yielding an infiltration area (sidewalls + end walls + bottom) of 20.5 m2. As for filling material, basaltic crushed stone with assumed porosity of 40 % was used (Harrington1989), yielding a total water storage volume of 1.56 m3. With a storm duration of 2 h and an assumed saturated hydraulic conductivity of the weathered bedrock of 1.5 x 10-5 m/s, a volume of approximately 2.21 m3 will percolate into the bedrock during the rain event. The sum of trench storage volume and volume infiltrated during the event is 3.77 m3, i.e. exceeding the 2-year storm volume of 3.2 m3. An extra storage volume of 0.4 m3 is provided by the trapezoid-shaped gutter in front of the speed bumper (0.2 m deep, 0.5 m wide and 7.8 m long), and another additional storage volume of 0.1 m3 is provided by the tree planting pit (0.7 m by 0.7 m by 1 m, assuming a water-holding capacity of the substrate of 25% volume).

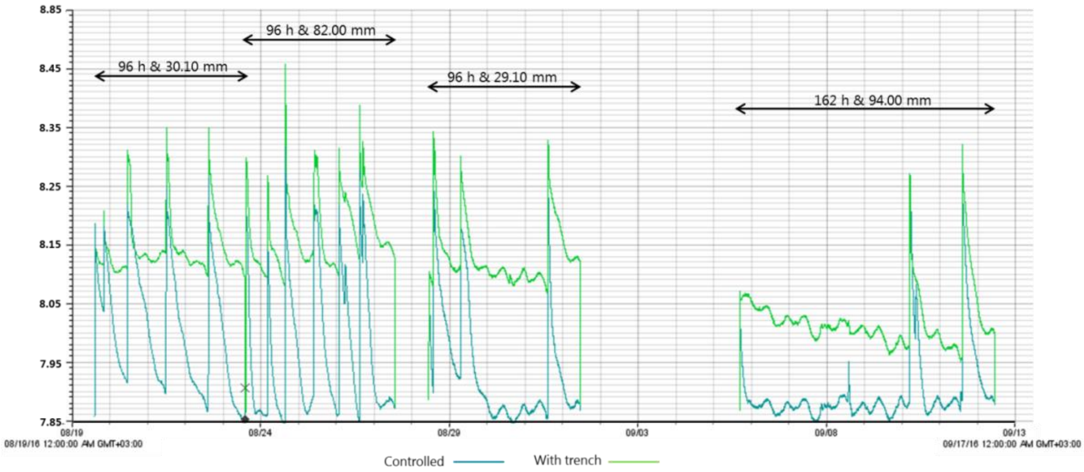

Figure 7: Water level in monitoring wells in the period August 19 to September 13, 2016, including four logging campaigns. Blue: Well 1 (no trench). Green: Well 2 (with trench). 7.85 m corresponds to empty wells.

The 24 d long rainy period was logged in four campaigns (as also indicated in Fig.7): period #1: 96 h and 30.1 mm, period #2: 96 h and 82 mm, period #3: 96 h and 29.1 mm, and period #4: 162 h and 94 mm. As seen from Figure 7, the water level was generally highest and dropped more slowly in Well 2 (with trench) compared to Well 1 (no trench). Although unexpected, this drainage pattern is ascribed to subsurface water transport in the gravel layers beneath the cobblestones, as interpreted graphically in Figure 8: Rather than just percolating vertically through this layer, infiltrating precipitation remains in the bedding layer and starts to flow downhill, taking advantage of the higher hydraulic conductivity in this layer compared to the underlying clayey soil. In effect, the infiltration trench presumably trapped not only surface runoff from the 160 m2, but also water flowing in the gravel layers, under passing the street bumper and gutter. This extra volume may potentially originate from the entire uphill street section, reaching to the street top point some hundred meters away. When looking at the water logging data, the higher peaks and slower decline rate in Well 2 compared to Well 1, reflects a higher volume being trapped, ascribed to contributions from both surface runoff and subsurface flow, and the period for water entering being extended since the subsurface flow likely continued for a period after the rain had stopped.

Table 1: Maximum, minimum, average and change in water level in meters of extreme rain events from four logging campaigns

Condition of the monitoring wells with stormwater runoff	Four logging campaigns 19th August to 13th September															
	August 19-23				August 23-27				August 28-September 1				September. 5-13			
	Max.	Min.	Av.	Δ	Max	Min	Av	Δ	Max	Min	Av	Δ	Max	Min	Av	Δ
Water level from well (w1) without trench	8.36	8.10	8.23	0.26	8.46	8.08	8.27	0.38	8.33	8.07	8.20	0.23	8.31	7.95	8.13	0.36
Water level from well (w2) with trench	8.26	7.86	8.06	0.40	8.33	7.84	8.08	0.49	8.24	7.85	8.05	0.39	8.28	7.86	8.09	0.42
Water level differences Δw2 –Δw1				**0.14**				**0.11**				**0.16**				**0.06**

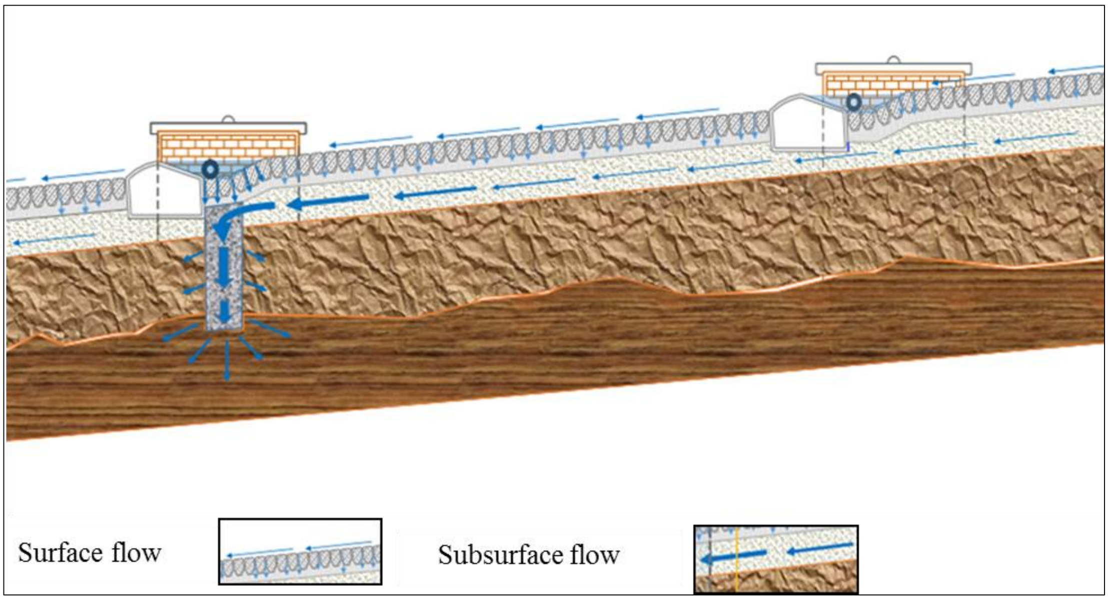

Figure 8: Section drawing of the anticipated flow, consisting of both surface flow (narrow blue arrows) and flow through gravelly cobblestone bedding layer (thick blue arrows)

As illustrated in figure 8 above, the anticipated flow of runoff is not only surface flow as assumed during the design of the Infiltration Bumper with Tree Planter. While the control monitoring well received surface flow only from Catchment Area 1, the test monitoring well received surface flow from both Catchment Area 2 plus subsurface flow from a larger area, probably extending uphill to the top-point of the street. In a full-scale design using several infiltration trenches, the interception of subsurface flow from the gravelly bedding layer allows for an even simpler design.

If in fact, the flow is as interpreted here, an even simpler design may be suggested. The gravel layers used as leveling and bedding materials for the cobblestone pavement can be connected directly to infiltration trenches, making the street bumpers and trapezoidal gutters optional. Connection to a tree gutter may still be an advantage for city greening, and for filtering of surface runoff.

The proposed design is suitable for streets located on permeable soil with some depth (e.g. at least 1 m) to the groundwater table, and it is assumed to function well if implemented regularly with adequate spacing between each drainage unit. The spacing may vary according to the slope and the width of the streets. The sizing of the trench should be based on the street area connected to the projected system and the hydraulic conductivity of the local soil. In this case, a GIS-based suitability analysis may be helpful in determining adequate spacing. A simple GIS-based layout may provide an effective decision support system, allowing designers and planners to solve more complex tasks within a short period of time. As shown in Figure 8, the unforeseen subsurface water flow from the uphill portion of the street section may distort the test result. However, this flow can be intercepted and eliminated by installing a sufficient number of proposed elements on the uphill section, based on the decision support system.

Infiltration based stormwater management elements such as trenches and soak ways are usually susceptible to clogging after a period of operation due to straining of particles suspended in the stormwater runoff (Siriwardene et al. 2007). In the case of the Infiltration Bumper with Tree Planter, the system does not allow the water to enter directly into the infiltration trench. Both the substrate in the Tree Planter and the gravel in the cobblestone bedding layer will have a filtering effect, removing suspended solids and associated contaminants, much like the processes in filter soil. Regarding the clogging risk of gravel in the cobblestone bedding layer, it is difficult to avoid this, but due to the large permeable street surface area, a full clogging is not likely to happen until after many years, as experienced with permeable asphalt paving (Pezzaniti et al. 2009). In case of clogging the fraction of surface runoff will increase on behalf of flow in bedding layer, pointing to long term stability obtained with tree pits as entry points.

The design and construction of the system may vary with the specific characteristics of the site. In the case of the experimental site, the depths of the infiltration trench and tree pit were around one meter. This one-meter depth was required in order for the trench to gain contact with the higher hydraulically conductive bedrock. In the case of sites with deep soil, the gravel trench may be extended into the tree pit, forming the tree pit bottom, which is then finished off with a growth substrate in the upper part of the tree pit. The use of HOBO water level loggers allowed us to compare the filling and drainage patterns of the two monitoring wells in response to precipitation events, but the loggers did not provide data for the total water balance of the system. If combined with flow meters on the inlets and outlets of the monitoring wells, the amount of retained water can be estimated. In this way, a full water balance could be achieved, including estimates of groundwater recharging volume.

Groundwater abstractions are not often carried out without the basic understanding of the groundwater recharge, lateral and vertical extent of aquifers, nor of the available groundwater reserve (Ayenew et al. 2008). In recent times, the building and street construction activities in the city of Addis Ababa sealed more and more open spaces in the upstream areas. This activity may diminish the groundwater recharge capacity of the city's natural landscape. If the city incorporates the proposed design solution as the standard drainage system for local streets, it will contribute rather than hinder the recharging of groundwater resources, as is the case with today's drainage systems based on discharge.

Economically, the cost of re-constructing cobblestone streets with the proposed design solution will be higher compared to conventional cobblestone streets drained with a ditch or pipes. The extra costs are due to the deeper excavation of soil and more complicated construction with not only trench but also bumper, gutter and tree planter. A more simple design, excluding the bumper and gutter, will reduce costs significantly. The costs will in all cases depend on the number of units to be installed. In areas with relatively flat topography and good hydraulic conductivity of native soil, the spacing of the system will be wider and development costs correspondingly lower, and vice versa for steep streets and low permeable soils. Realizing the important role played by the cobblestone bedding layer for the runoff flow pattern, however, it may turn out that this subsurface flow process is so pre-dominant that the diversion bumpers can be avoided, in which case the construction costs are reduced. If stormwater generated from adjacent properties can also be managed in other separate systems and thus make any additional underground piping or open ditch for drainage redundant, the system will be more cost-effective. In terms of operation and maintenance costs, the proposed system is assumed to be low maintenance, since clogging is assumed to be avoided, as explained above. If the added benefits of reduced flood risks, the additional groundwater recharging and the reestablishment of vegetation cover are included, together with the lower cobblestone pavement repair costs thanks to less erosion, the overall cost-benefit calculation is assumed to be positive.

One of the main challenges of installing the system into the already developed streets of the urban area is the demolition cost and subsequent traffic management during the construction period. If the Infiltration Bumper with Tree Planter is implemented simultaneously with the conversion of soil streets to cobblestone streets, the costs of development and traffic management problem will be minimal.

Cobblestone is the oldest paving materials in cities of Europe and North America for paving streets, walkways and parking areas. The conventional drainage system developed to manage stormwater generated from the pavements of those cities can be replaced or supplemented using the proposed nature-based solution we have described here. Our solution can be applied to both newly developed urban areas as well as retrofitting strategy for streets in already developed urban centers. With the proposed diversion bumper and tree planter used as an inlet, the Infiltration Bumper with Tree Planter (IBTP) may be used in combination with any type of pavement, including non-permeable asphalt streets, and as such, may also be attractive as retrofitting means for local streets in the cities of developed nations.

4.5. Conclusion

In times of climate change and rapid urbanization, with the conversion of permeable land into non-permeable, innovative solutions characterized by resilience and sustainability thinking are much needed. Stormwater drainage schemes targeting the full water cycle must eventually replace conventional discharge-based systems, and in the many developing cities where the first wave of land conversion from rural to urban is subsequently replaced by conversion of soil streets to paved streets, there is a unique window of opportunity for managing stormwater runoff as a resource rather than wastewater, i.e. introducing a new mindset in line with transition to sustainable urban development. With the suggested street drainage scheme based on a number of infiltration trenches cutting oblique or perpendicular to the street at repeated intervals, we have an important tool for such a transition for the management of the freshwater resource. Based on four logging campaigns, the Infiltration Bumper with Tree Planter system has been found to operate in a promising way, although the runoff flow pattern of cobblestone streets turned out to be more complicated than first anticipated, in that the infiltrated precipitation on streets in sloping terrain was apparently trapped in the bedding layer and converted to a downhill subsurface flow, beneath the pavement. To confirm and fully describe this flow pattern, additional experiments are needed. It may turn out that in the case of cobblestone streets, the bedding layer may render the proposed diversion bumper unnecessary. Since the proposed solution is based on well-known principles for on-site management of stormwater runoff, the solution may be recommended straight away as a new drainage scheme for the conversion of soil roads to cobblestone roads, as is currently taking place in Addis Ababa at a rapid pace. Further, more precise estimates of the co-benefits of groundwater recharging, reduced erosion, and improved growth of street trees should be documented. The suggested road drainage design may also prove suitable for high-income cities.

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5. Paper II: City-wide planning of nature-based road drainage scheme with Arc-GIS

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Abstract

In urbanized catchments, roadways and roofs are the main sources of stormwater runoff that necessities catchment level implementation of different types of drainage solutions. In the era of climate change, an exclusive focus on conventional pipe-based discharge systems for stormwater management in urbanized catchment may need to be complemented with more nature-based solutions prioritizing retention of the water within the catchment to improve also drought resilience. While more and more nature-based drainage solutions are emerging in different parts of the world, their upscaling to a city-wide service call for appropriate decision support tools. Based on a set of criteria relating to rain intensity, catchment size, slope, soil texture and depth to groundwater this study demonstrates how Arc GIS can be used as a planning tool for city-wide positioning of drainage elements, returning maps showing suitable spacing of the selected multi-benefits nature-based element for road drainage, which is the Infiltration Bumper with Tree Planter (IBTP), presented in the previous chapter. In combination with tables of expected construction materials needed, a total cost

estimate is possible, in this improving the value of the tool for decision support. The case area was the urbanized catchment of Jemo-Hurbu River, which is a tributary to the Little Akaki River running through Addis Ababa, Ethiopia, representing good variation in slopes and thus representative spacing of the drainage element. The study identified 457.6 km of suitable roads with an average width of 7 m distributed over six major terrain classes with slopes ranging from 0-2 % to >20 %, and an estimated need of IBPT 10,773 elements, and 42,721m3 of gravel needed for construction. An additional 5 km of roads were identified as unsuitable for IBPT due to location on high sloping terrain (>20 %). The study recommended further consideration of the spacing of the tree planters needed in order to improve the drainage capacity of the IBTP system through evapotranspiration for roads developed over wet and flatlands. Regarding roads developed over higher slope terrain, the study recommends the authorities to revisit the suitability standards in settlement planning to avoid higher slope gradient and on the low-lying flood plains from land development and building practices. Arc GIS is considered a useful tool in realizing the ideas of nature-based solutions for the transition towards flood resilient cities.

Keywords: Upscaling, decision support tools, spacing criteria, watershed drainage, terrain characteristics, runoff coefficient & cost efficiency

5.1. Introduction

Settlements in steep terrain notably increase the risk of flooding, erosion, and landslides, during intense rainfall, and may cause catastrophes (Au, 1998), especially in case of informal settlements with deficit drainage infrastructure and weak building constructions (Parkinson et al. 2003). In highly urbanized catchments, road surfaces typically contribute a significant share of the entire impervious surfaces, in the range 1/3 to 50% (Davis & Birch 2009 &Yao et al. 2016). Thus, to control stormwater runoff, measures towards roof runoff as well as road runoff are needed. Although conventional ditch- or pipe-based drainage systems may be able to control the risk of flooding, the capacity of such systems may be overtopped due to climate change, and the basic idea of dislodging the stormwater volumes to downstream sites that the conventional systems rest upon has drawbacks and does not contribute to the ideal of resilience towards floods as well as droughts, or to integrated water management (Pittner & Allerton 2008). Furthermore, such systems are out of reach economically in developing cities.

Nature-based approaches to drainage are becoming increasingly common in developed countries and also in some middle-income countries (e.g Malaysia and Chile) which are introducing infiltration as a core urban runoff management strategy, but to date, there have been few attempts to apply these technologies in low-income developing countries (Parkinson et al. 2007). The new, more nature-based approach has resulted in innovative solutions like curb extensions and permeable pavements (Cederkvist et al. 2016). Expanding the applicability of such small scale decentralized solutions into diverse landscape conditions also needs the proper attention for upscaling strategy into new developments as well as to retrofit into the existing developments. In this regard, the design solution developed for the local cobblestone roads can be applicable for the entire cobblestone roads in watersheds by adjusting the spacing for the placement of the system in accordance with the geophysical conditions. In areas where the available and the widely practiced infiltration and retention-based drainage solutions are not applicable due to geophysical factors such as high slope and lower permeable soil conditions, such type of site-specific noble drainage solutions should be introduced. In previous chapter, a new drainage design is suggested referred to as the Infiltration Bumper with Tree Planter (IBTP) in which the basic unit of an infiltration trench (placed perpendicular or oblique to the slope direction) is combined with a tree planter together with a speed-regulating road bumper with a shallow gutter on its upstream side, aiming to provide a road drainage solution that minimizes risk of erosion and at the same time contribute to groundwater recharging and city greening. The proposed drainage design solutions for upscaling were developed for infiltration, detention, and retention -based drainage solutions in order to fit into high slope urban roads with slight terrain adaptations and use of locally available materials gravels and sand as a multifunctional standalone system.

The IBTP design was developed and tested on a local cobblestone road located on steeply sloping, well-drained soil with more than 1m the groundwater table, and was assumed to function well if implemented regularly with adequate spacing between each drainage IBTP unit. A simple GIS-based layout may provide an effective decision support tool in environmental planning by allowing designers and planners to solve more complex tasks within a short period of time (Bassolé et al. 2001). Researches to date have demonstrated the suitability analysis tool for site selection of the different type of widely known sustainable drainage design elements. For example, the studies conducted by Jato-Espino et al. (2016) and Viavattene et al. (2008) have focused on site selection criteria and the potential role of individual design solutions such as an infiltration trench, curb extensions, rain gardens and porous paving using arc GIS platform. Moreover, GIS can be used as a tool for processing input data to accept the output and enable a user-friendly representation of the results for different purposes (Heaney et al. 2001).

5.2. Objectives

The objective of this research was to demonstrate how Arc GIS can be used as a planning tool for city-wide road drainage, returning not only the adequate spacing of nature-based drainage elements in response to slope but also the amount of construction materials needed and the associated benefits in terms of groundwater recharging. We used Arc GIS to suggest a city-wide implementation plan for our recently introduced road drainage element, the Infiltration Bumper with Tree Planter, in a hilly sub-catchment of Addis Ababa, Ethiopia.

5.3. Methods and materials

A study area representing both a hydro-spatial entity and a good variation in slope was selected. Then criteria relating to the proposed stormwater management element for setting up GIS were defined. Finally, tables for accumulating elements and construction materials were extracted. This will ensure the applicability of the solutions in a wider spatial scale by providing adequate information on site selection, performance evaluation and cost estimation of the overall drainage system.

5.3.1. Description of the study area

The selected study area is the Jemo-Hurbu River watershed, which covers an area of 3106 ha and is located in the Southwestern fringe residential areas of Addis Ababa, Ethiopia. It extends from the rural Oromiya region in the Northwest (approximate coordinates 9o00’28” N; 38o38’25” E) to the Southeast through the increasingly urbanized areas of Alem Bank, Ayer Tena, Repi Hill, and the Jemo to the confluence of the Jemo River with Harbu River within Nefassilk Lafto sub-city (approximate coordinates 8o57’20” N; 38o43’35” E) (Fryd et al. 2016).

Over the last three decades, the area has transformed from the mixed forest and agricultural land into a residential district, largely driven by infrastructure development, especially the construction of a ring road connecting the area to the rest of the city. The new urban development represents an expansion of the city and consists of the formal development of single-family and multistoried public sponsored housing projects as well as informal settlements proliferating in the uphill areas and riverbanks (Yeshitela et al. 2017).

The local road network in the study area is rather diverse due to the terrain characteristics of the natural landscape and the legal status of the settlements. Within formally developed parts predominantly located on flat terrain, the road pattern is regular and the roads are paved with a good paving material in the form of cobblestones, while in the informally developed parts located predominantly in the uphill areas the road pattern is irregular with mud and gravel paving. Most of the roads within formally developed areas are equipped with an open drainage ditch with rectangular or trapezoidal cross-section, running parallel to the roads segment. However, the maintenance of the ditches and pipes is not good causing additional stress from blockage by solid waste which is a common problem in densely developed residential areas of the city (Belete 2011). Addis Ababa City Road Authority (AACRA) has a plan to expand the cobblestone paving program to all streets in the city, irrespective of the legal status of settlements. As a result, the entire road network developed over steeply terrains will be converted into cobblestone pavements in the near future, if the local residents are willing to contribute partial payment for the construction. From this perspective, the study area can help illustrate how the IBTP drainage system can be up-scaled and integrated into the road profile, and thus help resolve the drainage and blockage situation and show the way to citywide planning of the system.

5.3.2. Applied design standard of the suggested nature-based drainage element for upscaling

The main constituent parts of the system are crushed volcanic rock filling material for infiltration trench and tree pit, mass concrete for the bumper, and square-shaped brick wall for the tree pit. Except for the size change in the brick wall of the tree pits construction, the size of all constituent parts of IBTP drainage system is the same for upscaling into the local cobblestone roads of the watershed. In the case of the bricks wall, the depth of the wall was 1.4 m deep for experimental setups to control and measure the runoff accumulated within the pit (previous chapter). However, in real-life projects, only 0.4 m deep bricks wall above the natural ground is needed in order to hold a sand-soil mix as a tree growing media. The IBTP was dimensioned for a 2-year storm event corresponding to 40 mm over 24 hours. From the experimental setups developed over steep terrain with an average slope of 15.7%, the IBTP system was designed believed to manage a total of 4.3m3 stormwater through retention within the gravel-filled trench, percolation through the trench surfaces and detention volume provided by the trapezoid-shaped gutter in front of the speed bumps. This volume is slightly larger than the expected 2-year storm design volume corresponding to 3.2 m3 in the case area (experimental setups).

5.3.3. Spacing criteria for upscaling of the IBTP

The geophysical data to determine the infiltration and retention capacity of the landscape are limited to the case site that was generated by the researchers during the field survey. Moreover, the available map for soil type classification and groundwater table data for the watershed at the city-region level comes with a low level of accuracy, inferring some uncertainty in the developed maps as a decision support system at both the macro and micro level. The study developed slope based criteria for the possible spacing of the proposed IBTP drainage element using the available high-resolution DTM.

The spacing of IBTP drainage system was determined based on relevant parameters including the size of catchment area connected to the trench, runoff coefficient/fraction contribution depending on the slope (resulting in some "slope-spacing rules"), hydraulic conductivity of the local soil, and storage capacity of the soil. Regarding the catchment area, one of the deterring factors is the average width of the pavements, which was set at 7 m throughout the catchment, with some exception with wider road cross-sections in the commercial district of the city. The runoff coefficient of the cobblestone paving is assumed to vary depending on the slope of the road which is the most important parameter in determining the spacing of the IBTP system in the absence of more precise information of soil water storage and hydraulic conductivity.

Assuming similar rain intensity, soil texture and depth to groundwater over the case area, some spacing rules were suggested dependent on slope and runoff coefficients. These are presented in Table 2. It is assumed that the runoff coefficient increases with slope, i.e. the steeper the road, less water will infiltrate on-site, and more will runoff on the road surface and in the gravel bedding layer. The pilot-experiment was conducted on a road with a 15.1 % slope, and the spacing of 23 m between IBTP seemed adequate, even resulting in a slight excess volume capacity than required for a 2-y event (4.3 m3 versus 3.7 m3). This was used for slope category 5 from 15.1-20%.

For lower slope categories the distribution of precipitation on runoff and infiltration was adjusted with reference to literature. For the roads developed over flatland and well-drained soils, the runoff coefficient is 0.2 (Rim 2011). The spacing of IBTP for the roads developed over gently rolling terrains ranging from 2.1% - 5% was decided based on runoff coefficient value from an empirical study by Lucke et al. (2012). They found that at grades greater than 5%, the volume of stormwater that runs off the pavement does not exceed the volume that infiltrates into the pavement. Based on the finding of the same study, the runoff coefficient for permeable paving developed over gently rolling terrains from 5.1% and 15% is slightly above 0.5 and below 0.7. In this regard, the relative runoff volume infiltrated through the cobblestone road developed on five slope classes identified based on the above the empirical findings and our judgments (Table 2).

Finally, the spacing of IBTP elements for the slope classes ranging from 2.1% - 15% identified by extrapolating using the rational method from empirically known runoff values and infiltration capacity on the flat terrain of 0-2% and hilly terrain of 15-20%. In this regard, the only parameter applicable here to determine the spacing of the IBTP drainage solution is the runoff coefficient of the cobblestone road with respect to the corresponding road slopes. In case of roads developed on steeply terrains ranging from 15-20%, the spacing of the IBTP system determined based on our empirical study finding and for those roads developed over 20% terrains, the proposed design solution for upscaling will not be applicable.

Table 2: Upscaling parameters for the spacing of the IBTP drainage solution based on runoff coefficient of the cobblestone road with respect to the corresponding road slopes.

The range of road slope %	Percentage fraction of *runoff: gravel flow: infiltration to the soil* of 2-year event 40mm rain	Recommended IBTP spacing (L) in meters *L=4.3/7CI*
0 -2	*10:10:80*	75.0
2.1-5	*20:20:60*	39.0
5.1-10	*25:25:50*	31.0
10.1-15	*30:30:40*	26.0
15.1-20	*35:35:30*	23.0
>20	-----------	---

The Spatial Analyst tool of the ArcGIS platform using a DEM and shapefile of the road map of the city as input data was used to determine the spacing between each IBTP based on the slope criteria of the individual road segment (Table 1). Using a 5x5 m resolution DTM raster file, slope assigned to individual segments of local roads' centerline feature class accounted for measuring the length of local roads over different slopes from the entire network of the watershed.

5.3.4. Estimation of recharging volume and number of new road side trees

Based on the developed spacing parameters mentioned above, the total runoff volume managed if the IBTP system were to be implemented was estimated, and in the end, the potential volume fraction of groundwater recharged was identified. Moreover, the total resulting in the number of road tree pits for the growth of trees along the local roads as a co-benefit for the city was calculated.

Finally, in order to evaluate the watershed level drainage performance and thus contributions of the proposed IBTP, the fraction volume of runoff managed using the system compared with runoff generated from the entire watershed without any physical design interventions to infiltrate or retain the stormwater was estimated. This was done by the use of the stream network analysis tool developed on the Arc GIS platform.

5.3.5. Cost estimation

From the identified length of roads in the six slope classes and the corresponding number of IBTP elements, the total cost of development for implementing the IBTP drainage system into the entire watershed was estimated. The size of each constituent part of the system was determined based on data from the 7 m wide road section with the same size bumper and 1 m deep infiltration trench and tree pit during as used in the pilot experiment (refer fig 6, in chapter 4). To develop the system over the watershed, the total cost of development estimated by multiplying with the current unit price of each item based on the city construction market. Finally, a cost comparison of the proposed system with the conventional pipe-based system was conducted by using per meter linear construction cost of open rectangular ditch obtained from AACRA and community mobilization section of the local authority in the study area.

5.4. Results

5.4.1. Spacing and placement of the IBTP system

Based on the suggested slope-spacing rules for placement of the Infiltration Bumper with Tree Planter' (IBTP) road drainage element, the Arc GIS analysis returned the numbers, distributed on different slope classes, as shown in Table 3.

Table 3: Total length of local cobblestone roads in six slope classes and associated estimated runoff volume managed, if the IBTP system was to be implemented over the entire watershed

The range of Road slope %	Length of each road segment In meters	Number of proposed IBTP *Road length /spacing -L*	Volume of runoff managed in m^3 *No of IBTBx4.3m³*
0 -2	160,612	2142	9,209
2.1-5	158,578	4066	17,484
5.1-10	99,365	3205	13,782
10.1-15	24,161	930	3,999
15.1-20	9,872	430	1,845
>20	5,001	------	----------
Total	**502,587**	**10,773**	**46,319**

5.4.2. Contribution of IBTP road drainage system to total runoff

From the existing road map of the city, the study identified 457,589 m of local roads with an average width of 7 m (min: 5 m, max: 9 m). However, the municipality usually widens the minimum sized roads to 7 m during the paving process. Eventually, the entire roads in the watershed are expected to have equal pavement width within the existing right-of-way. Most of the roads (70 %) were located on rather a flat land with slopes up to 5%, while the remaining roads were located on more sloping land with slopes of to 20 %. Only 0.1 % of the roads were on terrain with slopes exceeding 20 %. Applying the slope-spacing rules returned a map of IBTP elements as illustrated in Figure 9. With the applied slope-spacing rules the suggested IBTP element can be implemented almost everywhere. In this case, the total volume of stormwater runoff managed using the IBTP system for 2 years events of 40 mm precipitation within 24 hours estimated to be 46,319m3. This corresponds to a reduction of 7 % of the total runoff generated from the entire watershed if it is assumed that all precipitation from a 40 mm event from the entire 3106 ha large watershed area is converted into runoff, generating some 712,807m3 based on the rational method computation and assuming a runoff coefficient of 1(Fig 9) that the entire watershed assumed to be paved. Furthermore, based on the land cover area it can be calculated that local roads cover 10% of the land and are assumed to contribute 10% of stormwater runoff generated from the watershed. This value was obtained by assuming the entire surface covered by an impervious surface. However, the entire roads within the watershed planned to be paved using cobblestone; at least 4% runoff generated from the surface infiltrated through the joints of the cobblestone surfaces and the remaining 7% will potentially be retained and infiltrated through the proposed IBTP drainage system.

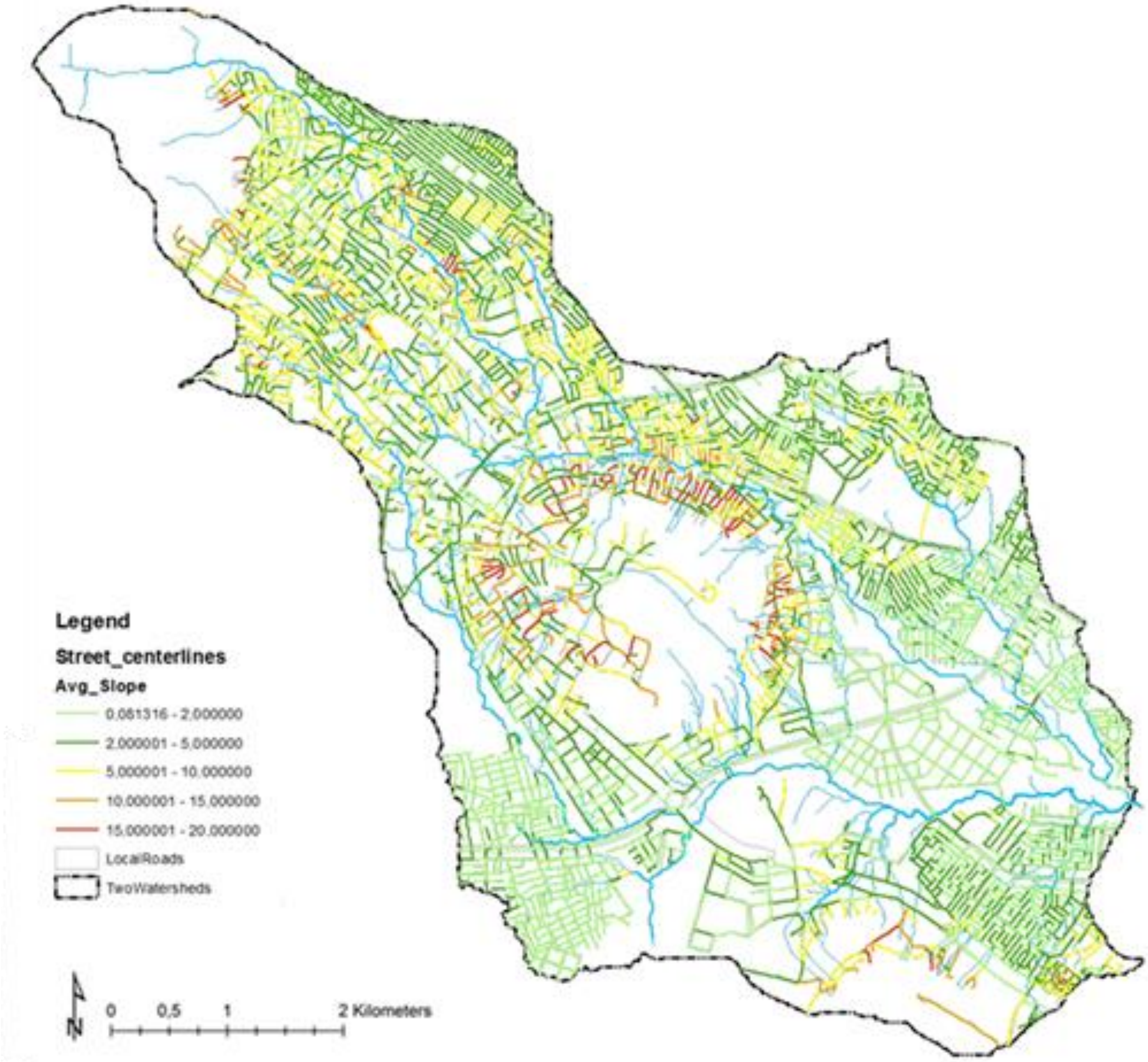

Figure 9: Distribution of local roads on terrain slope classes in Jemo-Hurbu watershed represented by five slope classes with five colors of centerlines for the upscaling of the proposed IBTP drainage system with the natural stream network map also represented by the blue line.

5.4.3. Estimated co-benefits

Applying the IBTP drainage system into the entire landscape will increase the volume of aquifer recharging and improve the greening status by 46,319m3 of water (table 3). If assuming a fraction of 1,077.3 m3 being consumed by trees (10,773 tree pits with a storage volume of 0.1 m3, chapter 4), the remaining 45,241.7 m3 of water still goes to recharging the aquifer in every rain event of 40mm of rain within 24 hours. On an annual basis, it can be assumed that the precipitation is captured in the IBTP corresponding 53 days with the highest number of rainy days of July - 27 days and August – 26 days with daily precipitation above 25mm (NMA) (45,241.7m3 X 53days) equal to 2,397,810m3 of water recharged to the groundwater system. The total runoff generated from the entire urbanized catchment of the city on an annual basis is estimated to be 350 million m3 (Backhaus et al. 2017).

5.4.4. Cost of development

The cost of development of the IBTP system is directly related to the cost of development for the constituents' parts of the system. Based on the full-scale development of the system in the experimental setup, accurate information on the labor and materials requirements of a single IBTP element was identified.

The excavation of the tree pit and infiltration trench encores direct labor or machinery costs depending on the preferred approach by the local contractors. As presented below in table 4, implementing the IBTP system over the entire local cobblestone roads requires 46,325 m3 of crushed volcanic stone fill material for the infiltration trenches and tree pits; 10773m3 of mass concrete for speed bumpers construction; and 19,300 m2 of bricks wall for the construction of the tree planters. Moreover, 46,325 m3 of native soil excavated and transported away from the sites, 2,155 m3 of fertile soil needed for tree planting over the individual tree pits. The total development cost of the IBTP system developed over the entire Jemo-Hurbu watershed was estimated to be 113,171,300 million in Ethiopian currencies which equivalent to 3.8 million US dollars.

Table 4: List of basic works to develop the IBTP drainage system and the material and labor cost in currency: Ethiopian Birr

Item list and descriptions	Unit size of each basic parts of IBTP system *(L x W x D in m)*	Total amount for 10773 pieces of IBTP	Unit prices in Ethiopian Birr	Cost of development in Ethiopian Birr
Excavation and removal of local soil for infiltration trenches	7.8x 0.5 x 1.0 *= 3.8 m^3*	40,938 m^3	200	8,187,600
Excavation and removal of local soil for tree pits	0.7 x 0.7 x 1.0 *= 0.5 m^3*	5,387 m^3	200	1,077,400
Crushed volcanic rock fill for infiltration trenches	7.8 x 0.5 x 1.0 *= 3.8 m^3*	40,938 m^3	650	26,609,700
Crushed volcanic rock fill for tree pit	0.7 x 0.7 x 1.0 *= 0.5 m^3*	5,387 m^3	650	3,501,550
Bricks wall for tree pits construction	(0.4 x 1.2) x 4 faces *= 1.92 m^2*	20,684 m^2	2500	51,710,400
Trapezoidal section concreate bumper	7.8 x 0.4 m x 0.3 *= 1 m^3*	10773m^3	2000	21,546,000.0
Fertile soil mix with river sand for tree pits	0.7 x 0.7 x 0.4 *= 0.2m^3*	2,155 m^3	250	538,650.00
Total development cost of IBTP drainage system				**113,171,300**

5.5. Discussions

The city of Addis Ababa planned to convert all the muddy roads surfaces into cobblestone pavement through the citywide mobility infrastructure improvement program (AACRA 2015). The motivation for launching this program was to improve mobility, access, beautify neighborhoods, and increase property values and tax revenues. The project's success offers important lessons for other cities across Africa as well as other countries that are tackling the challenges of managing rapid urban growth (ERA 2017). However, in the case of Addis Ababa, the issue of drainage and associated challenges are not adequately addressed for the proper functioning of the cobblestone roads as well as the entire urban system, leading to erosion of the pavement and flooding of downstream areas (chapter 4). In the case of Addis Ababa, with diverse land features, the watershed level application of the proposed nature-based drainage solution (IBTP) over the entire local roads will increase the serviceability of the roads by reducing pavements erosion and clogging with multiple co-benefits such as groundwater recharging and roadside greening.

Applying the system into a wider spatial scale with diverse geophysical conditions requires accurate information on the slope, soil texture and soil moisture of the entire watershed (Ballard et al. 2007). In the absence of soil texture and moisture information, the study relies on slope information by assuming the entire IBTP system implemented on the well-drained type of soil. In this case, the systematic approach developed based on empirical studies on the runoff coefficient of cobblestone roads at a different slope and soil condition (Lucke et al. 2012 & Rim 2011) utilized in order to develop more accurate Arc GIS-based layout plan for the placement of the proposed system. The GIS tools can be applied as a decision support system for the placement of IBTP system over the local roads in order to estimate the hydrologic performance of the system together with the development cost of the system in diverse terrains, except in areas with higher slope terrains. In the case of the study watershed as well as urban areas of developing countries, those marginal lands which are not suitable for urbanization frequently occupied by informal settlements (Main and William 1994). As a result, the settlements, as well as the entire cities, are seriously affected by recurrent drainage problems and other environmental crises (Parkinson 2003). For roads developed over higher slope terrains (greater than 20% gradients), the IBTP system will not be effective; rather an appropriate land use planning decisions are needed in order to avoid further drainage problems and associated environmental hazards originating from these areas.

In the case of roads developed over wet soils on the low-lying plains, the IBTP system will be effective by providing the IBTP system in a shorter interval with more tree pits to increase the infiltration and retention capacity of the system to drain the roads effectively during the rainy seasons. In this case, maximizing the evapotranspiration capacity of the system is a possible option by the provision of additional tree pits directly connected to the system to grow more trees and climbers parallel to the profile of the road. Contrary to our assumption to place one IBTP system every 75 meters distance over well-drained soils, we need more IBTP system in shorter intervals to divert the excessive runoff from the cobblestone surface to the tree pits for the plants.

Based on the arc GIS analysis, the watershed level contribution of the system in runoff volume reduction is significant in permeable soils. In this regard, the system will manage the entire runoff generated from the entire road surface by using the IBTP system together with the infiltrated volume of runoff through cobblestone pavers' joints. Regarding road erosion control capacity of the system, the system has a capacity to reduce erosion and fragmentation of cobblestone pavers by intercepting, infiltrating and diverting of the remaining sheet flow of stormwater runoff into the tree pits. Eventually, the risk of clogging will be reduced by trapping the sediments using diversions gutters and tree pits. Clogging is the main challenge of applying infiltration and gravel based sustainable drainage solutions by increasing the management cost of the systems (Lloyd 2001).

In terms of benefits associated with greening, the contribution of the system is more significant in an area with higher numbers of IBTP system installed. The roads developed over areas with steeper terrain and less permeable conditions require more IBTP elements with a shorter distance, compared to the case of roads developed over flat and moderate slope terrains with dry soils condition, where the contribution of the system in the provision of water for greening is limited. In this case, more water is infiltrated to the ground through gravel-filled trenches and the water volume diverted to the tree pits is correspondingly smaller. On the contrary, the contribution of the system in restoring base flow and groundwater recharging is more significant. In an urbanizing world, protecting the urban groundwater recharging system and maintaining low flow regimes that can support healthy stream ecosystems are important aims that can hopefully be achieved with locally enhanced infiltration (Bonneau et al. 2017). The IBTP drainage system managed at least 46,319 m3 of runoff from 352 hectares of cobblestone pavers within 3106 hectares of the study watershed which contribute 0.64% to the groundwater recharge from the entire 350 million m3 per year (Backhaus et al. 2017) of runoff generated from the entire city catchment of 52,700 hectares.

Compared to the conventional pipe-based system, the watershed level development of the IBTP elements is cost-efficient. There is still a need to validate appropriate benchmark standards, particularly in terms of quantifying long-term performance and as well as full life-cycle costs (HR Wallingford 2004). As listed in table 4, the direct cost of conventional and open ditch-based drainage system development for 457,589 m long local roads surface drainage is more or less equal to the cost of development of the proposed IBTP system. In this case, the proposed system is more functional and efficient in managing runoff volume with less maintenance cost compared to the more complex networks of pipes and ditches. Moreover, the co-benefits obtained from the IBTP system increase the value of the cobblestone roads in terms of long-term positive implications on the groundwater recharging and citywide green infrastructure improvement.

5.6. Conclusion

Planning of nature-based drainage solutions throughout the watershed for improving the performance of the urban drainage system as well as the hydrologic condition of the urban areas consisting of rivers, streams and other water surfaces and subsurface water features is becoming an important venture of today due to challenges associated with global climate change and rapid urban growth in different parts of the world. Expanding different types of nature-based solutions into a wider spatial scale with different land uses and land covers requires an appropriate decision support system in order to attain catchment level drainage and environmental improvement for urban areas. Several suitability analysis tools developed in the past for planning of widely practiced nature-based drainage solution with some limitation to apply for a context-based solution with a diverse landscape and biophysical situations.

The study developed an Arc GIS-based tool for planning of nature-based drainage solution for local cobblestone roads which planned to cover a substantial amount of land of the study watershed. Basically, the IBTP system developed to manage runoff generated from the road surface only and the planning tool also limited to cover only road surfaces within the watershed without considering runoff from other land uses and properties adjacent to the roads. Based on the developed suitability map, the proposed IBPT system is found to be applicable over the entire landscape of the study watershed over roads developed on terrain ranging from 0-20% and permeable soil conditions. Basically, the system was designed for higher slope terrains with permeable soil conditions and possibly applicable to a wider range of terrains with permeable soil conditions based on the GIS-based terrain analysis. In order to apply the system into wet areas with flat terrains, it is important to reconsider the design solution with a more interconnected tree pit system. Since the GIS approach developed based on terrain data of roads with some empirical evidence on the runoff coefficient, it is important to develop a tool to incorporate the texture and moisture condition of the native soil which is pertinent information for applying any type of infiltration and retention-based drainage solutions. If the planners have access to more precise information on soil texture and groundwater levels in addition to the terrain data, the GIS-based tool is assumed to return precise information on the adequate spacing of the proposed IBPT system both for dry and less permeable soil conditions of the urban local roads.

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6. Paper III: Stormwater storage design with gravels for the nature-based urban drainage in the low-lying plains

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Abstract

Settlements developed in low-lying plains of urban areas often suffer from waterlogging, and conventional drainage infrastructures fail to solve the problems. Well-practiced infiltration and detention based solutions such as rain gardens and swales are also not effective due to lower permeable soil and shallow groundwater table of the area. Based on wishes expressed in a community design charrette, and analysis of land cover, soil texture, and groundwater conditions, we designed and tested a nature-based above-ground stormwater storage system for control of waterlogging, with rainwater harvesting and aquifer recharging opportunities as co-benefits. The performance of the proposed system, which is referred to as an Elevated Retention-Detention Basin, was tested in a residential neighborhood in Addis Ababa, Ethiopia. Pressure transducers were used to observe water level dynamics in the basin. The proposed system performed well and proved to control the runoff volume generated from the connected catchment within the designed 40 mm rain event, and the experimental setup demonstrated the capacity of the system to harvest water for non-potable uses and to improve the groundwater recharging to the city. The option of

greening and cropping over the surface of the system is assumed to add some economic benefits. Further recording of water harvesting, groundwater recharging, and cropping potential is needed, before the impact of physical upscaling to similar low-lying areas, e.g. by use of GIS, can be completed.

Key words: Waterlogging, design charrette, terrain modifications, retention-detention basin, water harvesting and evapotranspiration

6.1. Introduction

Large-scale urbanization and population growth have led many people, especially the poor, to settle in the floodplains of Asian and African cities (Douglas et al. 2008 and Birhanu et al. 2016). The concurrent conversion of pervious surfaces, including natural flood storages such as paddy fields, into impervious surfaces, results in larger and faster-flowing stormwater runoff volumes (Ning et al. 2017), putting settlements in floodplains with underdeveloped drainage infrastructures at risk of waterlogging. Interestingly, cities in developed countries are also familiar with this situation, despite well-developed drainage systems. In Europe, the former riparian floodplains that used to cover large stretches along rivers have today declined to the level of elimination for agriculture, urbanization, and other major regional infrastructure development (EEA 2016), leading to incidents of frequent waterlogging, also ascribed to climate change with intense rainfall and climatic variabilities (EEA 2016). To cope with the problem of waterlogging, cities increasingly rely on large-scale hydraulic structures including massive pipe-based drainage networks, detention basins, pumping stations and levees along rivers. For instance, in the 1990s, many of the natural drainage lines of Dhaka, the capital city of Bangladesh were, with inspiration from developed countries, transformed into concrete culverts in response to the waterlogging problem caused by encroachment of the low-lying plains of the city, and none of them is today operating properly to serve the intended functions (Subrina & Chowdhury 2018). A major drawback of this large-scale approach is the inherited transfer of the problematic water to downstream areas, increasing the danger in case of system break down (Miguez et al. 2015). It may, therefore, be questioned if this response to increased runoff volumes should be recommended for cities with under-developed drainage structures. Waterlogging is one of the major water issues in most cities of China, reaching a level where it directly restricts the urbanization processes, and in an attempt to explore alternatives to failing conventional drainage infrastructure developments, the Sponge City Concept has been introduced (Xia et al. 2017). China's initiative is a recent nature-based approach in the Global South to reduce the impact of flooding instead of the pipe away through the conventional engineering approach (Jiang et al. 2018). The Sponge City Concept is similar to ideas developed in Global North since the 1980'ies (Fletcher et al., 2015), but it refines and lifts the ideas to a national strategic level. Such initiative will not only create opportunities for cities in China to leapfrog into a more resilient and sustainable state but also for cities in rapidly growing developing countries, particularly those with poorly developed water management systems (Zevenbergen et al. 2018).

Although measures to reduce the impact of flooding of urbanized low-lying plains do exist, most of them failed to solve the challenge of waterlogging and associated environmental concerns in a sustainable way. At a larger watershed level, the use of water pumps, detention ponds, and deepening of the river channel was the preferred solution in US cities (Blackburn & Bedient 2018), but costly, mono-functional and with a heavy resource and greenhouse gas footprint. At household and neighborhood level in urban areas of developing countries, the use of cisterns (water harvesting tanks) and open pond are well-known measures, but with limited capacity and mono-functional. Applying infiltration based solutions such as swales and rain gardens are also not effective on low-lying plains with clayey soil with shallow groundwater levels.

An example of an African city in rapid urbanization with under-developed drainage infrastructure is Addis Ababa, the capital city of Ethiopia. One type of area especially prone to waterlogging is the many new condominiums constructed by the city government to meet housing deficits, including 200,000 apartments between 2006 and 2010 (UN-HABITAT, 2011). Such acute drainage problems were observed at the local neighborhood level within the newly established residential areas of Jemo condominiums (Fig 10). The Jemo condominiums are one or residential establishments in the urban periphery of Addis Ababa. Developed mainly over land zoned as a conservation area in the previous masterplans but in the current master plan delineated only the areas along the Jemo and Hurbu rivers as 'hazardous land' (Herslund et al. 2017) preserved as open for rivers protection buffer area (Fig 10).

The entire land was a flood plain which served as a natural detention area for the overflow of stormwater from Jemo and Hurbu River which are the tributaries of the little Akki River system. The existing drainage system along the local roads, mainly equipped with open ditches are not effective to manage stormwater runoff generated from the entire neighborhood due to poor network of building level drainage systems. Moreover, the terrain of the area which is relatively flat doesn't allow the stormwater runoff to flow away from ditches around the buildings and open fields towards the main drainage lines along the local roads. The gray drainage line problem combined with flat terrain & shallow groundwater table condition of the area resulted in frequent inundation of open spaces and walkways around condominium during the rainy seasons of the year. In the long run, the waterlogging problem might affect the structure of the buildings and major infrastructures of the area. Moreover, open water within dense settlements that comes with waterlogging is potentially prone to pollution with solid waste, silt, and contaminants leading to an unhygienic environment and prevalence of various diseases (Mowla & Islam 2013). In the tropical climatic region in which the study area located, open water without any treatment may change into the breeding ground to mosquito transmitting malaria and other infectious diseases.

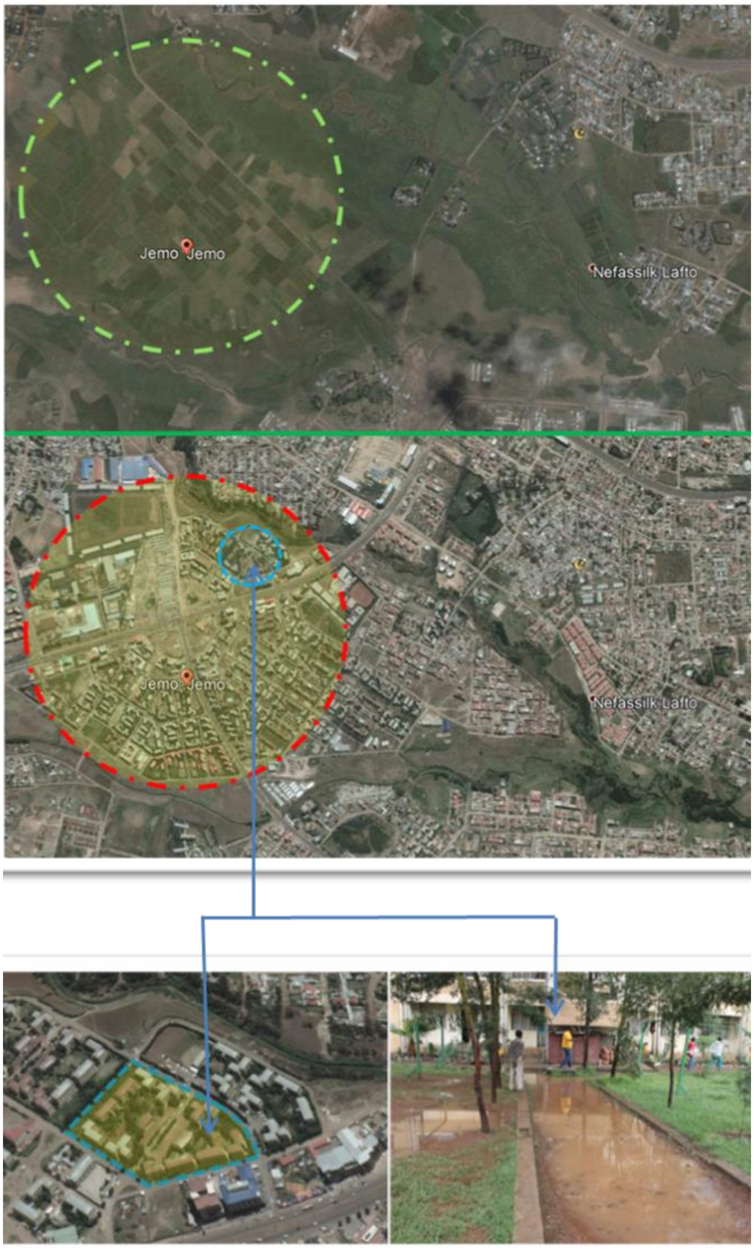

Figure 10: Aerial view of Jemo area in 2002. The site was open field occupied by crop land and pasture. Mid: Same area, 2018. Much land converted into roads and buildings for the establishment of Jemo 1 condominium. Bottom: Enlarged satellite image and picture of waterlogged open space and walkway within the site (Source: Google image and photograph by the author taken on June 2015).

Measures to control waterlogging in urban settlements located on flood plains in developing countries should rely on nature-based methods to be affordable, have a low resource requirement, and minimal greenhouse gas emission. Further, since the available open space in such settlements is limited, the measure should allow for pedestrian traffic and avoid permanent ponding to allow for multiple uses of the area to support livelihood and other co-benefits (European Commission 2015).

6.2. Objectives

The objective of this study was to develop a space-efficient multipurpose nature-based retention- and detention element for flood control in settlements developed on flood-prone plains of cities in developing countries.

Based on residents' wishes and concerns, we designed a semi-aboveground retention-detention element, serving flood control, stormwater storage, stormwater treatment, and groundwater recharging, and allowing for use of the area in between events. The element was tested by monitoring water levels over several rain events.

6.3. Methods and materials

The study was conducted using a flood plain condominium case area in Addis Ababa, Ethiopia. Utilizing a design charrette conducted with residents, requirements to the development of a multipurpose retention-detention element were obtained, and design ideas discussed. The final design was tested in the case study area and monitored for a short period.

6.3.1. Study area description

The case study area is Biruh Tesfa Housing Cooperative within Jemo -1 condominium project area and located 13 km from the city center of Addis Ababa in the southwest direction. Jemo Condominium is one of the establishments located 13 km southwest part of Addis Ababa, comprising over 10,000 dwellings (Planel & Bridonneau 2018) to accommodate over 50,000 dwellers. The case site covers 18032 m2 of land within two apartment clusters and accommodates 11 five-storied building blocks having 314 flats together with two 3-storied multipurpose communal buildings with parking area and open green spaces. The land use is presented in Figure 11, and the contribution of each of the five land cover classes is summarized in Table 5.

Table 5: Five major land uses and land cover classes represented by the area of each class, their surface characteristics and runoff coefficient to estimate volume of stormwater runoff generated from the case site

Land use type or specific site functions	Surface cover type	Area in m^2	% area	Runoff coefficient	Runoff volume /m^3	% volume of runoff
Buildings and pavements	Iron sheet & concreate	4139	23.0	0.80	132.4	52.0
Walk way and parking area	Sand and gravel mix	3741	20.7	0.40	59.9	23.5
Play field and seating area	Grass and bare land	2556	14.2	0.20	20.5	8.1
Lawn and communal garden	Trees, shrubs and grass	6875	38.1	0.10	27.5	10.8
Vehicular access road	Cobble stone pavers	720	4.0	0.50	14.4	5.6
Total		18031	100		254.7	100.00

Figure 11: Above: Existing layout map of the study area represented by five major land cover classes and contour lines. Below: Location map of the study area with in Jemo-1 condominium area (shaded by green color) bounded by Jemo and Hurbu rivers

Buildings and paved impervious surfaces cover 4139 m2 area of land, corresponding to 23% of the entire case site (Table 5). The remaining open spaces were estimated to cover 13,893 m2 or 77 % of the total area and consisted of green areas, pavements around buildings, walkways, and a central parking area (Fig. 11). The entire Jemo -1 condominium site is characterized by relatively flat land bounded by Jemo and Hurbu rivers just upstream from where the two rivers merge into a single watercourse to join the little Akakai River system.

6.3.2. Design idea input

The design was evolved during a three days community design charrette conducted at the case site, involving residents and municipal stakeholders, and targeting the overall waterlogging problems and lack of green infrastructure of the neighborhood. As described by Girling et al. (2006) Community Design Charrette is a decision support process for community planning. Initial ideas of developing a wet pond on the open common green area to control waterlogging were not appreciated by the residents due to concerns related to kids' safety from exposure to deep water in public area, and water-borne insect infestation. Likewise, cisterns were later rejected because of space scarcity to accommodate a large amount of rainwater within the available open spaces for a single purpose solution. The charrette further revealed a wish for better water supply in the area, which today depends on the municipal pipe-based system with many down-periods and thus supplement with water carried home from water vendors. In response to these requirements the idea of an aboveground detention volume in combination with a belowground retention volume for water supply and groundwater recharging, and use of the soil interface for treatment of infiltrating water, similarly to a constructed wetland, emerged (fig 12).

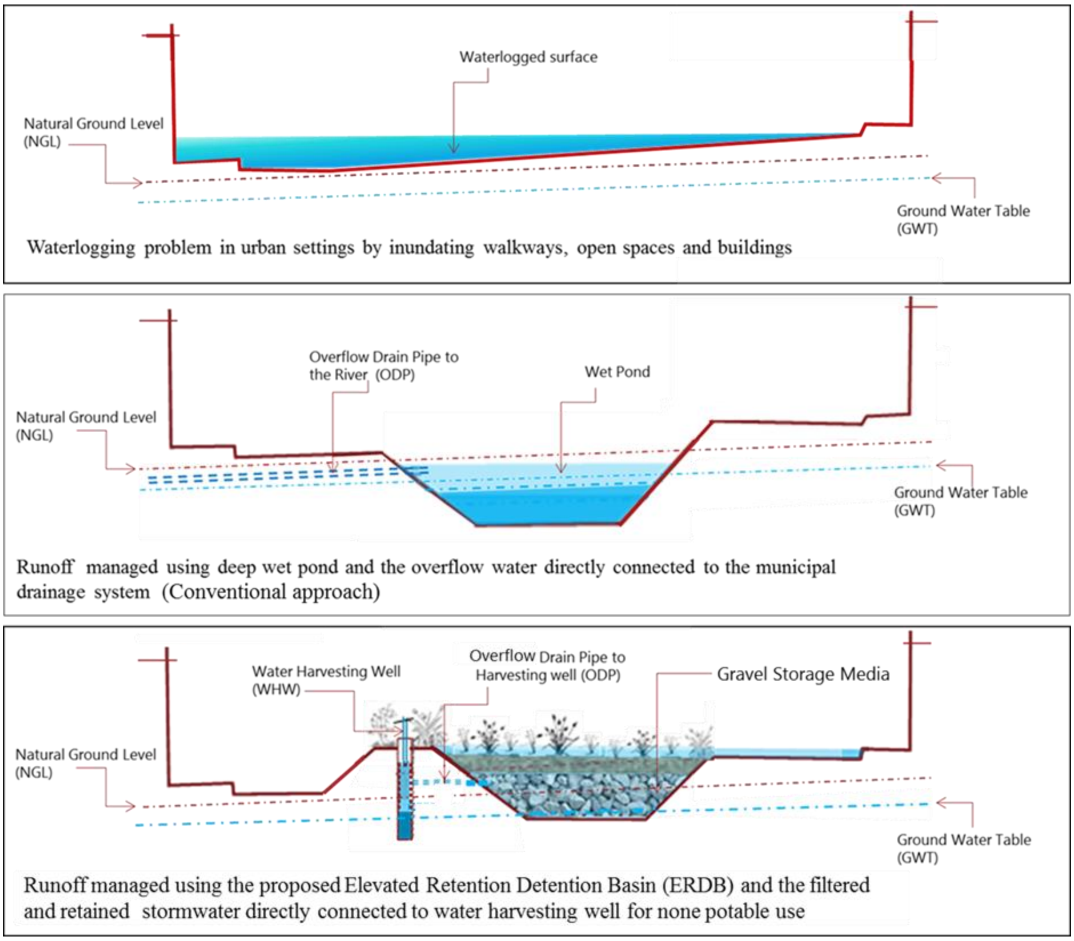

Figure 12: Schematic design idea development processes during the design charrette. Top: The flood problem on the walkway and open green space. Mid: Conventional and wet pond based solution later rejected by the charrette participants. Bottom: The idea of over ground detention of the flood together with gravel storage which was the most appreciated design idea by the local residents during the charrette.

6.3.3. Input data and sizing of the proposed solution

After consensus building with the local residents on the proposed idea, technical drawings were developed based on input data for precipitation, reduced area of contributing catchment, soil texture as proxy for hydraulic conductivity, and distance to groundwater table, as specified in the following:

- **Precipitation data:** Obtained from Bole International Airport and Ayertena Weather Stations in the vicinity of the case site

- **Topographic mapping:** Contour maps, building footprint, vegetation cover, drainage lines and others
- **Land cover distribution**: Computed using AutoCAD and Arc GIS software, based on municipal base map and validated using actual field survey
- **Geophysical survey:** Soil texture , soil moisture, rock type, rock depth using land the geotechnical laboratory equipment of EiABC, Addis Ababa University
- **Runoff coefficient C-values:** Determined based on assumption taken to different land surface covers by ASCE 1992 Manuals and Reports of Engineering Practice (No. 77) for the five land cover classes

The system was dimensioned for flood control of a 2-year storm event corresponding to 40 mm over 2 hours, which at the local site corresponds to a runoff volume of 171.5 m3 and the extra overland flow from the catchment area and excessive volume during extreme events connected to the municipal drain line (Table 5). However, the source of stormwater runoff causing waterlogging of the site originates from a 18032 m2 large catchment area, resulting in a total of 255 m3 (table 5). In this regard, the system has a capacity to manage 67 % of runoff generated from the entire neighborhood in case of a 2-y event (Table 6). The remaining 33% require additional similar or another type of nature-based stormwater management system depending on the natural condition of the available space. The available space at the downstream area over the playground is limited to 473m2 for surface ponding and 85.5m2 for shallow excavation. As listed in table 6, the system design to detain 118.5m3 of water as surface ponding during the rain event and the remaining water retained within crushed stone storage, sand filter media, and some infiltration into the ground. Regarding stormwater harvesting, the system was designed to retain 8 m3 within the crushed stone media, corresponding to the storage being replenished at storms of 40 mm fully.

Table 6: Details of each component of the suggested ERDB system consists of the design parameters in managing stormwater runoff

Components of ERDB	Hydrologic process	Contribution fraction	Size of media	Volume/m^3	% volume
Surface ponding area with turf over play ground	Detention &evapotranspiration	100 % of its volume detain water	473 m^2 by 0.25m average depth	118.3	69.0
Flood protection dike	Retention and evapotranspiration	15 % of its volume retain water	52 m by 2 m^2 typical cross section	15.6	9.0
Sand-soil mix plant growing and filter media	Retention and infiltration	25 % of its volume hold water	99.5 m^2 by 0.30m average depth	7.5	4.4
Crushed stone storage layer	Retention	40 % of its volume hold water	85.5 m^2 by 0.45m average depth	15.4	9.0
bottom surface of excavated area	Infiltration	Infiltrate water at the rate of 10^{-6} m/s	85.5 m^2 bottom surface area	14.8	8.6
Total runoff volume managed through the system				171.6	100

6.3.4. Experimental setup

The proposed design was built in full scale on the available open space. Monitoring well, in form of a square (0.7 m by 0.7 m), 1.2 m deep manhole made from bricks, was built next to the detention-retention element and connected to it by use of perforated pipes (Fig 13). A pressure transducer (HOBO U20 Water Level Logger) was placed in the monitoring well, and the water level was recorded at 5-minute intervals. A second transducer was used to measure atmospheric pressure for calibration. The data was converted into a water level graph using software provided with the transducers (HOBO ware graphing and analysis software). The observed water levels were compared with precipitation data gathered from the rain gauge in Ayer Tena weather stations.

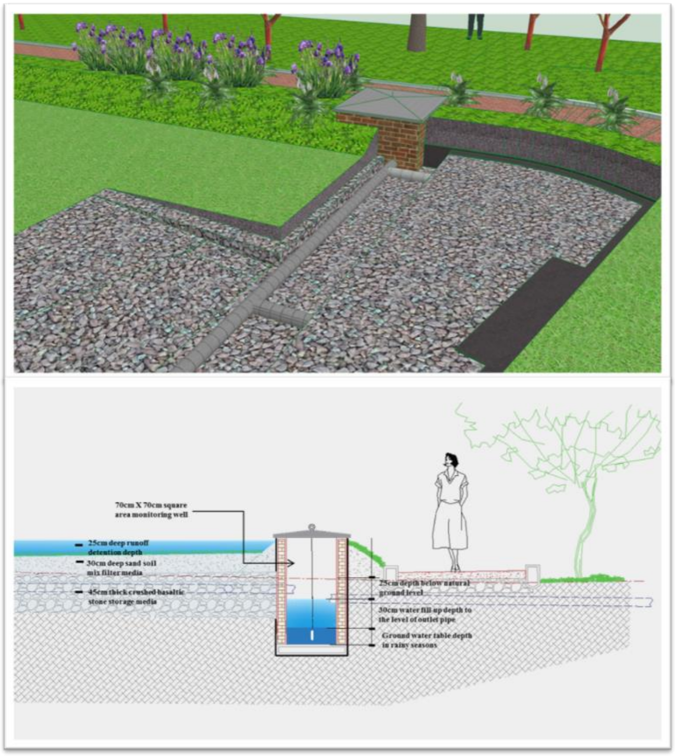

Figure 13: Presentation of the experimental setup. The monitoring well was directly connected to the retention-detention basin using perforated pipe (gray) inside the storage filled with crushed basaltic stone. Bottom: Profile of proposed ERDB system and water logging in monitoring well.

6.4. Results

The suggested detention-retention element, ERDB..., is shown in Figure 13. The element is placed partly aboveground, partly belowground with a separating soil layer in between. The aboveground volume serves as detention volume, with a mode of operation similar to a dry detention basin, i.e. it drains completely after events through a throttled connection to the municipal drainage pipe (Nascimento et al. 1999). The belowground volume serves as retention volume and should be filled with a porous material without capillary forces, e.g. gravel, to ensure the free flow of water inside the storage and options for full emptying. Immediately, the gravel layers saturated and the retention volume of water within the system can be pumped up through a well. The soil and sand layer between the surface water and lower gravel storages serves as a cleansing element, operating in a mode similar to filter soil as a bio-filtration system (Hatt et al. 2007a), by removing suspended solids by straining of particles in the soil matrix, and by sorption and degradation of contaminants and nutrients. The hydraulic conductivity of the soil should be relatively high, e.g. around 10-4 m/s, in order to allow filling up of the storage in the retention volume, before significant discharge to municipal drains. The soil covered area may serve additional purposes, like cropping of fruit-trees, area for drying clothes, etc.

6.4.1. Details of the construction

The detention-retention element was constructed with minimal terrain modifications by excavating an area of 100 m2 to a depth of 0.30 m and piling up the excavated soil to create an up to 0.8 m high perimeter dike along the lowest-lying contour line to ensure a level crown edge. The excavated volume was stabilized with crushed basaltic stone to a 0.45m below and above the natural ground level, corresponding to the retention volume. Sand–soil mix was added to the gravel to serve as a substrate for vegetation and cleansing of incoming water. The upper detention part had an average depth of 0.25m volume, corresponding to the detention volume area created over the surface of the proposed system to hold a fraction of stormwater runoff for infiltration rather than direct discharge.

The system was mainly equipped with natural materials including (Fig. 14, from below) crushed stone as storage media, sand-soil mix as filter media and grasses over the surfaces to maintain the hydrologic performance of the system. The vegetation consisted of high water intake plants with good pollutant removal capacity to be planted over the dike. Moreover; we proposed evergreen fruit trees and shrubs over the surfaces entire system together with undergrowth consisting of grasses and suitable hedges. False banana, banana, and false bamboo are important plat species that have a capacity to sustain in longer dry seasons with good pollutant removal capacity. Specifically, planting widely available species in Addis Ababa like Shembeko (Arundo donax) with good pollutant removal capacity (Amberber 2016) and Enset (Enset vetricosum) with good drought tolerance (Nybom et al. 2004) can contribute a lot for better performance of the system. The anticipated function of vegetation established across the surface of the dike as well as over the filter media is to increase the hydrological performance of the system by root growth stabilizing the soil structure and mitigating clogging, for example, Pham et al. (2012).

Runoff from the entire catchment was diverted to the inlet of the system by means of gravity and redirecting some haphazard flow of stormwater runoff with minor terrain modification. Overland sheet flow of stormwater runoff from the entire catchment was accumulated over the modified land surface until the water-filled within the void space of gravel, filter media and eventually to the top level of the dike. The system also operates by infiltrating stormwater runoff into the native soils but, the contribution of the infiltration processes to control waterlogging is insignificant due to the high groundwater table of the study area. In terms of harvesting stormwater for non-potable uses, the system increases the retention capacity of the landscape to extract water through the introduced well.

6.4.2. Evaluation of the performance of the system

The system was initialized in July and August, and water levels were subsequently collected in the peak rainy season for fourteen days (Fig. 14). As seen, the lowest water level in the lowest level in the ERDB was 8.3 m (initial level of the groundwater table) when the logging campaign started and the monitoring well was filled more with groundwater during wet seasons. Thus, the datum level for the logging campaign is 8.3m which is 0.55 m below the natural ground level and 0.30 m below the outlet pipe of the monitoring well. The water level in the monitoring well was raised up only in one extreme event to the level of the 8.6 m which is 0.3 m above the initial and datum level of the logging campaign (Table 7). This shows that the system controlled the entire runoff generated in all 14 days events except a one-day event on the 26th of August with 38.6 mm of precipitation which was the highest records from the 19th of August to the 3rd of September near to the 40 mm design event. In addition to mitigating waterlogging, the system is designed to contribute to the water supply through harvesting and groundwater recharging. The obtained water quality improvement was not yet documented. Likewise, the water supply contribution was not documented.

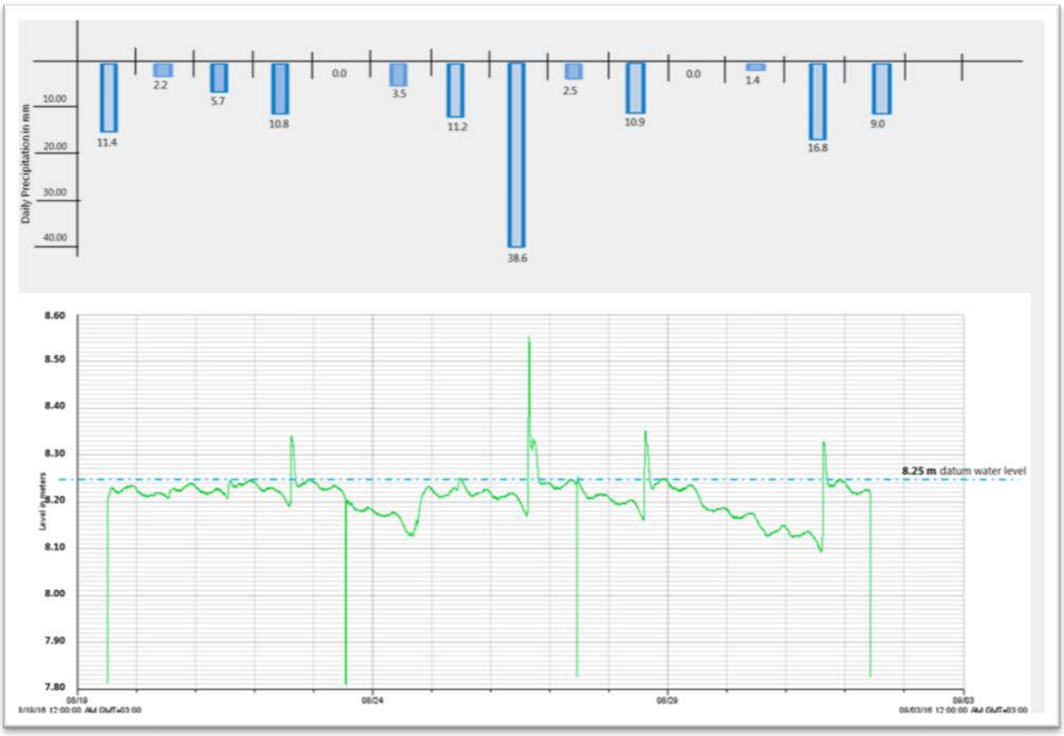

Figure 14: Water level fluctuation measured from the monitoring well from August 19 to September 1, 2016 represented by the blue line graph at the bottom and the corresponding precipitation pattern in the same period represented by blue bar chart at the top.

Table 7: Response of monitoring wells towards daily precipitation in the study area represented by the water level fluctuation in meters and daily precipitation data for comparison

	Rainfall data from 19th August to 1st of September													
	19	20	21	22	23	24	25	*26*	27	28	29	30	31	1
Daily precipitation in mm	11	2.0	6.0	11	---	4.0	11	*39*	3	11	2,0	1.0	17	9.0
The highest water level in monitoring well (logging started from 8.3 meters initial level = of ground water table)	---	8.3	8.3	8.4	8.4	8.2	8.3	*8.6*	8.3	8.4	8.3	8.2	8.2	8.3
Rise in water levels from ground water table within monitoring well in each event	---	0.0	0.0	0.1	---	-0.1	0.0	*0.3*	0.0	0.1	0.0	-0.1	0.1	0.0

6.5. Discussions

The proposed ERDB represents a nature-based retrofitting solution targeting densely developed urban areas located on waterlogging land with clay soils and shallow groundwater table, using available open green spaces. Applying wet ponds in densely developed urban areas with high pedestrian traffic is not likely due to public safety and health risk reasons specifically in urban areas of developing countries. With the proposed system the flood control part consists of a dry retention detention system, thus not posing a safety issue except during heavy rain. The system mainly operates by mimicking the natural stormwater flow pattern in the well-drained landscape through the incursion of porous material into the wet area through minimal terrain modifications. Moreover, the system can improve water quality through the natural water purification capacity of green plants and sand soil filter media. In this regard, further monitoring of the quality of water improvement is needed by taking a stormwater sample before and after passing through the system.

In urban areas of developed nations, wet pond consists of subsurface gravel wetland is a recent innovation in low impact development design that offers a high level of treatment for nonpoint source pollution for waterlogging lands (Mann 1997). This type of design is more applicable in a low-density urban area with ample open spaces to develop wet ponds in isolation from day to day pedestrian activities. The ERDB system is also applicable in permeable soils with some site design adaptation over small-sized open spaces for stormwater management effectiveness and co-benefits.

There are several environmental benefits obtained from installing the system ranging from ecosystem services in terms of water supply, greening, local climate modifications, and others. Among the co-benefits of the system, the stormwater harvesting is dominant by providing water for domestic use and irrigating the gardens to improve the open green space quality and urban agricultural practices. There are possibilities to harvest more than the estimated fraction of rainwater (8m3 of water) after every minor rain event from 10mm to 40mm of precipitation within 24 hours if adequate additional storage facilities connected to the system. In this regard, the extra volume of water beyond the 40mm design event can be harvested by connecting the outlet pipe to extra storage facility out of the system.

Specifically, the system is assumed to improve the moisture status of open spaces in the dry period of the year by retaining stormwater within the dike, and filter and storage during wet seasons. In both wet and permeable soil conditions, moisture retained within the system will be a good source of water for the growth of grasses, shrubs, and trees during the dry seasons over the surfaces of the ERDB.

In particular to the study area, the contribution of green plants on the surface of the system in runoff reduction is not considered and documented. However, the growth of vegetation such as banana, avocado, papaya, guava, orange, and others using harvested water will have multiple benefits in terms of green area improvement as well as food production. Moreover, the system will also contribute to the local climate modification through the evapotranspiration process in hot weather conditions of the sub-tropical climate of the case site.

The other important factor considered in the design and development of the system is social acceptance by residents. A careful terrain modification through the excavation of flat land to create dike and water storage space is a good opportunity for landscape architects to enhance the visual quality of open flat land. In contrast, massive terrain modification may lead to over-dimension and predominantly dry elements where sediment and waste can accumulate, maintenance needs intensify, and local community support may start to decrease (Backhaus and Fryd 2012).

The system is susceptible to clogging like any other gravel-based solutions such as infiltration trenches and soak away pits after a period of operation. In addition to gravel fill storage media, sandy soil filter media will also be clogged within a short period depending on the sediment load from the drainage catchment. In this regard, the mulch layer and the type of plants grown on the surface of the system determine the rate of clogging of subsurface materials. To minimize the risk of clogging of the system, careful maintenance of the landscape of the drainage area needed to avoid entering more silt and other sediments to the system. Unlike the pipe based drainage system, the maintenance of gravel based solution focusses on source control of sediment load. To reduce the maintenance burden, spread out of the silt and other sediments throughout the landscape rather than concentrating on the system is a commendable action (Dechesne 2004). The construction cost of the system could be part of the landscaping cost with some additional money. This will make the development cheaper by using locally available gravel fill or recycled material, soil and vegetation with limited excavations cost. Compared to the pipe-based drainage solution with more additional construction material which is alien to the natural landscape, the system will be more cost-efficient in both of its development and operational cost. In developing pipe-based drainage in the low-lying plains, due to the slope limitation, water flows along the land surface quite slowly together with the difficulty of digging deep drainage channels where the groundwater level is high; this means that drains have to be relatively wide to have sufficient capacity (Parkinson 2003). In the case of the proposed system, the major cost is the periodic replacement of the sandy soil filter media and crushed stone fill. Perhaps, the development cost of the entire system can be encompassed into landscape development cost of neighborhoods. It is possible to fit the system into ordinary landscaping with some additional cost for excavation and piling up of the dike and gravels. Therefore, both initial cost outlays required to achieve desired performance levels and maintenance costs related to effective upkeep is important for comparing location, type, and design possibilities (Green Nylen and Kiparsky 2015). In the case of the densely developed residential area on the low-lying plains, the system seems applicable. So that, the replicability of the system into the larger spatial scale with a similar situation will have the capacity to eliminate the waterlogging challenges during smaller rain events without additional pipe-based drains. Moreover, if the system applied carefully into the entire Jemo condominium area as a retrofitting strategy, it will relieve the downstream farmlands and settlements within little Akaki catchment from recurrent fluvial flooding and contribute to the groundwater recharging of Akaki well field. In this regards, GIS-based decision support system will be helpful for physical upscaling of the system with some design adjustment to fit into high and medium slope lands. The suggested ERDB is considered suitable for flat land of 2% and below, however with the provision of minor modification, it will also perform well with some design modification to the mid-slope lands for flood and erosion control and more environmental benefits.

6.6. Conclusion

As a result of inconsiderate land use planning practices, urbanization over the low-lying plains is becoming a serious problem to the settlements as well as the downstream farming communities. In the era of climate change, the governments and academia in different parts of the world have to look into other sustainable drainage options for areas prone to waterlogging instead of depending on conventional pipe-based drainage solutions. To control waterlogging and improve the hydrologic condition of the residential area in the low lying plains of areas Addis Ababa, the study proposed and tested a standalone gravel-based drainage system with some terrain modification on the available open spaces.

Based on the finding of the study, the proposed Elevated Retention -Detention Basin (EDRB) has been found to perform very well. The system has a full capacity to reduce the risk of waterlogged settlement through the development of a productive landscape by converting stormwater runoff into a resource rather than wastewater. Furthermore, the system designed and tested based on the principles of well-known retention and detention mechanisms with some design adaptation to fit into the local context of the case site. It will be applicable as a solution for other settlements on high and mid slop areas with permeable as well as over less permeable soil situations depending on the size and availability of open space. Further monitoring is needed to document water harvesting and groundwater recharging potential.

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7. Discussion and conclusions on the findings of the entire research

7.1. General

The two nature-based drainage design solutions are developed and tested mainly for flood and erosion control in flood-prone areas of Addis Ababa with co-benefits for the local residents and the entire city in terms of green infrastructure development. However, citywide application of the system requires more pilot projects as a showcase to demonstrate the performance of the system in particular neighborhoods that are affected by flooding. Pilots are important to demonstrate performance and thus persuade the local residents, professionals and the city authorities to proceed for a technological transition going from relying only on gray to greener drainage systems. Furthermore, citywide consideration of the nature-based solution is needed in order to reduce the negative impact of flooding and green infrastructure development initiative of the city master plan. To achieve this, more documentation on the relevant information including rainfall statistics, geophysical conditions of the city landscape and current traditional practices in applying nature-based solutions are needed.

The technological transition to the green drainage system will take more time and money in cities of developed countries compared to cities in the developing countries. In the case of cities in developed countries, replacing the existing well developed gray drainage infrastructure is a huge task, because the existing system has to be gradually replaced. On the contrary, provision of nature-based solutions in urban areas of developing countries is an easier task, especially in those areas without any drainage facilities in place, the transition is likely to be smooth and cost-efficient without demolition any built system. This is the basis for talking about technology leapfrogging. In order to achieve smother socio-technical transition, the current urban design and planning practices need to embrace the concept of nature-based solutions at the micro or macro level. At the micro-level, there is no regulatory provision at building or local development plans level. The city-wide masterplans at the macro level do consider the green area improvement and the idea of green infrastructure development. However, the plan missed considering the key aspects of green infrastructure development in the highly urbanized city regarding stormwater drainage, which call for different nature-based drainage solutions to integrate the fragmented open green spaces and degraded rivers.

The entire study has looked at three issues on the applicability of nature-based drainage design solutions in the context of cities of developing countries for stormwater management and green infrastructure development by taking two case studies from Addis Ababa Ethiopia. The first issue is the design and development process of nature-based drainage design and solutions to improve the drainage problem of flood-prone areas due to challenging geophysical features that are steeply and extremely flat to apply the widely applicable nature-based drainage solutions. The second issue is focused on evaluating the performance of the design solution for flood control and other co-benefits. The third issue is focused on the planning of the designed and developed solutions through upscaling into the wider area for flood control and green infrastructure improvement.

The literature review explored the theoretical backdrops with contextual reviews to conceptualize the applicability of nature-based drainage design options in line with multifunctional green infrastructure development for more co-benefits and eventually to build urban resilience. In the following section, the two contextual nature-based drainage design solutions are discussed in line with the need for the development of multifunctional nature-based drainage solutions as green infrastructure for urban resilience.

7.2. The IBTP drainage design solution and urban resilience

The suggested and tested IBTP system contributes to groundwater recharging and street greening and represents a multi-functional urban street drainage solution. Introducing the drainage design solution in an urban setting can increase the green cover of deserted urban local streets of cities by improving the moisture status of the tree pits along the street segment. Street trees enhance the cityscape quality from landscape architecture traditions and contemporary urban design and planning perspectives. Urban trees are more visible to people and can generate stronger public support than a less visible urban forest despite multiple benefits (Yang et al. 2009). Moreover, linearly arranged street trees can link patches of urban green spaces like parks, river buffers, and other conservation areas. As such, trees provide connectivity between forest remnants and riparian vegetation strips in cities, potentially providing corridors for the dispersal of small mammals, birds and other animal species (Angold et al., 2006). Considering the extent and the spatial distribution of local streets in the city, a significant impact of the suggested IBTP solution can be expected in the city environment, if implemented properly for ensuring the connectivity of isolated green patches for green infrastructure development. Moreover, street trees in the urban context have numerous benefits consists of aesthetic, psychological and socio-economic nature (Schoeder and Cannon, 1983).

The ecosystem services obtained from installing the IBTP design solution is mainly regulatory services consisting of stormwater runoff reduction and urban heat island mitigation. Sustainable Drainage Systems as part of an integrated approach to water management, cost-effectively provide many benefits beyond the management of water quality and quantity (Ashley et al. 2015). By improving the moisture status of the tree pits and linear open spaces along the local streets, the system will provide supporting ecosystem service by enhancing nutrient cycling in environmentally degrades urban settings. Furthermore, in the case of cities with a suitable agro-climatic condition for growing fruit trees, the system will also offer provisioning services from fruit grown along the local streets.

Urban forests and open green spaces might serve as spaces where people engage in productive landscape gaining political traction; this is seen in urban areas of the United States among societies which have their roots in the food security movement in the past (McLain et al. 2012). In this regard, by growing fruit trees along with the IBTP system, the local people within their neighborhoods benefited from fruit production and contribute to improving the livability of urban areas and livelihood improvement of local residents.

Even if, the existing gray street drainage infrastructure is well developed in those cities of developed nations, the technological transformation from gray to more greener options still continued in order to cope up with the unprecedented drainage challenges associated with rapid urbanization and climate change. In the case of cities in developing countries, there is still a need for further exploration of the applicability of sustainable urban drainage systems and the potential for transformation towards sustainable urban water management particularly in Sub-Saharan urban contexts (Mguni 2015). In this regard, IBTP design solution as a nature-based option will be a good opportunity for technological transition for cities of developing countries with a deficit in urban drainage infrastructure. It will be a simple and cost-effective approach for a smooth transition from depending on gray to more greener and sustainable drainage infrastructure, eventually to build urban resilience in the era of climate change and rapid urbanizations.

In the context of Addis Ababa, the surface of the local streets of the city is recently in the process of transformation from mud and gravel into cobblestone pavers. The integration of the IBTP drainage solution as the main drainage system of the local streets holds the potential to significantly support the city with green infrastructure for stormwater management and other environmental objectives of the city. In this regard, the study developed a GIS-based upscaling strategy as a decision support system for the city-wide planning of the IBTP. In this case, developing appropriate decision support tools will be helpful for the municipality to develop the system in different parts of the city with adequate information on the placement of the system and cost implications.

Like other types of gravel-based natural drainage solution, the system will be more susceptible to clogging and posed additional operational cost, if the fine particles and pollutants transported from other land uses are not controlled adequately. In order to achieve more results both in water quantity and quality management from the system, the adjacent land uses consist of residential and institutional plots should control pollutants and solid particles that contribute to the rapid clogging of the system.

7.3. ERDB drainage design solution and urban resilience

The ERDB design solution developed and tested on the available open green space was mainly aiming at improving the drainage, waterlogging and flooding problem of multistoried residential areas in the low-lying plains of Addis Ababa. In addition to the flood control function, the drainage solution contributes to water harvesting and green area improvement as a multi-functional open green space development. The drainage design solution improves the vegetation cover of the open space of the case study neighborhood by maintaining the moisture status of the area throughout the year. In the urban context, nature-based drainage design solutions as a green infrastructure can help to restore natural features (Ellis, 2013). In this regard, the suggested vegetated dike developed to intercept and accumulate the stormwater runoff, enhance the visual quality of open space from landscape architecture tradition perspectives, and minimizes the soil work by creating an above natural ground surface storage. In this case, careful landscape design consideration is required to ensure public safety and visual quality over the open spaces, and thus the public acceptance after the implementation of the design solution. Moreover, the system links the green space with water for green infrastructure development of the entire neighborhood.

The ecosystem services obtained from installing the ERDB drainage solution are mainly regulatory services which are stormwater runoff reduction from waterlogging settlements. There are several indirect ecosystem services obtained from the design solution. Among these services, the provisioning service from water harvesting opportunities is the most important for the local community in the case of the study areas, with a shortage of piped water from the municipal systems. Tokyo city has taken several measures to meet the increased water demand and to find alternative ways towards sustainable water use, while urban development has altered the nature of the water cycle (Furumai 2008). The rainwater harvesting on a small scale in Tokyo city provides a model example for the sustainable approach in megacities.

The design solution will provide more water for none potable uses such as car wash and irrigating gardens in the context of the case study area. The other provisioning service provided by the system is the opportunity for urban farming to produce fruit and vegetables over the dike and available open spaces in the vicinity of the system.

The system will also have a supporting ecosystem service by improving the moisture status of the open green spaces, eventually, enhancing nutrient cycling. In this way, the ERDB drainage solution may provide jobs and food for the local people within their neighborhood and contribute to the livelihood improvement of local residents. Moreover, the development of the system enhances the livability of the area by moderating the local climatic condition by linking green space and water. Here, the linking of green infrastructure and people in the case study area is a way to improve the livability and livelihoods of the local residents without compromising the existing cultural ecosystem services provided by the playground.

In the case of waterlogging urban areas, the development of gray and pipe-based drainage infrastructure is expensive. The initial cost for the development of the drainage system as well as the management cost is high due to the wetness and low terrain character of the natural landscape. In particular to settlements developed on low-lying plains with waterlogging problems, additional provisions with greener solutions are required in order to minimize the risk of flooding in addition to the existing adequate gray drainage infrastructure system. In line with this, the technological transformation from relying on the only gray to greener drainage system has to continue to keep up with the challenges of flooding in the waterlogging lands of cities of developed nations. In the case of cities of developing nations, ERDB drainage solution will be a good option for technological transition in settlements with a deficit in drainage infrastructure for a smooth transition from relying on the only gray towards a greener and sustainable drainage options. The applicability of the drainage design solution may vary depending on the local context as a standalone system or as complementary to the existing gray drainage system in building urban resilience to flooding throughout the world.

In the context of Addis Ababa, large scale high-density residential establishment in the southern fringe of the city mainly occur in relative flatlands that are susceptible to flooding. The case study area is one of the major establishments developed on the low-lying plains with the waterlogging problem. The integration of the ERDB drainage solution as the main drainage system for such type of housing areas has the potential to significantly reduce the waterlogging and flooding problem in the downstream areas. Furthermore, the system may contribute significantly to city-wide green infrastructure development for stormwater management and other environmental objectives of the city. In this regard, the study forwards a sort of recommendation to develop the appropriate type of upscaling strategy after the identification of waterlogging lands of the city using multi-criteria analysis tools.

8. Reflections and recommendations for future research

8.1. Citywide use and applications of nature-based drainage solutions in general

This study focused on exploring the option for the nature-based drainage design solution to improve the flooding, erosion and waterlogging problems in settlements developed over flood-prone areas of cities in developing countries. The areas are mainly characterized by high slope terrain and low-lying plains which are susceptible to flooding, erosion and waterlogging from recurrent storm events. As a result of the geophysical features, installing pipe-based gray drainage infrastructure is expensive and the development of well-practiced nature-based solutions also a difficult task. This thesis has come up with context-based drainage design solutions through terrain modifications of the available open spaces and the use of locally available natural construction materials, thereby enhancing the hydrologic performances of the landscape for effective stormwater runoff reduction.

The available and well-practiced nature-based solutions will be more promising solutions for on-site source control of stormwater runoff in both quantity and quality control aspects in cities of the developing world. In this regard, incorporating site adapted nature-based solutions for household or neighborhood level applications in cities of the developing country will be another area of research for the technological transition from gray and pipe-based toward greener solutions. Adopting and testing the performance of well-known small scale nature-based drainage solutions on private plots and local open spaces contribute a lot to the development of an overall citywide system. Presenting the technics and potentials of developing drainage solutions using pilot sites needs more academic and practical researches. Furthermore, research in line with participation and collaboration with the local residents and relevant actors working on the urban drainage and green infrastructure sector will be helpful for technology transfer in the transition process from gray to more green and nature-based solutions. At the current condition, the majority of open green spaces in the city are found within individual plots or housing clusters. Studies on developing manuals to train with the local residents and technicians for the dissemination of the knowledge and skills in the development and management of nature-based solutions is one of the most important research areas.

The other research area is developing a method to evaluate the performance of a different type of nature-based solutions with quantification of the flood reduction capacity of the system and estimating the co-benefits in the context of Addis Ababa with the tropical highland climatic zone. This particular climatic factor consists of the long dry season and shorter rainy season with enormous precipitations within three months that need special attention from academia. The majority of well-practiced nature-based drainage solutions have been developed and tested in temperate climate regions of North America and Europe. There are pieces of research finding and practical nature-based solution projects in the case of cities in Australia, with a similar tropical climate to Addis Ababa that can serve as a starting point for further research. In this case, specific researches and innovations are needed in the case of Addis Ababa to apply different types of nature-based solutions due to the higher rainfall intensity compared to cities in Australia. In order to create or adopt the widely practiced types of nature-based drainage design and technologies in the global north, the innovation of context-specific nature-based solutions is one of the most important research areas in the future. Innovations in the nature-based solution for urban drainage services are needed to align communities with sustainable development (D´Archy 2013). Furthermore, there should be a focus on a selection of the appropriate type of plant species with livelihood and livability potentials in addition to water supply schemes including both aboveground and belowground storages, as indicated with the ERDB system.

In the case of Addis Ababa, the existing gray drainage infrastructure is underdeveloped and the use of available and well-practiced nature-based drainage solutions is very limited (Mguni 2015) except some attempt in the use of permeable paving over the local streets of Addis Ababa. Investing in nature-based solutions is a good opportunity for Addis Ababa, in order to compensate for the existing drainage infrastructure deficit as well as for green infrastructure development eventually to go forward and create urban resilience to flooding. In this regard, citywide assessment and documentation on the geophysical condition are needed for the identification of potential areas in citywide planning and applications of nature-based drainage solutions for green infrastructure development. Further documentation in traditional practices, either from urban or rural settings that will contribute to establishing knowledge in nature-based solutions should be one of the components in academic inquiries for applying nature-based drainage solutions in the context of Addis Ababa.

The current master plan for Addis Ababa attempted to incorporate a green space plan and the idea of green infrastructure development as part of the environmental protection plan of the city (Herslund et al. 2018). However, incorporating the available and well-known nature-based drainage solution will ensure the practicality of the plan by considering the local geophysical factors and institutions of the city. Establishing city-wide green infrastructure through the integration of nature-based solutions is the potential research area in the future in the context of Addis Ababa. In order to achieve this, the nature-based drainage solutions have a capacity to create linkage for the most fragmented green and blue features of the city through minor geophysical interventions with creative landscape design solutions. Within diverse landscape features and suitable tropical climatic situations, the solutions offer more benefits by compensating the degraded green spaces and river system with more vegetation and water. To achieve this initiative, the city needs further investigation on the existing data sets, and the provision of accurate information on groundwater hydrology, soil texture, geology and other key parameters that are pertinent for the design and planning of citywide nature-based solution as for citywide green infrastructure development. In addition to the master plan, the guidelines for road drainage practice should be updated to include the IBTP system. Research on how to efficiently embed upcoming technologies in the rapidly expanding road infrastructure is much needed.

Finally, in developing countries, particularly in Addis Ababa, there should be more research on the institutional transition in the urban drainage system in addition to the technological transitions towards greener drainage options. The institutional transition in the municipalities and other relevant sector offices helps to ensure the practicality of the newly introduced nature-based approaches which encompasses several green infrastructures and other related issues other than the urban drainage system. In this regard, the researches should also consider comprehensive transitions in urban stormwater management that address the planning and management of other factors that influence the implementation of nature-based solutions. Managing the resources in the form of co-benefits like domestic water supply, water for irrigation, green spaces, vegetation, and others represent another area of research from institutional transition perspectives. Furthermore, there should be more research to align the nature-based solutions in an urban context with policies and guidelines already in use to allow for a smooth transition away from gray towards green. The main policy framework in this regard is Ethiopia’s Climate-Resilient Green Economy. It is a strategic document with the ambition to build a green economy based on the pillars consists of agriculture, forestry, power, transport, industrial sectors, and buildings. The preliminary assessment of the document mainly focused on waste management and urban greenery in growing cities and towns of the country with no specific provision to stormwater management. The inclusion of the nature-based solution for urban stormwater management will be a good instrument for building a climate-resilient green economy, by addressing water harvesting and urban agriculture issues.

8.2. Specific to the application of IBTP and ERDB drainage design applications

As an academic exercise, this Ph.D. study has some practical, methodological and conceptual limitations. The number of case studies to test the performance of the proposed novel nature-based drainage design solutions is limited to only two sites. Besides the two case sites, there are different settlement types affected by similar problems with different spatial configurations and geophysical conditions. For example, the study has to test the performance of IBTP drainage solution in streets developed on the low-lying plains with lower permeable soil conditions and flat topography. In this regard, the street developed on such types of geophysical features requires special treatment in order to drain more water through the different hydrologic processes. This treatment affects the sizing and components of the IBTP drainage solution, which needs to be modified to this type of land and to allow the solution to rely more on detention and evapotranspiration mechanisms than retention. In the case of streets developed over well-drained lands in densely developed urban centers, the system can rely more on infiltration and retention within the native soil.

The ERDB drainage design solution developed in the second case study site is also applicable for permeable soil conditions in condominium housing and single-family residential areas developed on permeable soil conditions with some design adjustment to fit into the geophysical conditions. In this case, the hydrologic performance of the system may shift from depending only on the detention and retention process to include more infiltration of stormwater into the native soil. This may influence the sizing of individual ERDB drainage design solutions. In this regard, by increasing the number of case studies, the upscaling strategy can be based on more empirical pieces of evidence rather than with some assumptions for extrapolations, and analytical validations.

The other important factor that the research needs are incorporating feedback from the local residents and authorities after the development of the two drainage solutions for further improvements and upscaling. Except for some informal discussion with the local residents in the two case sites, there were no well-organized and documented feedback mechanisms on the perception of local communities about the designed and developed drainage solutions. Conceptually, the study applied action research methods, for improving flooding and waterlogging problem from the study area together with local communities, experts and concerned stakeholders. Such type of research needs appropriate feedback mechanisms for further improvements in the implemented solutions. However, the political unrest in the country and lack of willingness of the local residents for further action, specifically at the second case study site (Jemo condominium), the researcher prohibited to include the feedbacks for some adjustments and corrections on the design and experimental setups for a more accurate result.

This Ph.D. study relies on the results of full-scale implementations of the proposed drainage design solutions with empirical pieces of evidence from experimental setups. Regarding the design and development process, the study achieved the key objectives of the research by developing two novel nature-based drainage solutions together with local people and other concerned parties. However, regarding the experimental setups, to evaluate the performance of the two solutions, the study was needed to generate more data from one rainy season logging campaign. To qualify the experiment more, it was important to repeat the experiments at the list for an additional one rainy season with additional measurements of the water levels by readjusting the experimental setups for different geophysical design parameters with additional measuring equipment. This is not least the case for the documentation of the IBTP, where the inter-flow in the gravel bedding level needs to be further explored. In terms of the equipment used for this experiment, the study generated data using only water level data loggers that didn't include the volume of runoff managed through the system accurately, and also needs volumes quantification to estimate the co-benefits in terms of water harvesting opportunities.

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