


Dissertation

SPATIAL SCENARIO MODELLING FOR THE SUSTAINABLE PLANNING OF URBANISING REGIONS IN SUB-SAHARAN AFRICAN CITIES.

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“Growth is inevitable...

The question is not whether your part of the world is going to change. The question is how”

Ed McMahon

ABSTRACT

Urban population growth and future expansion of settlement areas are among the major challenges that cities in Sub-Saharan Africa are currently facing. The built-up areas of African cities are growing and also expanding into the peri-urban regions leading to high losses of green infrastructure and the ecosystem services it provides. Consequently, the urban population is increasingly put at risk by natural hazards such as flooding and heat waves as well as shortage of local food supply. For urban planning there is a need to better understand the relationship between urban dynamics and its consequences for green infrastructure and ecosystem services. Moreover, urban planning needs tools to assess the impact of urban development strategies on the surrounding environment.

Against this background, this dissertation aims to investigate the impact of urban growth on the surrounding environment of urban areas in Sub-Saharan Africa: to increase knowledge of the factors driving urban growth in some African cities; and to introduce and test a method to assess the impact of urbanisation on the urban ecosystem services under different scenarios of urban growth.

This research employs an Urban Spatial Scenario Design Model (USSDM), which is a spatial scenario modelling approach to simulate settlement expansion and development in different settlement density scenarios using the case study of Addis Ababa (Ethiopia) and its surrounding region. Spatial indicators and environmental as well as hydrological models are used to study the impact of settlement expansion on food provisioning and flood regulating ecosystem services. These services are assessed under current conditions and in the future for different scenarios of settlement expansion. The losses of farmland and the potential exposure of urban inhabitants to flood hazards were estimated. Finally, settlement area expansion in the sub-watershed of the little Akaki River (regional area of Addis Ababa) was modelled with the use of a hydrological model to analyse the consequent changes in flood patterns inside the city.

Settlement expansion in the high-density scenarios led to lower losses of Green Infrastructure and lower exposure of people to flooding hazard. In the peri-urban region, a dramatic loss of suitable land for cultivating important crops was observed in the business-as-usual scenario as compared to the high-density scenario. Controlling urban sprawl and promoting a more densified form of development would help to reduce the loss of vegetated land cover types, which act as natural channels and help retaining floodwaters. This would also help to better protect permeable soils during settlement expansion. Results of this research suggest that settlement expansion in the peri-urban will lead to an increase in flood hazard (and consequently higher vulnerability) in the inner city even though located kilometres away.

The findings of this research have practical implications for urban planners who are seeking to achieve a more sustainable planning of urbanising regions in Sub-Saharan African cities. There is a need to adopt a new model for compact urban development, which protects and integrates green infrastructure and farmland in order to increase urban resilience and food security. Planning of cities should take into consideration the hydrological characteristics of the ecosystem as a whole in the outlying areas surrounding those cities. Assessment of ecosystem services provided by the environment should be an important step that precedes the allocation of future residential areas. Managing the environment of the peri-urban interface has significant consequences for the livelihoods and quality of life of the inhabitants and for the sustainability of urban and rural development. Both the scenario modelling approach introduced and the specific results of this research can provide useful information for local administrations and decision makers to support evidence based development of land use policies favouring reduction of the adverse effects of urban growth on the environment.

KURZFASSUNG

Das Bevölkerungswachstum und die zukünftige Ausbreitung der Siedlungsgebiete gehören zu den größten Herausforderungen, vor denen die Städte in Subsahara-Afrika derzeit stehen. Die bebauten Gebiete afrikanischer Städte wachsen und dehnen sich auch auf die Randgebiete aus, was zu hohen Verlusten an grüner Infrastruktur und den damit verbundenen Ökosystemdienstleistungen führt. Folglich wird die städtische Bevölkerung zunehmend durch Naturgefahren wie Überschwemmungen und Hitzewellen sowie durch die Verknappung der lokalen Lebensmittelversorgung gefährdet. Für die Stadtplanung ist es notwendig, den Zusammenhang zwischen der städtischen Dynamik und ihren Folgen für grüne Infrastrukturen und Ökosystemleistungen besser zu verstehen. Darüber hinaus benötigt die Stadtplanung Methoden zur Bewertung der Auswirkungen von Stadtentwicklungsstrategien auf das Umland.

Vor diesem Hintergrund zielt diese Dissertation darauf ab, die Auswirkungen des Stadtwachstums auf das Umland der städtischen Gebiete in Subsahara-Afrika zu untersuchen. Die Untersuchung will die Kenntnisse über die Faktoren, die das Stadtwachstum in einigen afrikanischen Städten antreiben, verbessern und eine Methode zur Bewertung der Auswirkungen der Urbanisierung auf die städtischen Ökosystemleistungen unter verschiedenen Szenarien des Stadtwachstums einführen und erproben.

Diese Forschungsarbeit verwendet das Urban Spatial Scenario Design Model (USSDM), eine Methode zur Simulation von Siedlungsexpansion und -entwicklung in verschiedenen Siedlungsdichte-Szenarien am Beispiel der Metropolregion Addis. Räumliche Indikatoren und ökologische sowie hydrologische Modelle werden eingesetzt, um die Auswirkungen der Siedlungsausweitung auf die Nahrungsmittelversorgung und die hochwasserregulierenden Ökosystemdienstleistungen zu bewerten. Diese Dienstleistungen werden unter den aktuellen Bedingungen und in Zukunft im Rahmen verschiedener Expansionsszenarien bewertet. Die Verluste an Ackerland und die mögliche Exposition der Stadtbewohner gegenüber Hochwasserrisiken werden ermittelt. Darüber hinaus wurde die zukünftige Siedlungserweiterung in den Randgebieten von Addis Abeba modelliert, um deren Auswirkungen auf geeignete Ackerflächen, die möglicherweise verloren gehen würden, zu bewerten. Schließlich wurde die Erweiterung der Siedlungsfläche im Einzugsgebiet des Little Akaki-Flusses (regionales Gebiet von Addis Abeba) mit Hilfe eines hydrologischen Modells modelliert, um die daraus resultierenden Veränderungen der Hochwassermuster innerhalb der Stadt zu analysieren.

Die Ausweitung der Siedlungen in den Szenarien mit hoher Dichte führte zu geringeren Verlusten an grüner Infrastruktur und zu einer geringeren Belastung der Menschen durch Hochwasser. In den peri-urbanen Region gehen geeignete Flächen für den Anbau wichtiger Nutzpflanzen im Business-as-usual-Szenario im Vergleich zum High-Density-Szenario dramatisch verloren. Die Eindämmung der Zersiedelung und die Förderung einer verdichteteren Form der Entwicklung würden dazu beitragen, den Verlust von Landbedeckungstypen, die den natürlichen Abfluss begünstigen und dazu beitragen, Retentionsflächen zu erhalten, zu verringern. Dies würde auch die Bewahrung von wasserdurchlässigen Böden fördern. Die Ergebnisse dieser Forschung deuten darauf hin, dass die Siedlungsexpansion am Stadtrand zu einer Zunahme der Hochwassergefahr (und damit zu einer höheren Anfälligkeit) in der Innenstadt führen wird, auch wenn sie mehrer Kilometer weit entfernt liegt.

Die Ergebnisse dieser Forschung haben praktische Auswirkungen auf Stadtplaner, die eine nachhaltige Planung von wachsenden Stadtregionen in Afrika südlich der Sahara anstreben. Es ist dazu notwendig, ein neues Modell für eine kompakte Stadtentwicklung zu entwickeln, das grüne Infrastrukturen und landwirtschaftliche Flächen schützt und integriert, um die Widerstandsfähigkeit der Städte und die Ernährungssicherheit zu erhöhen. Bei der Planung von Städten sollten die hydrologischen Merkmale des gesamten Ökosystems in den Randgebieten dieser Städte berücksichtigt werden. Die Bewertung der von der Umwelt erbrachten Ökosystemleistungen sollte ein wichtiger Schritt sein, der der Zuweisung künftiger Wohngebiete vorausgeht. Das Management der Umwelt an der Schnittstelle zwischen Stadt und Umland hat erhebliche Auswirkungen auf die Lebensgrundlagen und die Lebensqualität der Einwohner sowie auf die Nachhaltigkeit der städtischen und ländlichen Entwicklung. Sowohl der eingeführte Ansatz der Szenariomodellierung als auch die spezifischen Ergebnisse dieser Forschung können wertvolle Informationen für lokale Verwaltungen und Entscheidungsträger liefern, um Landnutzungsstrategien, die die Verringerung der negativen Auswirkungen des städtischen Wachstums auf die Umwelt fördern, wissenschaftlich zu unterstützen.

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LIST OF ABBREVIATIONS

AAOIDP	Addis Ababa and the Surrounding Oromia Integrated Development Plan
BAU	Business as usual
CA	Cellular Automata
CAD	Computer Aided Design
CLUVA	CLimate change and Urban Vulnerability in Africa
CN	Curve Number
CSA	Central Statistics Agency of Ethiopia
DEM	Digital Elevation Model
EC	European Commission
EiABC	Ethiopian Institute of Architecture, Building Construction and City Development
ES	Ecosystem services
GIS	Geographic Information System
IHDP	Integrated Housing Development Program
OWWDSE	Oromia Water Works Design and Supervision Enterprise
TWI	Topographic Wetness Index
UGI	Urban green infrastructure
UHI	Urban heat island
UMT	Urban Morphology Type
UNDESA	United Nations Department of Economic and Social Affairs |
UN-Habitat	United Nations Human Settlements Programme
USSDM	Urban Spatial Scenario Design Model
WHO	World Health Organisation

LIST OF PUBLICATIONS

Paper 1: Abo-El-Wafa, H., Yeshitela, K., & Pauleit, S. (2017). The use of urban spatial scenario design model as a strategic planning tool for Addis Ababa. *Landscape and Urban Planning.*

Summary

Urban population growth and expansion of settlement areas are among the major challenges that African cities are facing. Addis Ababa's settlement area has been expanding into the city's peripheral area at the expense of losing green infrastructure (GI) of farmland and vegetated areas. The protection of GI is impeded by the lack of foresight information and tools to support urban planning. Therefore, a GIS-based urban spatial scenario design model (USSDM) was applied for modelling the settlement expansion in Addis Ababa. A business as usual scenario (BAU) and a densification scenario (DENS) were modelled to evaluate the impact of population density on the green infrastructure and the implications of excluding settlement development from flood-prone areas. Training and workshops were conducted on the use of USSDM in the Addis Ababa master plan review. The results of our study indicated that increasing population density from 166 to 350 inhabitants per hectare would almost halve the losses of the green infrastructure. Moreover, the settlement development in the densification scenario would be located closer to the vicinity of the built-up area rather than spreading along the eastern part of the city, which is currently occupied by farmland in the case of BAU. Densification would also slow down the expansion of settlements in river corridors but might expose more inhabitants to flood hazards. USSDM is one of few models in Africa that is designed towards application by urban planners as a tool for assessing the impact of urban development strategies on the surrounding environment.

Author’s contribution

The first author H. Abo-El-Wafa developed the research concept and theoretical framework, performed the modelling and spatial analysis work, composed and wrote the manuscript under the supervision of the co-authors. Both co-authors contributed to the manuscript by scientific advice and paper review.

Paper 2: Abo-El-Wafa, H., Yeshitela, K., & Pauleit, S. (2017). Exploring the future of rural–urban connections in sub-Saharan Africa: modelling urban expansion and its impact on food production in the Addis Ababa region. *Geografisk Tidsskrift-Danish Journal of Geography, 117(2), 68-81.*

Summary

The built-up area of Addis Ababa and its surrounding towns is expanding into the peri-urban region leading to high losses of farmland, directly influencing the food production for the urban population. This paper investigates the patterns of settlement growth in the region surrounding Addis Ababa and their impact on peri-urban agriculture using an urban spatial scenario design model. The effects of two population density scenarios are explored within the framework of a proposed master plan. The model output was used to estimate areas of different suitability levels that would be lost to the modelled settlement expansion. The settlement area in 2038 would represent 29% of the case study's total area in the low-density scenario but only 19% in the high-density scenario. Compared to the low-density scenario, the high-density scenario would only require a third of the agricultural land transformed into settlement areas. Settlement development would contribute to higher losses of land suitable for cultivating important export products, high nutritional value and import-substituting products. The scenario approach can support sustainable regional planning for settlement expansion that conserves valuable farmland in the peri-urban area and contributes to building capacity for strategic planning of the city regions of sub-Saharan Africa.

Author's contribution

The first author H. Abo-El-Wafa developed the methodological framework, collected the data from different sources, performed the modelling and spatial analysis work, and composed and wrote the manuscript under the supervision of the co-authors. Both co-authors contributed to the manuscript by scientific advice and paper review.

Paper 3: Abo-El-Wafa, H., Speranza, G. & De Paola F. (2018). Modelling urban growth and future flood hazard: the case of Addis Ababa. *Urban and Environmental Engineering (submitted).*

Summary

Urban growth increases the risk of flooding due to the replacement of vegetated areas by impervious surfaces and changes in stream morphology. This research models the settlement area expansion in the subwatershed of the little Akaki River (regional area of Addis Ababa) using an urban spatial scenario design model (USSDM). The consequent changes in flood patterns inside the city due to the modelled settlement expansion are simulated using a hydrological model. The model estimates the volume and the flow depth of water to delineate a hazard map for the years 2011 and 2038. The modelled settlement expansion in the subwatershed leads to an increase in the flood hazard area's extent within Mekanisa (domain area). Both the volume and the velocity cellular values generally increase, which contributes to a higher risk of flooding in the domain area. Incorporating urban growth models with hydrological and hydraulic models can help assess the impact of urbanization on the flood regulating ecosystem services provided by the natural and semi natural vegetative land cover. The output of such models would be useful in generating knowledge and empirically based evidence that assist in the sustainable planning of cities and their surrounding regions.

Author's contribution

The first author, H. Abo-El-Wafa developed the methodological framework, collected the data from different sources, performed the spatial scenario modelling and spatial analysis work. The first author composed and wrote the manuscript. The second and third authors supported the flood modelling work and collaborated in the writing of the related part.

1. INTRODUCTION

1.1 Background and problem definition

According to a 2018 UN report on World Urbanisation Prospects, the urban population of the world has grown rapidly since 1950, having increased from 751 million to 4.2 billion in 2018. At 13%, Africa has the second largest share of the total urban population in the world after Asia. The report also highlights that 90% of the urban population growth in the world is happening in Asia and Africa (UNDESA, 2018). Africa, the least urbanised content, is the world's second-fastest urbanising region with an average annual rate of change of urban population of 4.1% for the period 2010–2020 (UN-Habitat, 2014).

The urban population of Sub-Saharan Africa has increased from 163 million inhabitants in 1995 to 359 million inhabitants in 2015 and is projected to reach 522 million inhabitants in 2025 (UNDESA, 2018). Globally, in the period of 1995-2015, the rate of change of the urban population (%) is the highest in Africa (3.44%) with western and eastern Africa being the regions of the highest rates of 4.3% and 4.1% respectively (UN-Habitat, 2016).

Due to the growing urban population, urban areas are continuously expanding (Khan, Arshad, & Mohsin, 2014). According to a global study conducted by Seto, Güneralp, and Hutyra (2012), the rate of increase in the urban land cover is predicted to be highest in Africa. They expected that the expansion will be concentrated in five specific regions of which, the greater Addis Ababa in Ethiopia is the only region surrounding a city.

Urbanisation is occurring in a context of low urban institutional capacities, inefficient governance mechanisms coupled with high levels of poverty (Parnell & Walawege, 2011; UN-Habitat 2014; Vedeld et al., 2015). Poorly planned and managed urbanisation leads to a mismatch between infrastructure provision and residential concentration; inadequate public space and street networks; and low-density development (UN-Habitat, 2016). Moreover, cities are growing beyond their administrative and physical boundaries into the peri-urban area in which the traditional governing and planning structures become outdated. This trend has led to expansion not just in terms of population settlement and spatial sprawl, but the functional areas of cities and the people that live and work within them are transcending physical boundaries (ibid).

The uncontrolled low-density settlement development causes large losses in green infrastructure. Green infrastructure has been defined as an “interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations” (Benedict and McMahon, 2006; Lovell and Taylor, 2013). Especially in developing countries, urbanisation is considered as the main driver leading to agricultural land conversion (Azadi, Ho, & Hasfiati, 2011; Dadi et al., 2016). Agricultural land (such as land for cultivating field crops and vegetable farms) and other vegetated areas (such as plantation forest, mixed forest, riverine vegetation, and grasslands) are regarded as critical components of green infrastructure that reduce the vulnerability of the rapidly developing cities in sub-Saharan Africa (Lindley et al., 2015). The loss of green infrastructure directly decreases the provision of ecosystem services such as food and timber provision, climate regulation, nutrient cycling as well as cultural identity (Arku, 2009; Foley et al., 2005). Continuous transformation of green infrastructure into built-up areas also increase the risk of flooding in cities due to the replacement of vegetated areas by impervious surfaces, changes in stream morphology and poor drainage systems (Huong & Pathirana, 2013). Encroachment of settlements into flood-prone areas such as river valleys increases the risk of major disasters (Doberstein & Stager, 2013; UNISDR, 2009). Only few studies (such as Cilliers et al., 2017; Lindley et al. 2015; Lindley et al., 2013; Shackleton et al., 2017; Van der Walt, Cilliers, Du Toit, & Kellner, 2015) have adopted the concept of green infrastructure for African urban areas (Schäffler & Swilling, 2013).

As the residential and commercial development areas expand, urban expansion leads to a loss of agricultural land globally (Erickson, Lovell & Méndez, 2013). It also has a considerable impact on farming systems in the surrounding regions of urban areas, where agriculture is often the primary traditional occupation of the peri-urban areas’ inhabitants (Tacoli, 2003).

Agriculture in urban and peri-urban areas of African cities has a vital role in both supplying food for urban inhabitants and providing sources for income generation (FAO, 2012; Halloran & Magid, 2013). Urban agriculture is still considered a significant means of livelihood for urban households in Africa as compared to other continents (Zezza and Tasciotti 2010). Urban vegetable production in sub-Saharan Africa is regarded as one of few stable income sources for farmers with limited qualifications (Drechsel and Dongus 2010).

Food production through urban and peri-urban agriculture is particularly important for the urban poor. They usually have irregular and inadequate access to food and insufficient purchasing power as the food supply and distribution costs from rural areas to the urban areas, or to import food for the cities are continuously increasing (AAOIDP, 2013; Tolossa, 2010). Hence, agriculture in peri-urban areas of developing countries can reduce vulnerabilities of their regional food systems either for local consumption or for export (Pribadi & Pauleit, 2015; UN-Habitat, 2016).

In the case of a Sub-Saharan African city, such as Addis Ababa, urban vegetable farming creates employment opportunities, income generation sources and improves food availability (Gebrekidan, 2015). More than 50% of the field crops and 70% of the vegetable production within Addis Ababa is used for household consumption (CSA, 2002). The expansion of urban centres and the transformation of agricultural land into residential, commercial and industrial areas occur in parallel with transformation in the inhabitants' livelihoods with the urban poor being the most disadvantaged group (Tacoli, 2003).

Flood-related disasters in Africa have increased over the past 40 years (Figure 1 Occurrences of flood related disasters in Africa in 1900-2015 (Data source: EM-DAT), whereas, almost half of the disasters recorded in Sub-Saharan Africa in the period 1981 - 2010 are floods (Tiepolo & Macchi 2014). Moreover, climate change projections show that flood risk will increase in the future due to a higher frequency of extreme rainfall (World Bank, 2015).

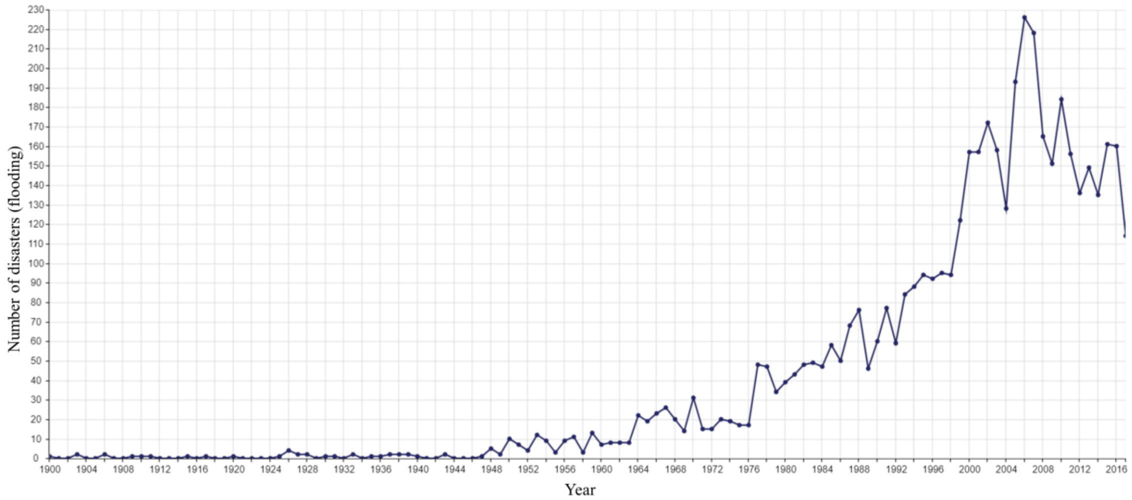


Figure 1 Occurrences of flood related disasters in Africa in 1900-2015 (Data source: EM-DAT)

Flooding in urban areas is linked to heavy rainfall, extreme climatic events and dramatic changes in the built-up area (Douglas 2008). Moreover, urbanisation leads to the increase of impervious areas by covering the ground with roads, pavements and roof areas that tend to obstructs natural channels where floodwaters usually go, consequently, accumulating drains where water moves to rivers more rapidly than it did under natural conditions (ibid).

Urbanisation in floodplain areas exacerbates flooding risks due to increased peak discharge and volume and decreased time to peak (Campana and Tucci, 2001; Nirupama and Simonovic, 2007 and Saghafian, Farazjoo, Bozorgy & Yazdandoost, 2008). Encroachment of settlements into floodplain areas exposes them to a higher risk of flooding. Moreover, the change in the land use pattern due to urbanisation negatively affects the hydrological processes in a catchment. The increase in impervious areas disrupts the natural water balance. Reduced infiltration increases runoff and leads to higher flood peaks and volumes even for short duration low-intensity rainfall (Suriya & Mudgal, 2012). When urbanisation occurs inside a river watershed, runoff volume and peak discharge increase in comparison with the undeveloped land.

Conventional land use and master planning approaches need to be reconsidered in order to cope with the unprecedented urban population growth rates that were not foreseen when the master plans were developed for several African cities (Watson & Agbola, 2013). Master plans are usually outdated by the time of their implementation due to the rapid population growth and the consequent urban expansion. According to the world cities report (UN-Habitat, 2016), there is a shift in urban planning towards a more strategic and integrated planning (Herslund et al., 2015) across different scales of urban areas (UN-Habitat, 2016). This new approach places a higher focus on the process of planning itself rather than seeing the plans as the main products.

According to Friedman (2004), strategic planning "is a way of probing the future in order to make more intelligent and informed decisions in the present". In order to make such decisions, there is a need to generate strategic knowledge and tools for urban planners. This knowledge should provide detailed information on how urban population growth rates translate into spatial patterns of expanding settlement areas in the future of a city as well as the impact of this growth on the surrounding ecosystems and the services obtained from these ecosystems. (Printz, Abo-El-Wafa, Buchta, & Pauleit, 2015). Extensive knowledge on current land use patterns, future settlement expansion patterns in a city and their influence on the decline of ecosystem services due to the loss of green infrastructure and the vulnerability of city inhabitants that might settle in hazardous areas is needed (Printz, Abo-El-Wafa, Buchta, & Pauleit, 2015). The analyses needed to gather this knowledge requires spatial information that enables forecasting future urban expansion patterns (Weber & Puissant, 2003).

Moreover, environmental planning for the peri-urban interface should be inclusive and participatory to bring together a wide range of stakeholders and experts from different urban, regional and on rural areas (Marshall, Waldman, MacGregor, Mehta, & Randhawa, 2009). The focus of this planning should be on natural ecosystems which are not limited to rural or urban landscapes and should aim to develop “new forms of collaborative arrangements that transcend the boundaries between rural and urban” (Allen, 2003).

To address the different urban planning challenges and to achieve a sustainable future development ensuing from such an explosive urban population growth, effective tools and techniques are needed to monitor the unprecedented growth of cities in order to evaluate the effect of urban growth on the natural ecosystems. (Haas & Ban 2014).

An understanding of urban expansion processes and patterns in cities of Sub-Saharan Africa is needed in order to address their urban planning challenges. Knowledge on the factors that influence settlement expansion and to which extent these factors are influencing the growth is required. Moreover, the influence that settlement density has on the green infrastructure and the change in the ecosystem services needs to be better understood. This analysis should go further than calculating the losses in the green infrastructure land cover types due to settlement development towards understanding the value and quality of the land that would be lost along with the land’s varying potential for providing ecosystem services for the urban inhabitants (Pauleit et al., 2013). In order to generate such foresight knowledge, scenario modelling tools are required that allow to assess the impact of urban growth on the surrounding environment under different growth conditions. Such an approach should be based on suitable indicators and be designed for easy integration into planning processes in the African context. In order for these tools to be easily integrated into urban planning processes, they need to be transparent and flexible that could be easily adapted to the needs of planners and other stakeholders. (Abo-El-Wafa, Yeshitela, & Pauleit, 2017).

1.2 Objectives of the thesis

The overall aim of this thesis is to investigate the impact of urbanisation and urban growth on the surrounding environment of urban areas in sub Saharan Africa, to increase knowledge on the factors driving urban growth in some African cities, to introduce a method to assess the impact of urbanisation on the urban ecosystem services and to analyse the potential impact of urbanisation on these services. It focuses on Addis Ababa, Ethiopia which is one of the most rapidly growing cities in Sub-Saharan Africa. The thesis begins with an understanding of the current state of research through a literature review on the development and application of urban growth models and of the different approaches to assess urban ecosystem services as well as what information is lacking. This is followed by three different applications of an urban spatial scenario design model (USSDM) to simulate future urban growth in Addis Ababa on different spatial scales in and around the city and an evaluation of its impact on the urban environment.

The following are the main objectives of this research:

- Objective 1:

  Examine the potential and limitations of spatially explicit scenario modelling as a tool to support urban (Paper 1) and regional (Paper 2 and 3) planning in Sub-Saharan Africa cities.

- Objective 2

  Assessing the potential impact of settlement growth on the loss of farmland and other vegetated areas as well as the flood vulnerability of the urban inhabitants in different urban population density scenarios (Paper 1).

- Objective 3:

  Investigate potential future settlement growth patterns in the peri-urban interface and the potential impact of settlement development on suitable farmland and its capacity to provide food to urban inhabitants (Paper 2)

- Objective 4:

  Determine whether settlement growth in the peri-urban region increases the flooding hazard within the city and evaluate the consequent changes in flood patterns inside the city.

Finally, practical implications for urban planning are discussed in order to translate the scientific results of this thesis into recommendations that can be used in decision-making. Moreover, this work provides policy and land use planning recommendations to support a more sustainable planning of the peri-urban area surrounding large cities in the process of urbanisation.

1.3 Structure of the thesis

The structure of the thesis goes in line with the research objectives. Paper 1 starts by addressing objectives 2 and 3 through applying, a spatial scenario model for the case of Addis Ababa. It then includes a preliminary analysis of the loss of farmland and the population's vulnerability to floods. The paper acts as a building block for reaching objective 3 (Paper 2), which applies an improved version of USSDM and closely investigates the impact of settlement expansion on the food provisioning services provided by farmland. Objective 4, applies USSDM to a transect that stretches partly in the city and partly in the regional area using a biophysical delineation approach (Hydrologically delineated river sub-watershed). It assesses the impact of settlement development on simulated flood vulnerability using hydrological and hydraulic modelling (Papers 3). The 3 papers analyse different areas within and around the city, which demonstrates the interrelationship within and around the different scales of African cities.

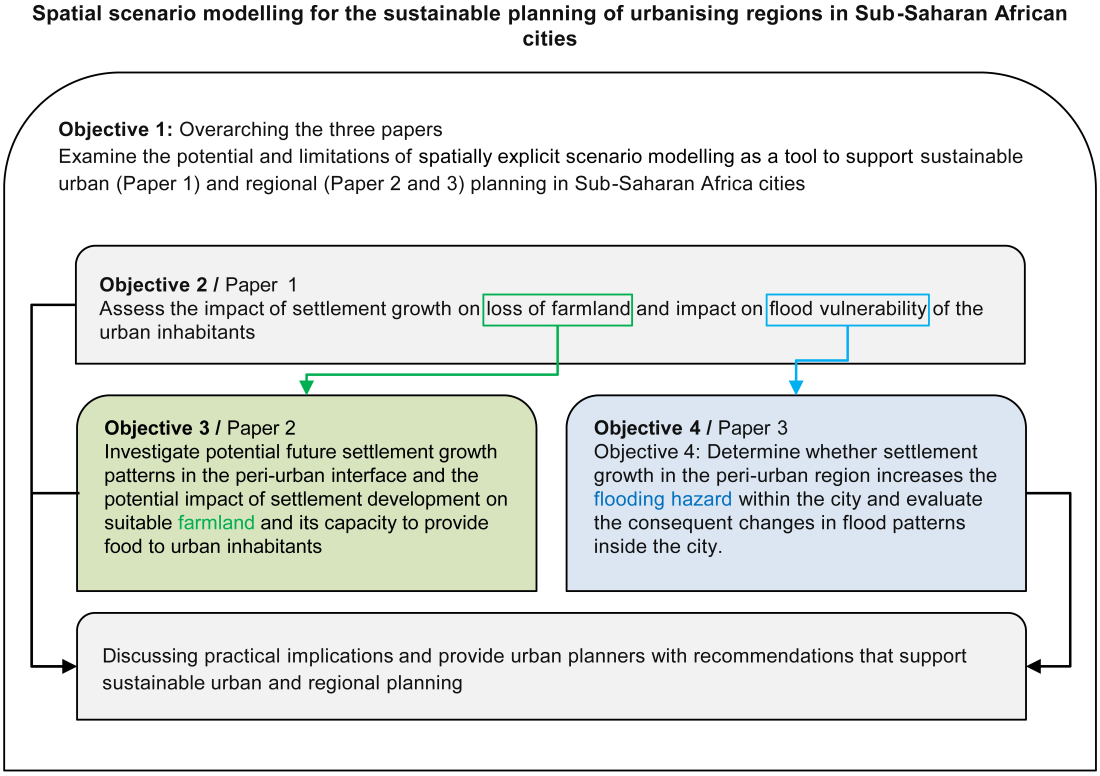


Figure 2: Structure and overview of the thesis and the related publications

The thesis is structured into the following, **Section 1** provides a general background on urban growth, urban planning and urban ecosystem services in Sub-Saharan Africa. **Section 2** reviews relevant concepts on urban growth modelling approaches and modelling urban ecosystem services in order to formulate the theoretical framework used in this research.

Section 3 presents the approaches and methods used in this research. **Section 4** summarizes the results achieved in this research. **Section 5** discusses the results and presents the urban planning guidelines derived from these results. **Section 6** draws conclusions for sustainable urban and regional planning.

KEY CONCEPTS AND THEORETICAL FRAMEWORK

2.1 Spatial scenario modelling

2.1.1 Urban Growth modelling in literature

In scientific literature, two main approaches are used for modelling spatial changes (growth or decline), the top-down approach which divides the spatial system into manageable elements which are modelled by using deterministic models. This approach has its limitations in including self-organisational and behavioural attributes of complex systems (Li, 2011). The other approach, the bottom-up approach, has a higher capability in modelling complexities of spatial systems, which considers cities as a self-organising complex system with certain geographic characteristics. The modelling of these characteristics involves both spatial and temporal processes (Batty, Xie & Sun, 1999). In bottom-up approaches, specific constraints and controls influence local change processes producing macroscopic patterns of urban form (Ward, Murray, & Phinn 2000). Examples of such approach are cellular automata models (CAs) (Batty et al, 1999; Barredo Kasanko, McCormick, & Lavalle, 2003 and Ward et al, 2000) and agent-based models. (Lievano & Olaya, 2012). The Cellular Automata approach is widely used for modelling urban growth (Clarke, Hoppen, & Gaydos, 1996) and in urban simulation (Torrens and O'Sullivan, 2001; Waddell, 2002).

CA models' cellular structure represents the adjacency characteristics of land units in urban systems. The structure is usually a grid of equally sized cells, where the value of each cell can represent one state (e.g.: residential or agriculture) from a group of possible states defined by the system being modelled. (Ward et al., 2000)

Cells change their states upon some function based on certain transition rules which are considered as the growth generators. Moreover, the change of the cell state depends upon another function which relates the cell to what is happening in its immediate neighbourhood (Batty et al., 1999). The change can be from an undeveloped cell to a developed cell or other attributes represented by the cell state (Batty et al. 1999). However, some of these models fail to include the factors that influence urban growth such as the population growth, availability of land and proximity to road networks and city centres (Sudhira, Ramachandra & Jagadish).

There are various factors that were used in literature, which influence urban growth. Barredo et al., (2003) have categorized these factors into five categories, environmental factors, such as high slopes and floods, which prevent certain areas from changing into built-up areas. The spatial characteristics category, which includes factors such as proximity to roads and centrality, which represents certain spatial provisions that help in shaping the urban dynamics. Planning policies category such as city administration's land use zoning and building regulations also affects urban growth patterns. The neighbourhood category which represents the relation of all areas to the land uses in the surrounding. New urban areas tend to grow close to existing residential areas in an organic manner while in some other cases certain land uses can act as a repellent to other land uses. Tobler's first law of geography (Tobler, 1970) which states that "Everything is related to everything else, but near things are more related than distant things" presents the basis for neighbourhood factors, urban dynamics and consequently to urban growth modelling. It is considered as one of the most influencing factors that drive urban growth patterns. However, a balance must be considered between neighbourhood effects due to interactions among different land uses and neighbourhood effects caused by the driving factors themselves. If too much weight is attributed to the interaction between land use types themselves the modeller takes the risk to end up with a model that lacks causality (Verburg, Schot, Dijst, and Veldkamp, 2004). A final category is related to economic development, the socio-economic and the political system and also to individual preferences. Modelling of the fifth category is rather challenging since it involves human decision-making processes.

The factors that influence urban growth have varying importance and extent of influence. Within the modelling framework, the input parameters should be weighted to represent the varying importance of each factor and to allow the model to predict the possible direction and extent of each factor (Sietchiping, 2004). Cheng and Masser (2003) have successfully used a spatial logistic regression technique for analysing and modelling the urban growth pattern.

Geographical Information Systems (GIS) can be used to store, manipulate, and visualize spatial information for landscape analyses (Li, 2011). GIS stands out from different spatial information processing systems such as spatial databases, computer cartography and computer-aided design (CAD) with its spatial analysis feature. The spatial analysis feature has been developed in the last years to provide complicated analytical tools for studying spatial patterns and processes (Jiang, Claramunt, & Klarqvist, 2000). GIS (ArcGIS model builder) can be used as a framework to model urban growth using cellular automata principles to allocate both an understanding of the factors underpinning the urban growth dynamics and spatial expansion.

There are urban dynamics models that were introduced in different cases of cities in developed countries such as the models produced for Phoenix, San Francisco, Quebec City and Marseilles. Such cities' growth is mostly characterized by the existence of planned settlements which is not the case in the majority of African cities. The models used in the context of developed countries hence are unsuitable to capture the urban growth dynamics within developing countries due to the existence of higher levels of informality (Sietchiping, 2004).

In most of the developing countries, and particularly in Africa, the availability of spatial information for cities is rather limited and in some cases not existing. In most of the cases, the usability of existing spatial data is challenging because of several issues such as the lack of consistent classification methodology and appropriate scale. These issues are considered as obstacles in sharing spatial information among different sectors and also across different cities in Africa (Barredo, Demicheli, Lavalle, Kasanko, & McCormick, 2004).

The lack of suitable spatial information also affects the urban dynamics modelling in Africa as it relies heavily on the quality, consistency and the accuracy of spatial maps as an input.

Despite the limited data availability, urban growth models for different African cities using cellular automata have been applied. For Yaoundé, Cameroon, Sietchiping (2004) has utilized GIS to capture, generate and visualize spatial and temporal data and formally joined it with a cellular automata program in the form of a Visual Basic macro. For Dar es Salaam, Hill (2010) modelled the transformation process of cells into informal urbanisation based on their transition potential that is calculated using certain suitability factors and calculated future residential land demand exogenously based on population projections. Another urban dynamics model was applied to the City of Dar es Salaam by Abebe (2011). In this study, a logistic regression model of informal settlements growth was used to explore the driving forces of its expansion and densification. He investigated different proximity related urban growth driving forces, neighbourhood factors and population density to model the expansion and densification of informal settlements in Dar es Salaam. However, the above-mentioned models were limited to model informal settlements only. In Lagos, a cellular automata approach was applied by Barredo et al., (2004) where he used a probabilistic approach in which several factors drive land-use dynamics and the city's growth that represent the accessibility and suitability. Land-use zoning factor which represents the legal regulations for future land uses in addition to neighbourhood factor and a stochastic parameter that simulates the degree of stochasticity that is characteristic in most social and economic processes was used.

Stakeholder involvement in spatial scenario modelling work is a crucial component in order to gather valuable knowledge on the area being studied, regional development in the area and develop plausible scenarios for future development (Haase, Haase, Kabisch, Rink & Kabisch, 2010). Data analysis and desktop research have to be complemented by the knowledge of the local stakeholders in order to understand the processes and the dynamics of urban development. Although Barredo et al. (2004) have included master plans and planning documents in their research, no integration of stakeholders or input from local planning experts were accounted for in the modelling. In other studies, several cities were modelled, such as Linard, Tatem, and Gilbert (2013) who modelled growth of 20 large cities across Africa, while Seto, Güneralp, and Hutyra (2012) addressed the issue of urban growth on a global scale. Such regional and global approaches tend to put more weight on using a standardised approach to model different cities at once in order to produce comparable outputs rather than focusing on how to grasp the impact of urban growth. Additionally, such models do not consider the specific conditions of each city neither their specific planning contexts.

Generally, none of the above models was directly linked to urban planning processes (that included the participation of stakeholders/ planners). Hence, the need to develop models that can be easily integrated into urban planning processes and applied in a real-world context is relevant. Such models must be transparent, easy to use and flexible. They should enable users to change the model parameters and customise the model to meet the needs of the stakeholders. The model should allow visualise general urban growth patterns but not become an overly complex tool requiring heavy data input whose goal is to forecast urban growth. Moreover, models should be able to accommodate updates whenever new information is available.

2.1.2 Modelling challenges in developing countries

Various challenges face the development and the application of spatial modelling work in developing countries. Among these challenges is the lack of spatial data availability to monitor the past and current urban development processes and evaluate its environmental consequences (Pauleit, Ennos, & Golding, 2005; Barredo et al., 2004). In Africa as well as other developing countries, the challenge of limited spatial data is particularly present (Barredo et al., 2004). Spatial data that characterises both the physical features of urban areas and the various activities they accommodate help in determining the social and environmental features of the urban system (Pauleit and Duhme, 2000). The existence of multiple datasets for different time periods identifies the evolution in land cover and land use and provide temporally and spatially detailed information on urban changes (Weber & Puissant, 2003). While land cover data becomes increasingly available at high resolutions (Kang, Liu, Dong, & Xu, 2018; Hansen et al. 2013). Such information needs to be linked to urban land use to become fully relevant for planning (Pauleit and Breuste, 2011). One approach that provides such integrated spatial information on the urban built and green structure is the Urban Morphology Types (UMT). After being applied for several case studies in Europe (Gill et al., 2008; Pauleit & Duhme, 2000), the approach was applied for five cities in Sub-Saharan Africa within the framework of the Climate change and urban vulnerability in Africa (CLUVA), FP7 European Commission funded research project. Among these cities was Addis Ababa, Ethiopia, the case study in this research. UMT maps provide information on land use and land cover such as different settlement types, agricultural, forest areas, urban green spaces, natural ecosystems and different infrastructure types (Cavan et al., 2012).

UMT can be used as a basis for spatial scenario modelling to define existing settlement areas, commercial and services locations, road network and for defining the areas that would be excluded from modelling.

2.2 Urban ecosystem services

"Ecosystem services are the benefits provided by ecosystems." These services include provisioning, regulating, cultural and supporting services (Sarukhan, et al. 2005). In urban areas, the natural ecosystems promote public health and improve the urban inhabitants' quality of life (Bolund & Hunhammar, 1999). Changes in ecosystems that provide these services affect urban inhabitants both in direct and indirect ways. On the other hand, urban inhabitants also have a strong impact on ecosystem services both locally and at significant distances away from urban centres (Sarukhan, et al. 2005). The ecosystem services located in urban areas are closely linked to the land use and land cover (Pauleit & Breuste, 2011; Pauleit & Duhme, 2000). Land use and land cover transformation caused by urbanisation, have a strong impact on ecological integrity that leads to a decreasing supply of ecosystem services, on which urban inhabitants and the society as a whole depend (Burkhard, Kroll, Nedkov & Müller, 2012).

One method to assess the capacity of ecosystems to supply services is by developing a set of indicators (Van Oudenhoven, Petz, Alkemade, Hein & de Groot, 2012). These indicators should be quantifiable, scalable, temporally and spatially explicit (ibid). Ecosystem service supply and demand can be assessed, quantified and transferred to different spatial and temporal scales using suitable spatial indicators (Burkhard, Kroll, Nedkov & Müller, 2012). This can be done by integrating land cover information together with monitoring, interviews, statistics, or modelling (ibid). Some ecosystem services require the presence of animals (such as pollination, biological control, habitat and genetic resources) which are not only affected by the reduction of land inventory but are also impacted by land fragmentation and disconnection of landscapes due to man-made changes. However, other ecosystem services (such as nutrient cycling, climate regulation, waste treatment, raw materials and food production) are directly affected by the mere change in area and least influenced by changes in landscape patterns (Haas & Ban 2014).

Stakeholder engagement is an important aspect that needs to be considered in order to adequately relate ecosystem functions to human well-being. Stakeholders can help identify relevant services and functions that are available in the area being studied and continuously evaluate the suitable indicators needed to represent these ecosystem services. They also provide ground truthing for the development of management options. Thirdly, stakeholders help in evaluating the importance of the services either by ranking them or by assigning weights of importance to different services (Seppelt, Dormann, Eppink, Lautenbach & Schmidt, 2011).

2.2.1 Food provisioning

Food is one of the provisioning ecosystem services, which are "the products obtained from ecosystems such as food, fresh water, wood, fibre, genetic resources and medicines". The demand for food provisioning ecosystem services has grown significantly between 1960 and 2000 as the world population has doubled by then to 6 billion people. This growing demand has led to an increase in food production by roughly two and a half times at the same time period (Sarukhan et al., 2005). On the other hand, agricultural lands have been transformed into commercial and residential areas and this transformation usually leads to a net loss in the prime agricultural land (Erickson, Lovell & Méndez, 2013).

Morrison, Nelson, & Ostry (2011) have used agricultural Census and survey data to estimate local food production capacity. Syrbe and Walz (2012) have investigated the use of spatial indicators for the assessment of ecosystem providing services areas by examining where services are generated and what the underlying spatial structures. In a different study, Akıncı, Özalp & Turgut (2013) have used land suitability approach to determine the land potential for providing agricultural production.

In addition to assessing other functions (such as the suitability for forestry, urban development), land suitability for agriculture is defined as the capability of land to produce crops in a sustainable manner (Halder, 2013). Land suitability evaluation is a well-established approach to assess the potential of land for crop production (Bandyopadhyay, Jaiswal, Hegde, & Jayaraman, 2009). Applying this approach produces maps that show the suitability of each land-mapping unit for each crop type based on a standardized land suitability classification (FAO, 1976). Such information can provide a valuable input into land use planning (OWWDSE, 2011). Nevertheless, the land suitability approach has not been applied to the assessment of future impact from urbanisation in an African context.

Land suitability analysis is a process that verifies how fit a portion of land is for a specific use (Steiner, 1983). Suitability analysis aims to identify limitations and opportunities for future land development (Steiner, McSherry, Cohen, 2000). The land suitability analysis approach can provide planners guidance that helps them in selecting optimal uses of land by providing information on the opportunities and constraints in the use of an area (Mokarram and Aminzadeh, 2010).

In scientific literature, land evaluation and land suitability analysis methods have been used to assess land suitability to support the environmental planning of the territory. Mendoza et al. (2009) have used GIS to conduct a land suitability analysis to identify areas suitable for agriculture, cattle grazing, forestry and conservation of environmental services. While Speziale & Geneletti (2014) have assessed the suitability for new residential areas in different land policy and planning scenarios. However, the use of land suitability assessment as an indicator for food provisioning ecosystem services and analysing the agriculture suitability maps together with future urban and regional expansion (output of urban growth model) has not been conducted before.

2.2.2 Flood regulation

Ecosystems can contribute to reducing and delaying flooding through increasing soil infiltration rates, reducing run-off, and preventing soil erosion, increasing hydraulic roughness spanning the full width of floodplains, most notably where floodplains narrow and flood flows would otherwise accelerate, thereby reducing potential damage downstream and providing areas on the floodplain for flood storage (Smithers, 2016). Urbanisation in floodplain areas increases the risk of flooding due to increased peak discharge and volume and decreased time to peak (Suriya, & Mudgal, 2012) and increases the risk of major disasters (Doberstein &

Stager, 2013; UNISDR, 2009). Flooding is increased by the continuous physical alteration of the catchment areas due to the expanding cover of impervious areas, alteration of stream morphology, changes in stream morphology, poor drainage systems and development of informal settlements in the flood-prone areas (Belete, 2011; Huong & Pathirana, 2013; Mazhindu, Gumbo & Gondo, 2010). In conjunction with the modification of floodplains due to urbanisation, flood risks will rise (Nirupama & Simonovic, 2007). The impact of anthropogenic changes on the hydrology in watersheds can be assessed in terms of estimating flood peak after development to flood peak before development over different return periods (Kibler, Froelich & Aron, 2007). One of the main methods to assess flood hazard is by estimating the probability of different magnitudes of flooding such as the depth of inundation, duration of inundation and the velocity of moving water (National Research Council, 2015). Some studies (such as Miller et al., 2014) have investigated the changes in runoff resulting from the transformation of rural landscapes into peri-urban areas. Other studies (such as Du et al. 2012) have assessed the effects of future urbanisation on annual runoff and flood events using hydrologic and a land-use change model. However, modelling the future changes in a peri-urban area due to urbanisation and estimating the flood hazard inside the urban area using hydrological and hydraulic models is still less covered.

METHODOLOGY

3.1 Overall research approach

This research employs a spatial scenario modelling approach to investigate the impact of urbanisation and urban growth on the surrounding environment of urban areas in Sub-Saharan Africa. Urban spatial scenario design model (USSDM), a special scenario-modelling tool is used to simulate the future settlement development and expansion within different urban planning scenarios (Lindley et al., 2013). The model has been developed within the frame of the CLUVA "Climate change and Urban Vulnerability in Africa" project (Lindley et al., 2013), applied to the city of Dar es Salaam (Printz, Abo-El-Wafa, Buchta, & Pauleit, 2015) and further adapted for the purpose of this research as explained in this section. Spatial indicators were used to represent the different factors that influence urban growth on the different scales of investigation. USSDM was applied three times for three different scales, urban, regional and neighbourhood scales.

Spatial indicators and environmental as well as hydrological models are incorporated into USSDM to assess the impact of settlement expansion on selected ecosystem services provided by the natural and semi-natural vegetative land cover. Food provisioning and flood regulating ecosystem services are analysed in a present situation and in different settlement expansion scenarios. The research findings are then used to provide urban planners with recommendations that support sustainable urban and regional planning, which conserves valuable land cover types. The application of this study covers the urban, regional and neighbourhood scales in a broader urban perspective. The City of Addis Ababa and its surrounding region are used as a case study.

3.1.1 USSDM description and modelling parameters

USSDM is a raster-based model. The raster cell values represent the state of the cell, the land use, distance value (e.g.: proximity factors), or a user-defined score value. Each USSDM application has different modelling parameters, which sets the framework of the application. The modelling parameters used in this research are explained below.

The user defines a **spatial scale** which set the selected case study to be investigated and the study boundaries in which the settlement expansion will be simulated. The defined study area is represented by a number of raster cells that are of a certain size defined by the user based on the application and constrained by the input data resolution. The **temporal scope** sets the time period during which the simulation of settlement expansion will be conducted. This scale ranges between a specific time point in the past (a year) and another time point in the future. **Influencing factors** are different factors that are used to calculate the likelihood for the settlements to expand. These factors depend on the research area being analysed and the availability of input data. Different **modelling scenarios** are defined by the users which employ specific urban planning strategies. These strategies set a specific settlement density in each scenario. The scenarios are designed to model two contrasting situations of low and high settlement densities. **Exclusion areas** describe the cells that are not likely to transform into settlements within the model's temporal scope and are defined by the user in each application. **Future land demand** is calculated exogenously based on the projected population growth and input to the model to define the number of cells that will transform into settlements.

As shown in Figure 3, USSDM starts by excluding all cells that will not be processed by the model (defined by the user in each application). USSDM then calculates a weighted sum of all influencing factors (represented by score maps that are normalised from 0 to 100 using a feature scaling method in the first application and by continuous values in the second and third applications). The cells are then ranked in a descending order according to the weighted sum and the cells with the highest score transform into settlements meeting the future land demand. A raster file is produced, indicating the settlement area developed during the model's temporal scope. The excluded areas and the neighbourhood factor are continuously updated to include the new settlement areas.

The future demand for urban areas is estimated exogenously to cellular models (White, Engelen, & Uljee, 1997) where it is assumed that this demand is not directly related to the local spatial dynamics, but by the demographic growth and the applied settlement density (no. of units planned per area) of a city (Barredo et al., 2003). The post-analysis depends on the application and the topic being studied. In this research, the first application analyses the loss of farmland and other vegetated areas, the second application analyses the loss of food provisioning ecosystem services while the third application analyses the change of flood patterns depending on settlement expansion.

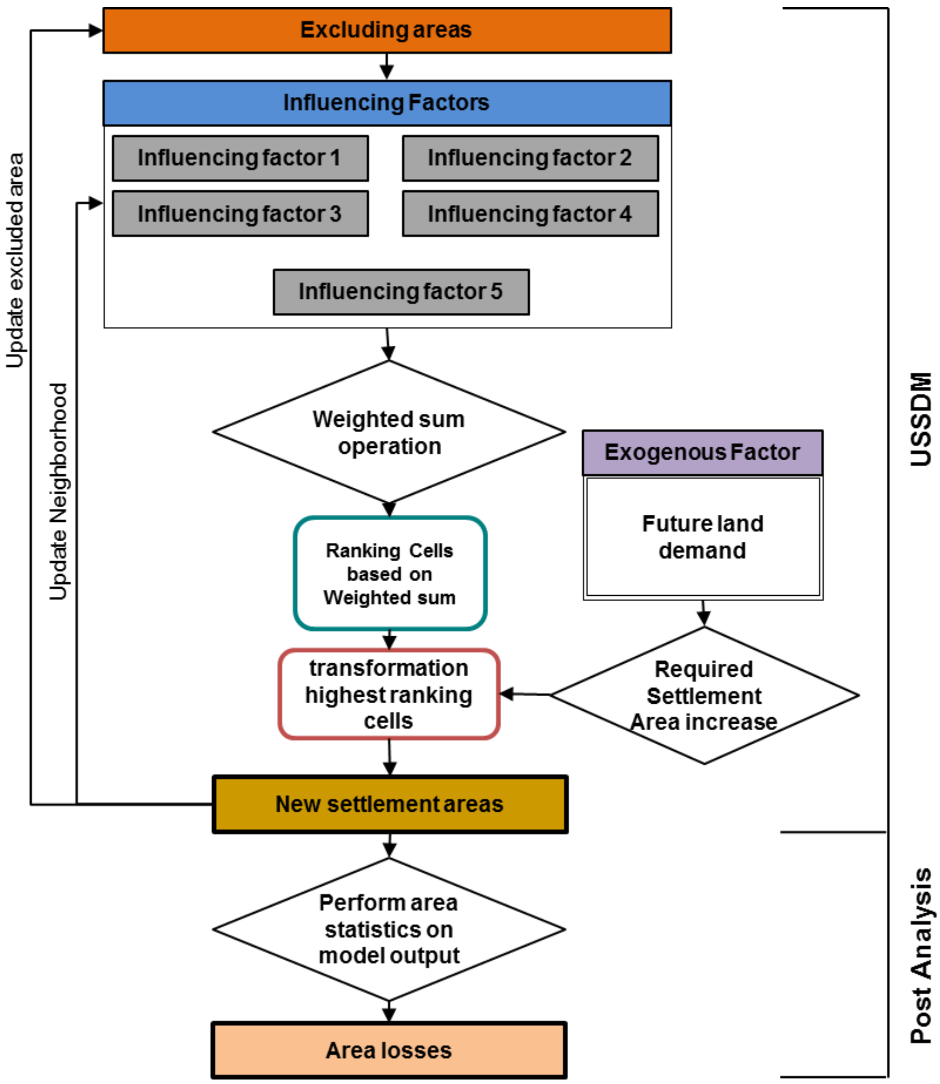


Figure 3 Conceptual diagram of USSDM

3.2 Geographical focus

The geographical focus of this research is on the urban areas of Sub-Saharan Africa. This focus was set due to the existence of a high urban growth rate, an increasing demand for settlement expansion due to rapid population growth and environmental challenges that exist within and surrounding the newly urbanised areas accompanied by a lack of suitable information on the region's urban populations and growth rates (Hanson, 2007).

The analyses were applied at different scales in and surrounding urban areas. These scales are the city scale for the first application (section 3.3), where the city is analysed considering the losses of the agricultural and vegetated areas; the regional scale for the second application (Section 3.4), where the regional area around the city is analysed with respect to the food provisioning ecosystem services provided in the area; and the neighbourhood scale for the third application (section 3.5) where the impact of regional settlement expansion on a selected highly vulnerable zone inside the city is assessed.

Addis Ababa has been chosen as a case study as the city has one of the highest growth rates in Sub-Saharan Africa and faces several challenges due to the rapid urbanisation. At the same time, the city administration of Addis Ababa makes considerable efforts for strategic planning of the city and the surrounding region. More information about the different scales of investigation is described in the following sections.

A challenge that was faced in conducting this research was the change in the political situation in Ethiopia. The research has used an initially proposed master plan that had a regional focus, with the geographic coverage extending into the peri-urban area that is located in the Oromia region. This plan was perceived by the Oromo ethnic group as an attempt to extend Addis Ababa into the territory of the state of Oromia (Regasa, 2015). Finally, the plan was cancelled in 2016 due to the political unrest. Although the unrest and the ultimate cancellation of the plan did not impact the research scientifically, they have posed challenges in terms of data acquisition from authorities due to the topic of the research which partly addresses the interlinkages between the capital city and the surrounding region.

3.3 Stakeholder integration

In this research, 20 urban related stakeholders were involved throughout the research study in order to gather, assess and validate the collected data and to evaluate and calibrate the analyses' preliminary outcomes. experts from the urban planning, transport planning, environmental planning and housing sectors were involved. The stakeholders involved in this research also included other urban stakeholders such as researchers from the EiABC, city officials, officers and managers from the Addis Ababa city administration as well as from the Oromia region, and team members of the master plan review project. The selection of stakeholders aimed to include experts from different fields of urban planning. The involvement of these experts was facilitated through the cooperation between the EiABC and the Addis Ababa city administration in the framework of the CLUVA project (Lindley et al. 2013). In addition to the continuous consultation that was conducted throughout the years of research, the major research input that was gathered with the help of the stakeholders was to define the factors that influence the transformation of different land use types into settlement areas; to determine the scoring classes that were used to represent the influencing factors; to define the settlement and the housing densities to be used for each scenario; and to provide knowledge on the areas that are not expected to transform into settlements within the modelling temporal scope.

The form of the stakeholder integration was through two joint workshops between researchers and urban planning practitioners, eight semi-structured interviews, and six field trips for data collection (Paper 1 Appendix)

The joint workshops were conducted with representatives from urban, transport and environmental planning sectors. The workshops' objectives were to explain USSDM, introduce its possible applications and gather input from the workshop attendees on the city's urban and regional development. The first workshop was conducted with the participation of representatives from the city's administration, urban planning institute and Master plan review project. In this workshop, the input parameters were discussed and modified with the help of the different experts. A second workshop was conducted in the master plan review office with the attendance of the master plan team leaders which had the same objectives.

Another aspect of stakeholders' integration was related to capacity building and training, in which the local GIS specialists and urban planners were trained in two training sessions on the use of USSDM to enable them to apply the model through 2 training sessions.

3.4 City USSDM application

3.4.1 Study area: Urban perspective

Addis Ababa, the capital city of Ethiopia was used as a case study for the first USSDM application. The city was defined by the administrative boundaries and has a total area of 520 km^2. Addis Ababa has a population in the year 2013 of 3,553,682 inhabitants (AAOIDP, 2013) and is projected to have almost 6 million inhabitants in 2030 at an average annual growth rate of about 4% (UNDESA, 2014). The city has 10 sub cities and 116 woredas. The city is facing several environmental challenges that are attributed to urban growth such as high housing shortages, unemployment, flooding, lack of proper sanitation and environmental deterioration (Birhanu, Kim, Jang & Park, 2016; UN-Habitat, 2017 & UN-Habitat, 2008).

The elevation of the city ranges from its lowest point in Akaki at 2,100 metres above sea level in the southern periphery and rises to over 3,000 metres in the Entoto Mountains to the north. The city has a pronounced rainfall peak during the summer (July–August) and a rainfall minimum during the winter (December–February) (CSIR, CMCC, 2013).

Addis Ababa is located in the centre of Ethiopia, a country where there is a lack of development policies in most urban areas except for the capital city. This urban bias has given the capital city most of the social and economic infrastructure in the country. People from different parts of the country migrate to Addis Ababa who are looking for better employment opportunities and services has led to a high rate of rural-urban migration.

The city's physical expansion in the last decades was dominated by single story building which kept the city's population density very low until recently (AAOIDPP, 2013). At the beginning of the century, the government started organised efforts and large-scale housing projects by building condominium housing in the fringe of the city (Haregewoin, 2007a, 2007b). Consequently, thousands of settlers from the densely built neighbourhoods in the city centre have been relocated to newly built, large-scale condominium housing, mostly located in the peripheral areas of the city (Wubneh, 2013).

Green spaces are being converted to other land uses such as housing and industrial development (Horst, 2006). The share of publicly accessible green spaces within the city's administrative boundaries is less than 1 m^2 per capita (AAOIDPP, 2013), compared to a 9 m^2 per capita recommended by the World Health Organisation WHO (Edwards & Tsouros, 2006). In the period of 2006 to 2011, high losses of farmland (−24%) and an increase in residential areas (21%) occurred (Woldegerima, Yeshitela, & Lindley, 2016).

Though informal settlement development is still occurring, current urban development in Addis Ababa is dominated by formally planned settlements at a large scale, where slum areas in the city centre are cleared through the Integrated Housing Development Programme (IHDP) (UN-Habitat, 2010; Wubneh, 2013).

UMT maps (2006 and 2011) were used as a basis for the USSDM's first application in order to determine the settlement areas in 2011, calibrate the change between 2006 and 2011 to develop the neighbourhood influencing factor and to identify the farmland and other vegetated areas in the city of Addis Ababa which will be used in the post analysis of USSDM output.

3.4.2 Urban application USSDM parameters

In this section the modelling parameters used for this application were as follows:

Spatial scale: The total Administrative area of Addis Ababa of 520 $km^2$was represented by 207,764 raster cells (50 m by 50 m cells). Input Dataset: Administrative boundary

Temporal scale: 2011–2025

Influencing factors: The influencing factors that were considered to influence the city's growth according to the stakeholders and through literature review were the following:

1. Road proximity (Euclidean distance): to the road network, Input Dataset: Road network in 2011 (DS1.2).
2. Centrality: Proximity (Euclidean distance) to sub-city markets, Input dataset: Sub-city markets in 2011 (DS1.3).
3. Land use dynamics: Ranking the UMT's based on area statistics of the change detection analysis between 2006 and 2011 UMT maps, Input Dataset: UMT maps [2006, 2011] (DS1.1).
4. Neighbourhood: Focal Statistics of 4 × 4 cell array using SUM statistic of neighbouring cells (value of 1 for settled and 0 for non-settled cells) Input Dataset: UMT maps in 2011 (DS1.1).
5. Slope: Calculated slope using spatial analyst extension of ArcMap. Dataset used: 5m contour maps of the research area (DS1.4).

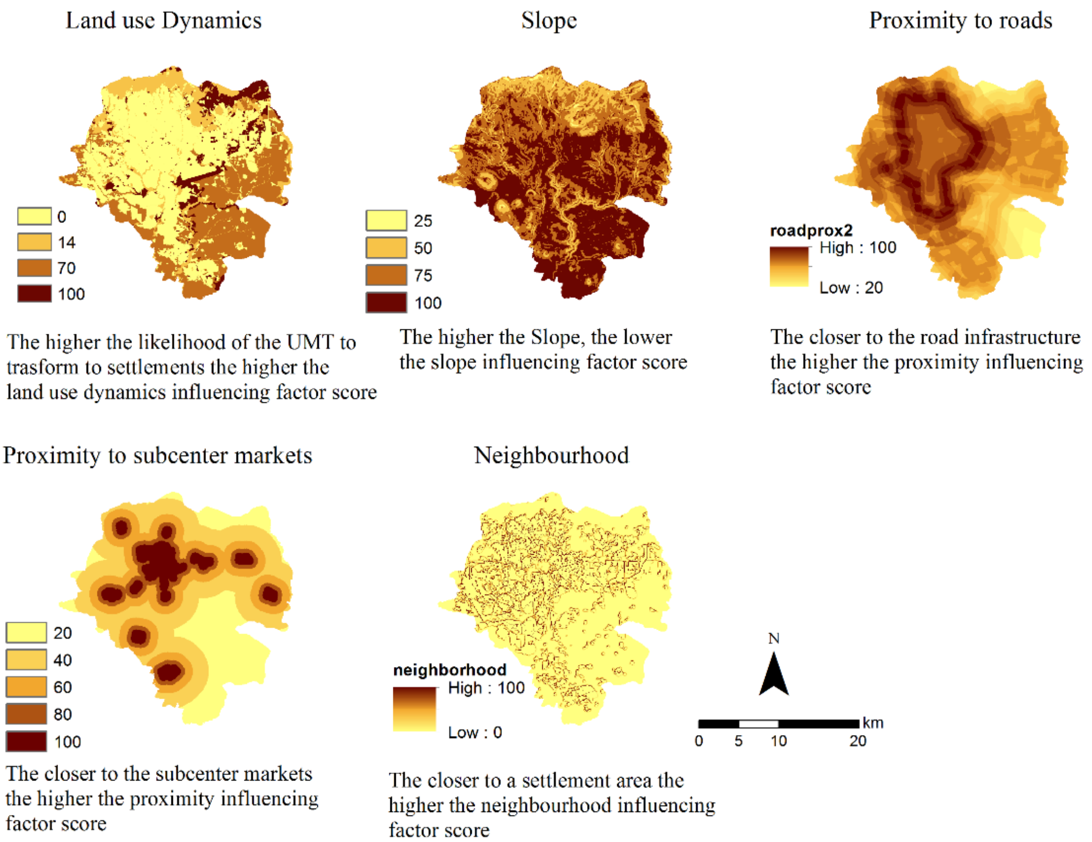


Figure 4 USSDM application 1: influencing factors (Abo-El-Wafa et al. 2017a)

Modelling Scenarios:

Scenario 1: A highly densified strategy was assumed with a settlement density of 350 inhabitants/ha, corresponding to the density of new condominium housing areas in Addis Ababa.

Scenario 2: represents the business as usual scenario (BAU). In this scenario, the calculated average settlement density of 166 inhabitants per ha was used, corresponding to the current average population density of Addis Ababa.

Exclusion areas:

All UMT's in the city (i.e. built-up areas and land near airport) were excluded except for bare land, agriculture, and vegetation.

Future land demand:

The future land demand used in the first application was directly calculated using the projected population growth and the required settlement area that accommodates this growth based on the two population density scenarios.

3.4.3 Losses of farmland and other vegetated areas and flood vulnerability

The output of USSDM in this application was used to determine the potential losses of the farmland and other vegetated areas due to settlement expansion. The modelled settlement expansion was overlaid on the land cover data and, using area statistics, the losses were calculated in terms of surface area. In a second analysis, USSDM output was overlaid on a flood-prone area dataset to identify future vulnerable settlement that would be located in flood-prone areas in both scenarios. The flood-prone areas dataset used in this research was obtained from Jalayer et al. (2014), who used the topographic wetness index (TWI) as an indicator to map urban flooding risk hotspots in Addis Ababa.

3.5 Food provisioning: Regional USSDM application

3.5.1 Study area: Regional perspective

The research area in the second USSDM application is the surrounding region of Addis Ababa which covers a total area of 755 km^2 (approximately 1.5 times the size of Addis Ababa). The population in the area was 202,980 inhabitants in 2013 and is projected to reach 1.1 Mio. in

2023 and 1.7 Mio. in 2038 (AAOIDP, 2013). The research area includes the surrounding towns of Sululta, Burayu-Menagesha, Sebeta, Dukem-Gelan and Legetafo and their rural surroundings (Figure 5). The delineation of the study area corresponds to the structural plan of the 2012 Addis Ababa and the Surrounding Oromia Integrated Development Plan (AAOIDP). Administratively, the research area belongs to the Oromia region that acts as an independent planning body different from the Addis Ababa administration.

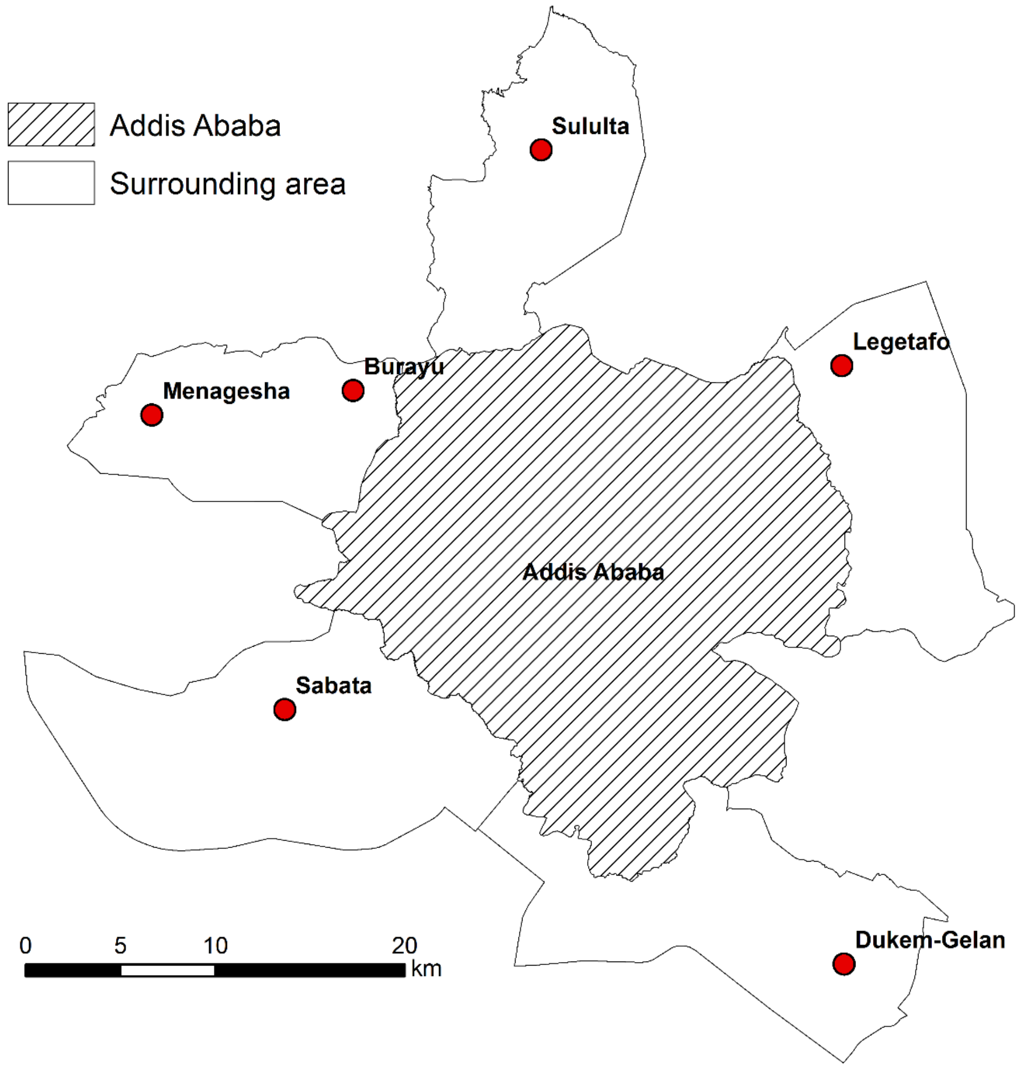


Figure 5 USSDM application 2: research area (Abo-El-Wafa et al. 2017b)

The growth of Addis Ababa is expanding at a rapid pace (approximately 4% p.a.) inside the city but also into the surrounding region along the major outlets of the city (Kassa, 2013). This growth results into an expansion of settlement area at the cost of declining farmland (AAOIDP, 2013).

Farmland has a very high importance in the area as agriculture is the main means of livelihood especially in the rural area where around 97% of the households practice agriculture as a primary or secondary source of income. Furthermore, the city of Addis Ababa relies on its surrounding area for supplying different resources such as drinking water, agricultural crops, fuelwood supply and construction materials (AAOIDP, 2013). Therefore, the selected area was considered as well suited for this study.

3.5.2 Regional USSDM parameters

Spatial scale: The region surrounding Addis Ababa of 755 $km^2$was represented by 1,887,500 raster cells of 20 m by 20 m in size.

Temporal scale: 2013–2038

Influencing factors:

1. Road proximity: Euclidean proximity distance to the nearest road network. Dataset used: Road network in 2011 (DS1.8).
2. Proximity to municipal facilities (schools, hospitals and markets). Dataset used: Facilities waypoints (DS1.6).
3. Neighbourhood: This factor determines whether adjacent areas were already settled Input Dataset used: Urban morphology type maps for the year 2013 (DS1.7).
4. Slope: Calculated slope using spatial analyst extension of ArcMap. Dataset used: 5m contour maps of the research area (DS1.9).

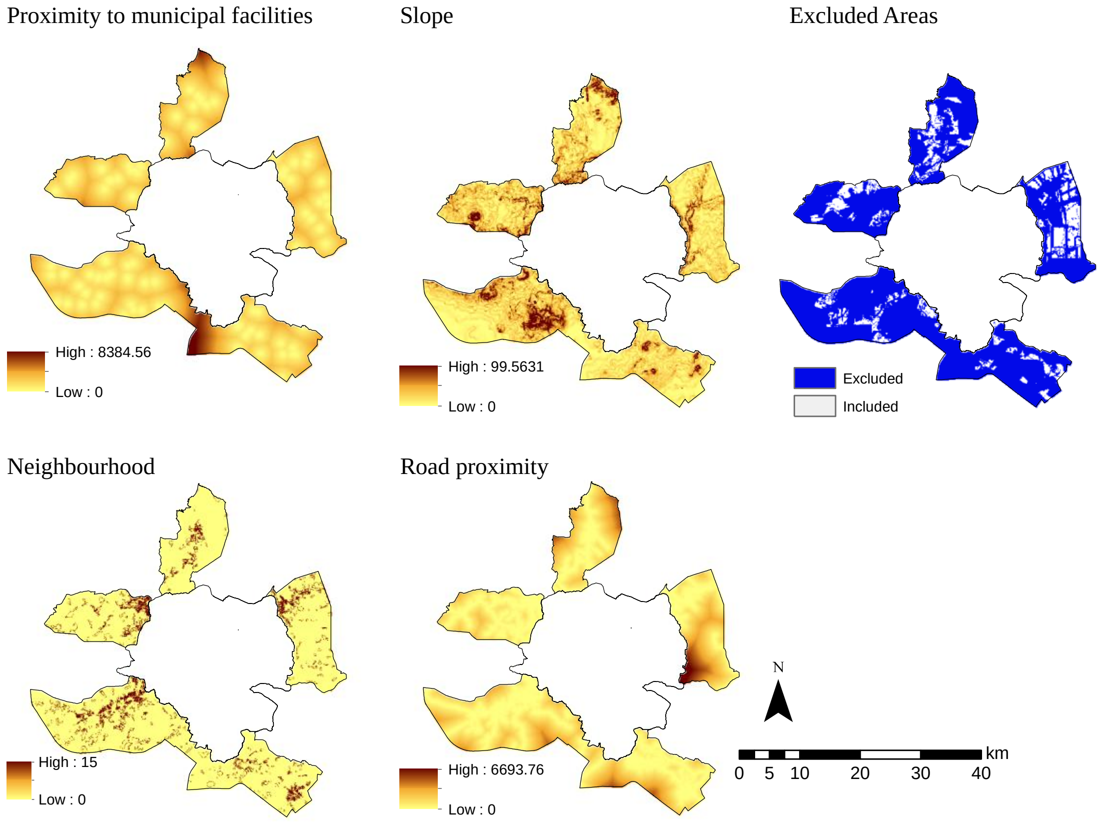


Figure 6 USSDM application 2: influencing factors and excluded areas

Logistic regression:

In this USSDM application, a logistic regression approach was introduced in order to allocate different weights for the influencing factors. The weights were calibrated through a change detection analysis (whether or not the land use changed from 2008 to 2013 to built-up area) and the effect of the different influencing factors for this change Dataset used: Land use maps for the research area (DS1.7). The logistic regression function z was calculated as follows:

$$z = I - Ws \times \text{SLOPE} - Wr \times \text{ROAD} + Wc \times \text{CENTRA} + Wn \times \text{NEIGH} \qquad (1)$$

Z: built-up area change (2008-2013) I: intercept

Ws: Weight for SLOPE SLOPE: Slope influencing factor

Wr: Weight for the ROAD ROAD: proximity to road influencing factor

Wc: Weight for CENTRA CENTRA: proximity to facilities influencing factor

Wn: Weight for NEIGH NEIGH: neighbourhood influencing factor.

Modelling Scenarios:

Scenario 1: A highly densified strategy was assumed based on the Masterplan recommendation of settlement density of 82 housing units/ha which results into a settlement density of 328 inhabitants/ha.

Scenario 2: The scenario assumes that the Master plan's designated areas for residential development would be completely converted to settlements at an average settlement density of 115 inhabitants/ha (corresponding to 29 housing units/ha).

Exclusion areas:

In this USSDM application, formal urban growth and a successful enforcement of land use zoning were assumed. Settlement expansion was only possible in the residential areas proposed by the master plan and all other areas were excluded. Furthermore, housing units on open land outside the current built-up area were considered (an estimate of 67% of the total housing units planned) with a housing density of 82 housing units/ha (AAOIDP, 2013).

Future land demand:

Future land demand for settlement expansion was determined based on the total housing units planned in the 2012 master plan review using an average household size of 4 inhabitants/ housing unit for the peri-urban area in the region (AAOIDP, 2013).

3.5.3 Food provisioning ecosystem service analysis

The scope of this application was to study the impact of settlement expansion on the food provisioning ecosystem service that the agricultural area in the region provides. Secondary Crop suitability data for 30 crops from a study conducted by the Oromia Water Works Design and Supervision for the Oromia region planning authority was used as a basis to perform the analysis (OWWDSE, 2011). The data were compiled by a group of local experts, who agronomically assessed the region based on a set of biophysical parameters including soil characteristics, altitude and climate using a land evaluation method proposed by FAO (1976).

The suitability values were classified as follows:

(1) Highly suitable (S1)
(2) Moderately suitable (S2)
(3) Marginally suitable (S3)
(4) Very marginally suitable (S4)
(5) Not suitable (N)

A two-stage analysis was performed to incorporate the food provisioning indicators into the USSDM output. In the first stage, all crops were used (with binary suitability levels of suitable and non-suitable) while in the second stage, a detailed analysis was made for selected high-value crops at all suitability levels (S1, S2, S3 and S4). The selection criteria were the crop group they belong to (cereals, vegetables and oil-seeds), high vulnerability due to modelled settlement development (based on the first stage results) and relevance to the local population (importance for local dietary, an economic support role for urban farmers and their potential for import substitution.)

In both stages, the modelled settlement expansion was overlaid on the crop suitability maps to estimate the amount of land that would be lost due to the modelled settlement expansion. The proportion of modelled settlement development located in suitable farmland was used as an indicator for identifying the crops most vulnerable to settlement development. In the second stage, the high-value crops were used to estimate the losses at all suitability levels (S1, S2, S3 and S4) due to settlement development.

3.6 Flood regulation: Sub-watershed USSDM application

3.6.1 Study area: Sub-watershed

The research area in the third USSDM application comprises of two different components, the sub-watershed and the domain area. The sub-watershed is a hydrologically delineated subwatershed of the little Akaki River that flows from the north-western town of Burayu into the city of Addis Ababa and covers an area of 169 km2. The majority of the subwatershed (127 km2) is located in Oromia, the largest region in Ethiopia while the rest of the research area and the domain area lie within the north-western part of Addis Ababa. The domain area is a small area in the Niffasilk Lafto sub-city of Addis Ababa, located at the south-eastern tip of the subwatershed (Figure 7).

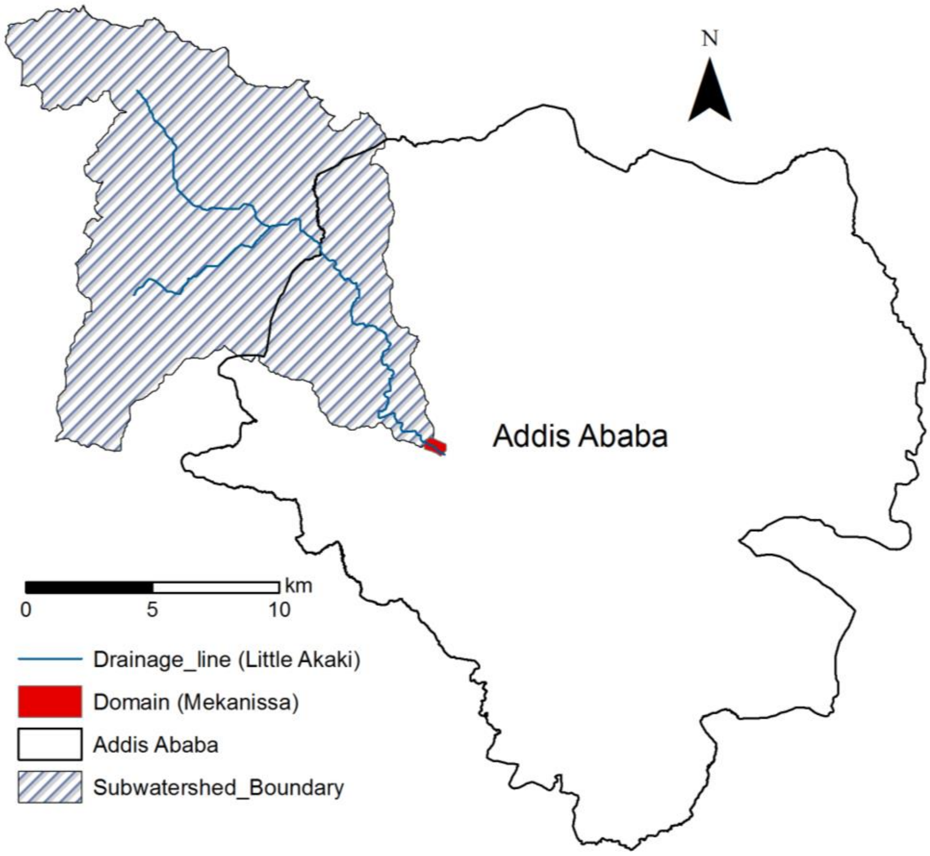


Figure 7 USSDM application 3: research area

Figure 8 shows the domain Area, the Mekanisa area, which was selected due to its vulnerability to climate-related risk and the existence of settlement areas which poses a risk to the inhabitants (Habtemariam, Tufa, Herslund & Mguni, 2018; Yeshitela, Mrema, Assefa & Mpyanga, 2015).

The future settlement expansion in the subwatershed would be modelled using USSDM. The domain area would be analysed by calculating both the flow depth and the velocity to delineate the flood hazard map for the domain area.

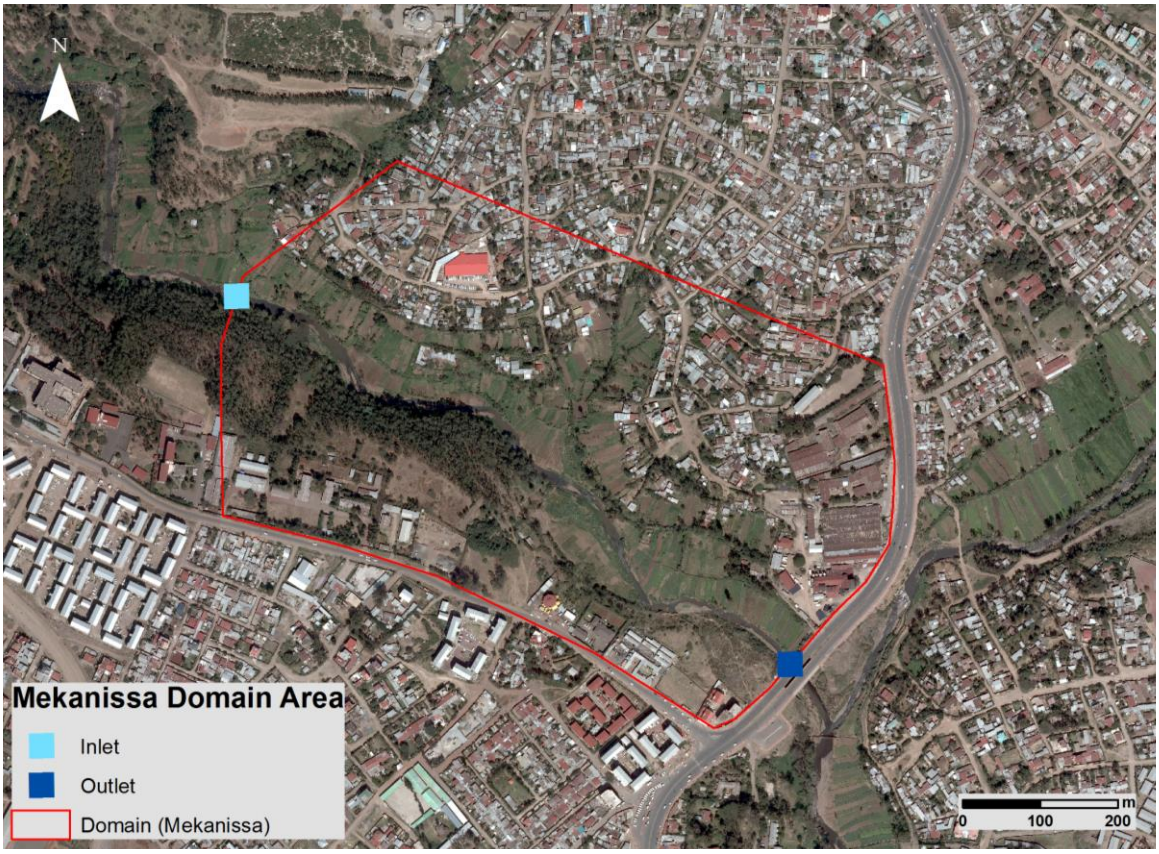


Figure 8 USSDM application 3: domain area (Aerial image source: CLUVA project, 2013)

3.6.2 Sub-watershed USSDM parameters

The modelling parameters that were used in the third application were as follows:

Spatial scale: The sub-watershed of the little Akaki River that flows from the north-western town of Burayu into the Mekanisa area of 169 km^2 which was represented by 424399 raster cells of 20m by 20m in size

Temporal scale: 2013–2038

Influencing factors: The influencing factors that were considered to influence the city's growth in this application were the following:

1. Slope (DS1.11).
2. Proximity to the road network (DS1.8).
3. Proximity to municipal facilities (schools, hospitals and markets) (DS1.6).
4. Neighbourhood (i.e. whether adjacent areas were already settled) (DS1.7 and DS1.1).

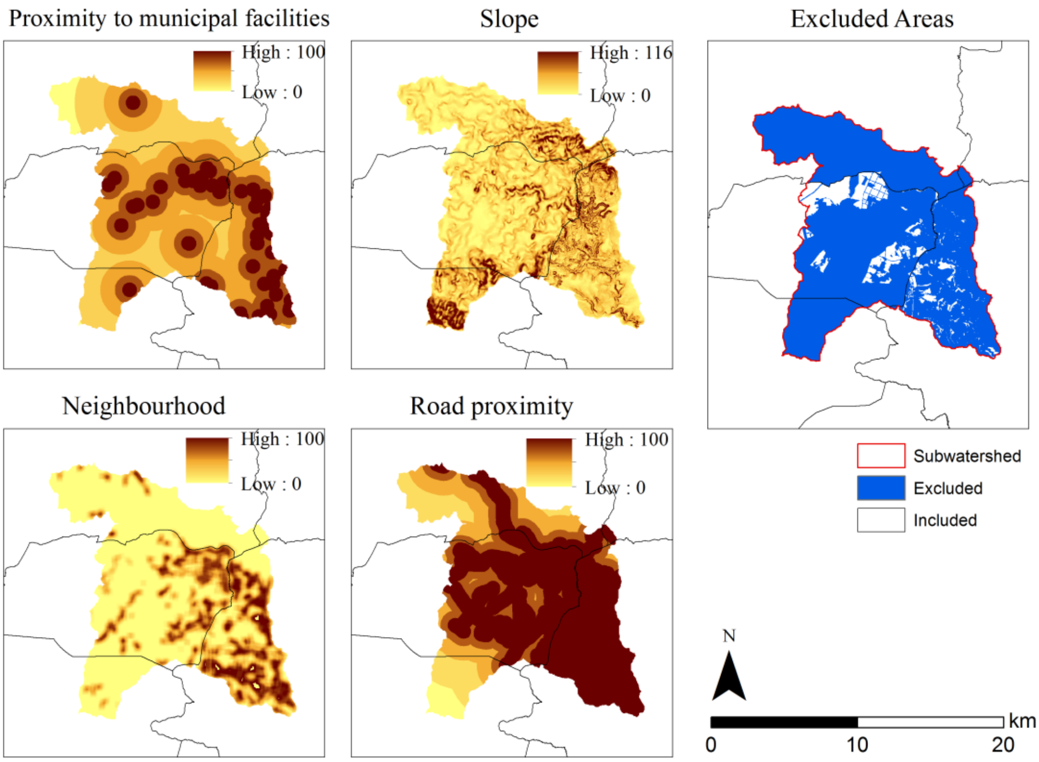


Figure 9 USSDM application 3: influencing factors and excluded areas

Logistic regression:

Similar to the food provisioning USSDM application, the logistic regression approach was used allowing different weights for the influencing factors.

Modelling scenarios:

Scenario 1: A high-density strategy was assumed based on the Masterplan recommendation of settlement density of 82 housing units/ha which results into a settlement density of 328 inhabitants/ha. This density was considered to be the Soil Conservation Service (SCS) manual's land cover of "Residential, 1/8 acre lots" (high-density residential) (SCS, 1975).

Scenario 2: The designated areas for residential development would be completely converted to settlements at an average settlement density of 115 inhabitants/ha (corresponding to 29 housing units/ha). The settlement area densification that is planned by the city was also accounted for in both scenarios by changing the SCS land cover from "Residential 1/4 acre lots" to "Residential 1/8 acre lots".

Exclusion areas:

In this USSDM application, formal urban growth and a successful enforcement of land use zoning were also assumed (similar to the food provisioning application). Settlement expansion was only possible in the residential areas proposed by the master plan and all other areas were excluded.

Future land demand:

Future land demand for settlements was calculated based on the planned housing unit development to accommodate the projected population growth whereas the household size is 4 inhabitants/housing unit with a 2/3 proportion of new housing built on green land with a density of 82 housing unit/ha (AAOIDP, 2014).

3.6.3 Flood Regulation ecosystem service analysis

This section focuses on the flood analysis and modelling on both the subwatershed and domain levels to determine the flood hazards in the domain area for in 2011 and 2038.

Archydro was used to delineate the subwatershed and the drainage lines of the major rivers in the Addis Ababa and surrounding towns to be used in the analysis. The little Akaki river drainage line was extracted and used for further analysis.

Curve numbers: Land use geological and soil Analyses are conducted on the subwatershed of the selected river (running through the northwestern region of Addis Ababa) to calculate the hydrographs for the various return periods associated with the rainfall patterns. The hydrograph refers to the flow discharge as a function of time and constitutes the input for the hydraulic diffusion model

FLO_2D: Diffusion of the total discharge volume (area under the hydrograph) based on the general constitutive equations of continuity and fluid dynamics using a bi-dimensional diffusion model (using FLO2D software). The inundation profile can be used to delineate the inundated areas for a given return period, as those areas within the zones of interest where the inundation height is greater than zero.

A hydrologic module through which, by extreme rainfalls and river catchment geological and land use characteristics, the peak volume and the peak discharge corresponding to a fixed return period was assessed; A hydraulic two-dimensional module was employed to delineate flood-prone areas evaluating cell by cell flood characteristics in terms of maximum flow depths, and maximum velocity. Flood hazard map is developed for the recent situation (2011) and for the future (2038) in both scenarios.

RESULTS

4.1 City growth: loss of farmland and flood vulnerability

Input data preparation

Future Land demand:

The future land demand that was used in the first application is shown in Table 1

Table 1 Future land demand for application 2

Year	Projected population (UNDESA, 2011)	Population increment	Required Settlement Cells	
			BAU (166 inh./ha)	DENS (350 inh./ha)
2011	3,041,002			
2015	3,343,730	302,728	7277	3459
2020	3,946,425	602,694	14,487	6887
2025	4,766,903	820,478	19,723	9376

Settlement development

Scenario 1:

According to the model, 10,731 ha would be transformed into settlements in 2025. The total settlement area cover in the city would be 28,644 ha representing 55% of the total area.

Scenario 2:

According to the model, 4,930 ha would be transformed into settlements in 2025. The total settlement area cover in the city would be 23,203 ha representing 45% of the total area.

In scenario 2, an area of 5,441 ha would be saved from being transformed into settlement area due to the higher population density used in this scenario.

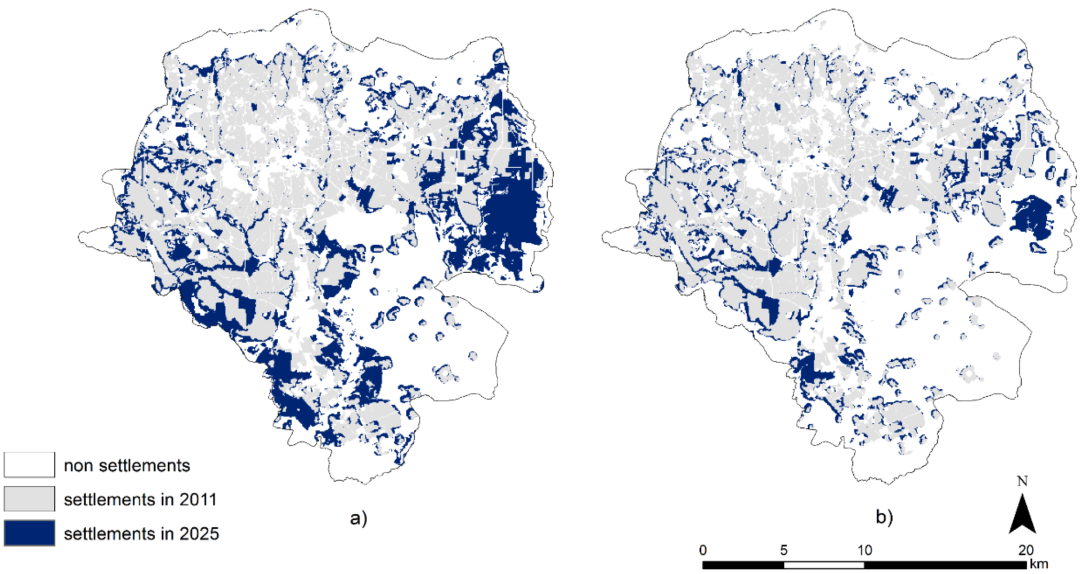


Figure 10 USSDM application 1: settlement expansion (Abo-El-Wafa et al. 2017a)

In both scenarios, most of the settlement development would take place in the eastern part of the city. The sub-cities that would have the highest share of settlement expansion are Yeka and Bole sub-cities. This is attributed to the relatively low slope, the high density of the road network and the proximity to markets. In contrary to scenario 2, settlements will develop largely in the south-western parts of the city (Niffas Silk Lafto and Akaki Kality sub-cities). Lower settlement expansion is occurring in the south-eastern part of the city due to the lower density of the road network, remoteness to central markets and existing settlement areas. The least settlement development is in the northern part of the city largely because of the steep slopes existing in this mountainous area.

Losses of farmland and other vegetated areas

Scenario 1:

According to the model results, 39.9% of the farmland (both field crops and vegetable farms) and 25.8% of the other vegetated areas would be lost in the period from 2011 to 2025. The proportion of farmland in Addis Ababa would decrease from 28.8% in 2011 to 17.2% in 2025 and the other vegetated areas would decrease from 14.5% in 2011 to 10.7% in 2025.

Scenario 2:

According to the model results, 14.7% of the farmland and 15.7% of the other vegetated areas would be lost in the period from 2011 to 2025. The proportion of the farmland in Addis Ababa would decrease from 28.8% to 24.5% and the other vegetated areas would decrease from 14.5% to 12.2%.

The spatial distribution of the farmland and vegetated areas lost in both scenarios are shown in Figure 11.

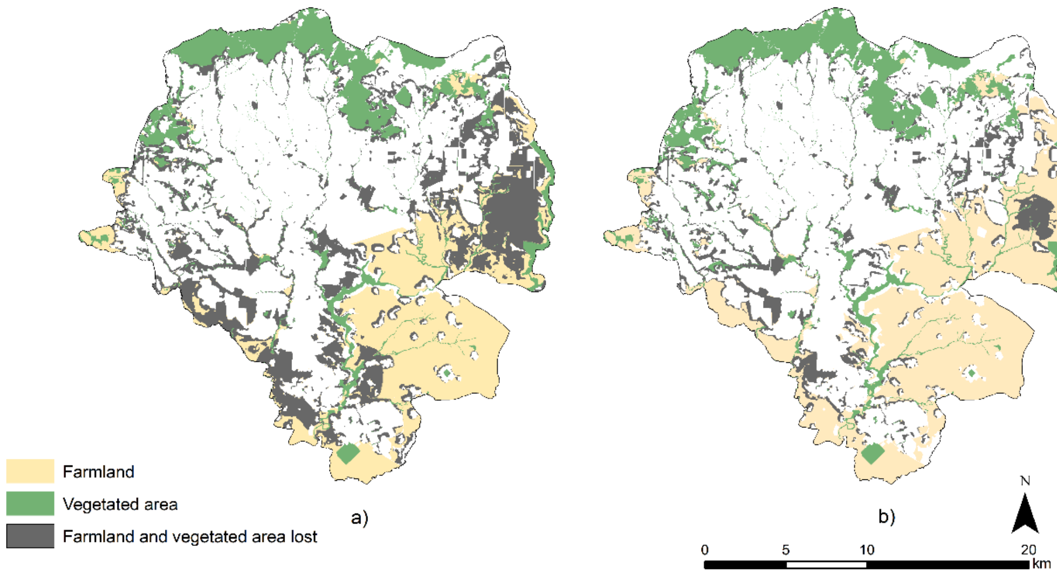


Figure 11 USSDM application 1: lost farmland and other vegetated areas (Abo-El-Wafa et al. 2017a)

Settlement development in flood-prone areas

In scenario 1, the newly transformed settlement area that would be located in a flood-prone area would be 990 ha, while in scenario 2, this area would be 574 ha. (Figure 12) However, using the estimated densities of each scenario, the number of inhabitants that would be settled in a flood-prone in scenario 1 and scenario 2 would be 200,900 and 164, 340 respectively.

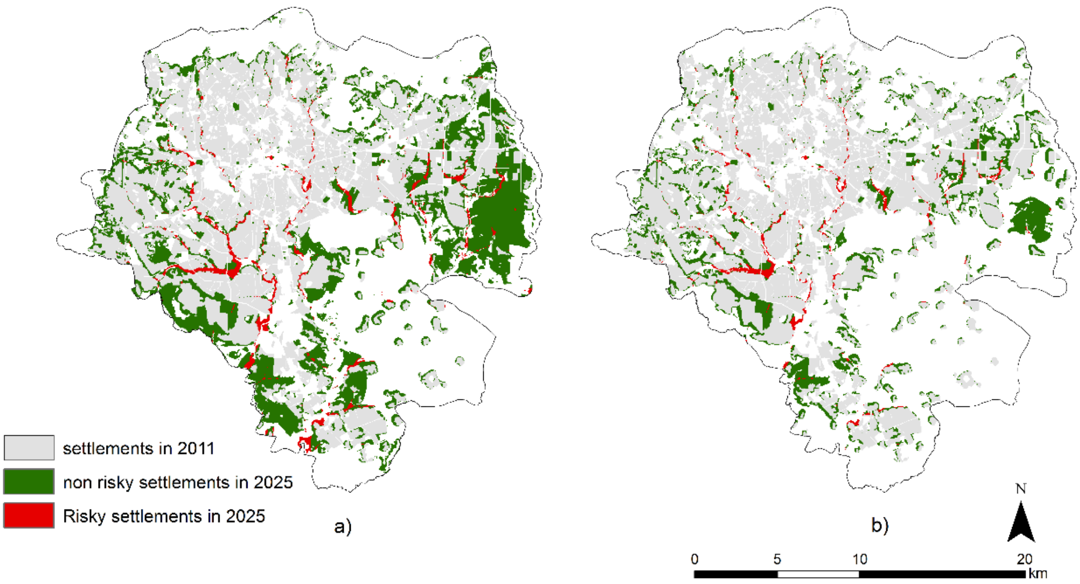


Figure 12 USSDM application 1: flood vulnerability analysis (Abo-El-Wafa et al. 2017a)

4.2 Regional growth: Food provisioning ecosystem services

Input data preparation

<u>Logistic Regression and influencing factors:</u>

A total area of 2015 ha has been transformed into built-up area in the period of 2008-2013 (Figure 13). For the logistics regression equation, the dependent variable is the (binary) change from 2008-2013 and the independent variables are the different influencing factors.

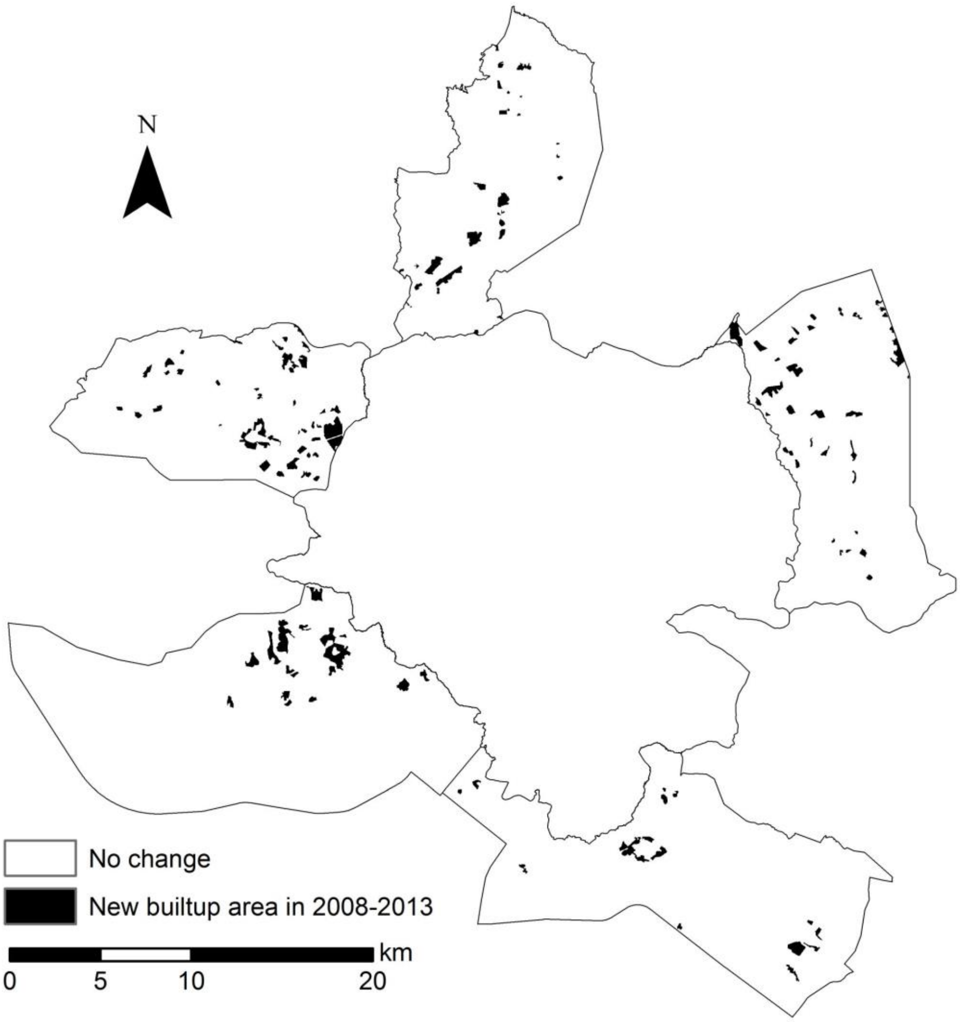


Figure 13 USSDM application 2: Change detection analysis output (Abo-El-Wafa et al. 2017b)

The result of the logistic regression (Table 2) shows the weights for the influencing factors used in this USSDM application (all results are significant at $p<0.01$).

Table 2 Influencing factors' weights for application 2

Parameter	Sululta	Burayu-Menagesha	Dukem-Gelan	Legetafo	Sabata
i	−3.19e+00	−2.36e+00	−2.81e+00	−3.63e+00	−3.66e+00
Ws	3.60E-03	−5.40e-02	−1.42e-01	−3.57e-02	1.73E-02
Wr	−2.36e-03	−2.65e-03	−1.33e-03	−4.93e-04	−3.00e-03
Wc	2.35E-04	3.55E-04	−3.04e-04	3.43E-04	4.32E-04
Wn	1.23E-01	4.47E-02	1.67E-01	1.56E-01	1.04E-01

Future land demand

The future land demand for settlements in 2038 estimated for this USSDM application is shown in Table 3.

Table 3 Future land demand for application 2

Town	Total housing units	Housing units in open land	Required area [ha]	Number of cells (20*20)
Burayu-Mena	116,504	77,669	947	23,680
Sebeta	115,000	76,667	935	23,374
Sululta	30,735	20,490	250	6,247
Dukem-Gelan	130,013	86,675	1057	26,425
Legetafo	124,314	82,876	1011	25,267

Settlement development

Scenario 1:

According to the model, 4,199 ha would be transformed into settlements in 2038. The total settlement area cover in the city would be 14,370 ha representing 19% of the total application area.

Scenario 2:

According to the model, 11,942 ha would be transformed into settlements in 2038. The total settlement area cover in the city would be 22,113 ha representing 29% of the total area.

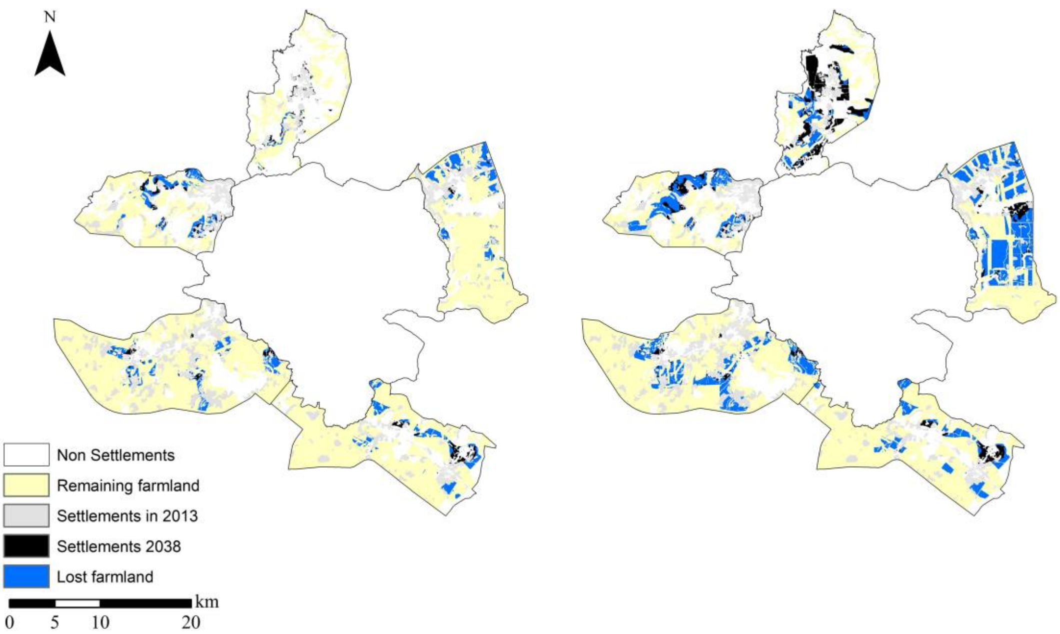


Figure 14 USSDM application 2: Settlement expansion and lost farmland (Abo-El-Wafa et al. 2017b)

In terms of area, 8750 ha of farmland would be lost due to the modelled settlement development in scenario 2 and 3230 ha in scenario 1 (Figure 14).

Food provisioning: Agricultural suitability

First stage analysis

Most of the modelled settlement development within the temporal scope of the model were located in areas that have no or low agricultural suitability. For the 30 crop types, an average of 76% of the modelled settlements is lying in this suitability range.

The proportion of modelled settlement development that is located in suitable farmland is used as an indicator for demonstrating the amount of losses of suitable farmland for cultivating each crop and for identifying the crops that are most vulnerable to be lost due to settlement development. For simplicity, the results were grouped into four groups (Figure 15 Proportion of modelled settlement area located in the suitable land for cultivation).

Figure 15 shows the proportion of modelled settlement development that is located in suitable farmland for all 30 crops

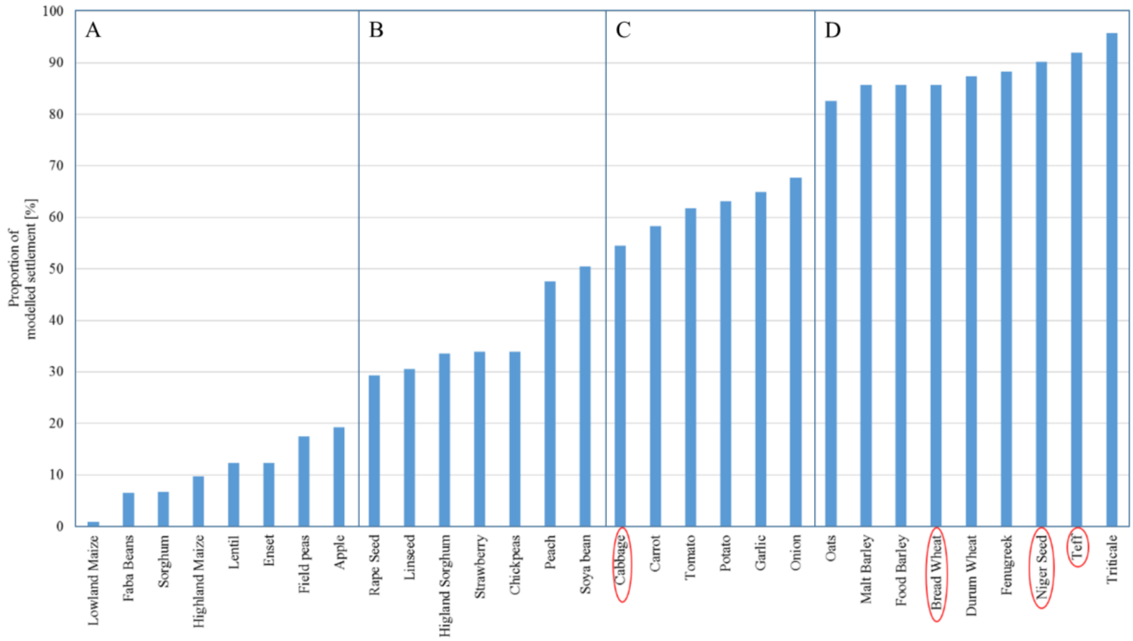


Figure 15 Proportion of modelled settlement area located in the suitable land for cultivation (Abo-El-Wafa et al. 2017b). Group A: 0-25% of the modelled settlement development is located on suitable land for cultivating the indicated crop types, and for groups B, C and D the proportions are 25-50%, 51-75%, 76-100%, respectively.

Second stage analysis:

The high-value crops that were used in this analysis are shown inTable 4:

Table 4 high-value crops selected for the second stage analysis

Crop	**crop group**	**Relevance to the local population**	**The proportion of modelled settlements in crop suitable land**
Teff	Grains (staple Crop)	Nutrition values, domestic use, Traditional	93%
Cabbage	Vegetable	local consumption, provides economic support for urban farmers	55%
Niger seed	Oilseed	economic support for urban farmers, export product	90%
Bread Wheat	Grains (staple Crop)	high potential for import substitution	83%

For the selected crops, the majority of the land is marginally suitable to cultivate the crop. There is no highly suitable land for cultivating any of the selected crops. The proportion of land that is moderately suitable for cultivating all selected crops is relatively small in the research area when compared to other suitability levels and ranges between 1% (niger seed) to 6% (bread wheat). The highest proportion of non-suitable land would be for cabbage (45%) and the lowest would be for teff (1%). (Figure 16)

Sabata area (south-west of Addis), Burayu-Menagesha area (North-west) and Sululta area (North) have land that is moderately suitable for cultivating the high-value crops selected. On the other hand, areas in Dukem-Gelan (Southeast) and Legetafo (North-east) are dominated by land that is marginally and very marginally suitable for cultivation of the high-value crops (Figure 16).

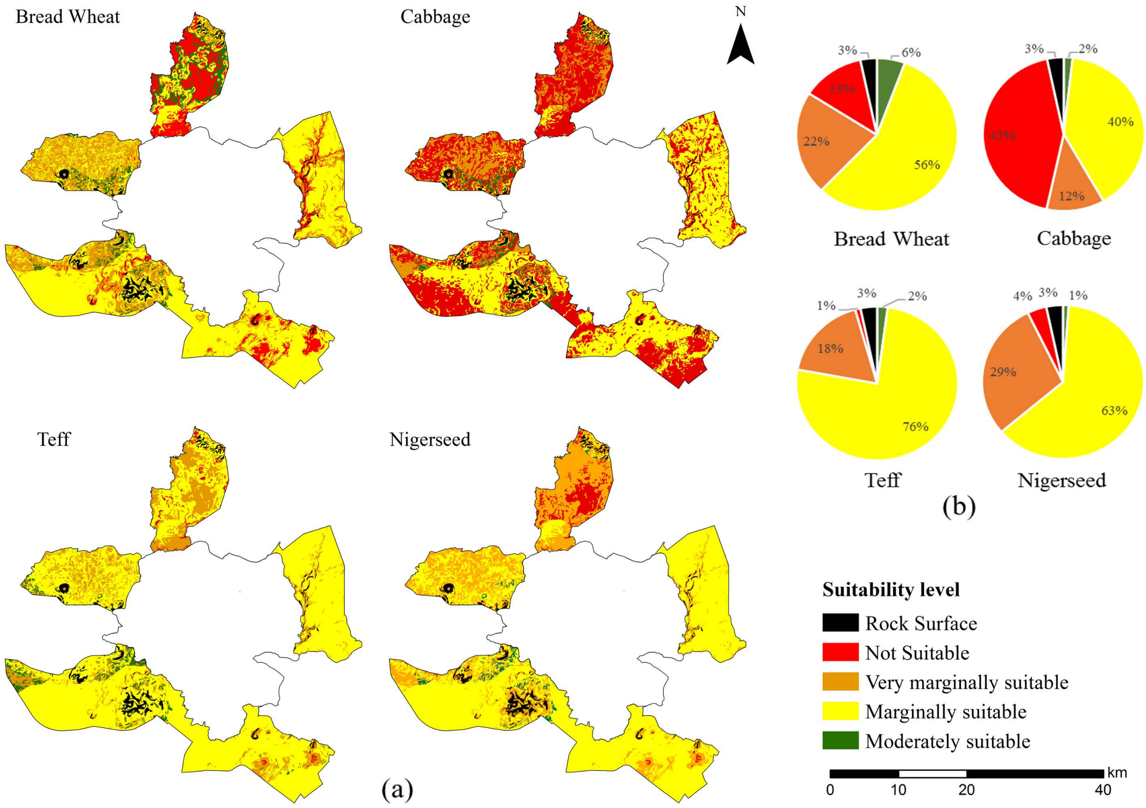


Figure 16 (a) Suitability maps for high value crops, (b) land inventory analysis in 2013 for high value crops. (Abo-El-Wafa et al. 2017b)

<u>Comparison of the two scenarios</u>

In comparison to scenario 1, the losses of marginally and the very marginally suitable land for cultivating the high-value crops in scenario 2 would have an average increase in scenario 2 of 160% and 200%.

Table 5 The relative increase (%) of land lost to modelled settlements in Scenario 2 compared to scenario 1

Crop	Moderately suitable Area [ha]	Marginally suitable Area [ha]	Very marginally suitable Area [ha]
Cabbage	51.6%	172.3%	212.8%
Bread wheat	468.9%	167.9%	131.6%
Teff	173.9%	178.7%	206.6%
Nigerseed	85.8%	153.8%	251.0%

On the other hand, land moderately suitable for cultivating bread wheat and teff in scenario 2 has suffered higher losses of 467% and 174% respectively when compared to scenario 1. This indicates the vulnerability of moderately suitable land for cultivating these two crops when compared to cabbage and niger seed that would have a moderate increase of 50% and 80% respectively (Table 5).

4.3 Regional city interaction: Flood regulating services

Input data preparation

The future land demand for settlements in 2038 estimated for this USSDM application is shown in Table 6.

Table 6 Future land demand for application 3

Town	2023				2038			
	Total Housing units	Housing units in green land	Land demand (Ha)	Land demand (20m*20m) cells	Total Housing units	Housing units in green land	Land demand (Ha)	Land demand (20m*20m) cells
Burayu-Menagesha	49,313	32,875	401	10,023	67,191	44,794	546	13,657

Logistic regression and influencing factors:

The result of the logistic regression is presented in equation 2 which shows the intercept and the weights for all influencing factors for the surrounding towns (all results are significant at $p < 0.01$).

z= -3.161e+00 -5.294e-02*SLOPE-2.287e-03*ROAD+ 1.118e-03* CENTRA +7.718e-02*NEIGH

Settlement development

Scenario 1: According to the model, 947 ha would be transformed into settlements in the subwatershed by 2038. The total settlement area cover in the city would be 4,553 ha representing 26% of the total area.

Scenario 2: According to the model, 1,300 ha would be transformed into settlements in 2038. The total settlement area cover in the city would be 4,907 ha representing 29% of the total area (Figure 15).

In scenario 2, an area of 5,441 ha would be saved from being transformed into settlement area due to the higher population density used in this scenario (Figure 15).

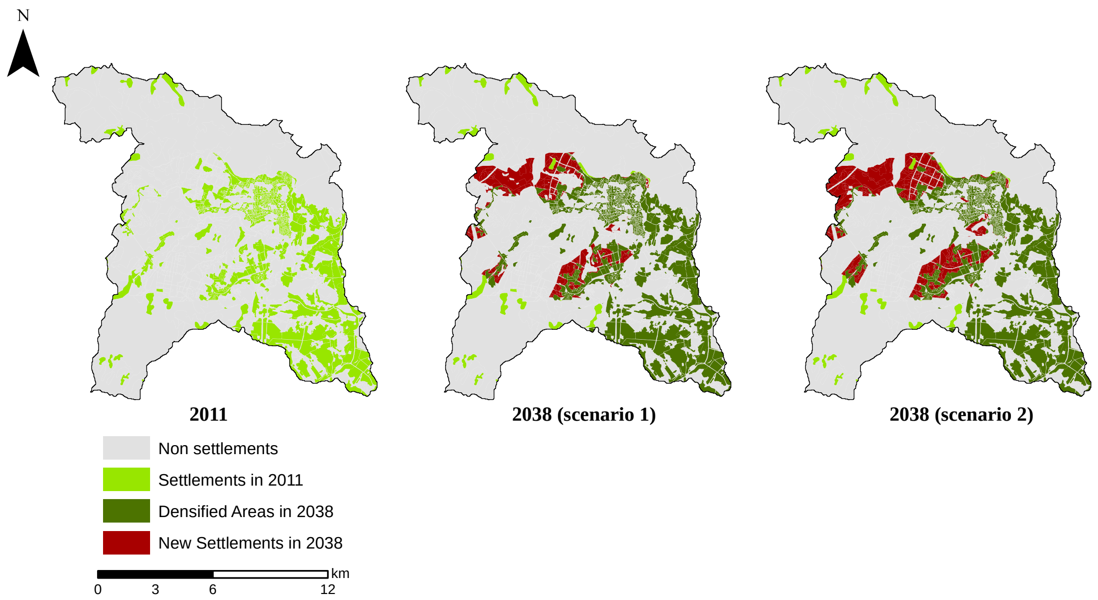


Figure 17 Modelled settlement expansion in 2038 for scenario 1 and 2 in the subwatershed

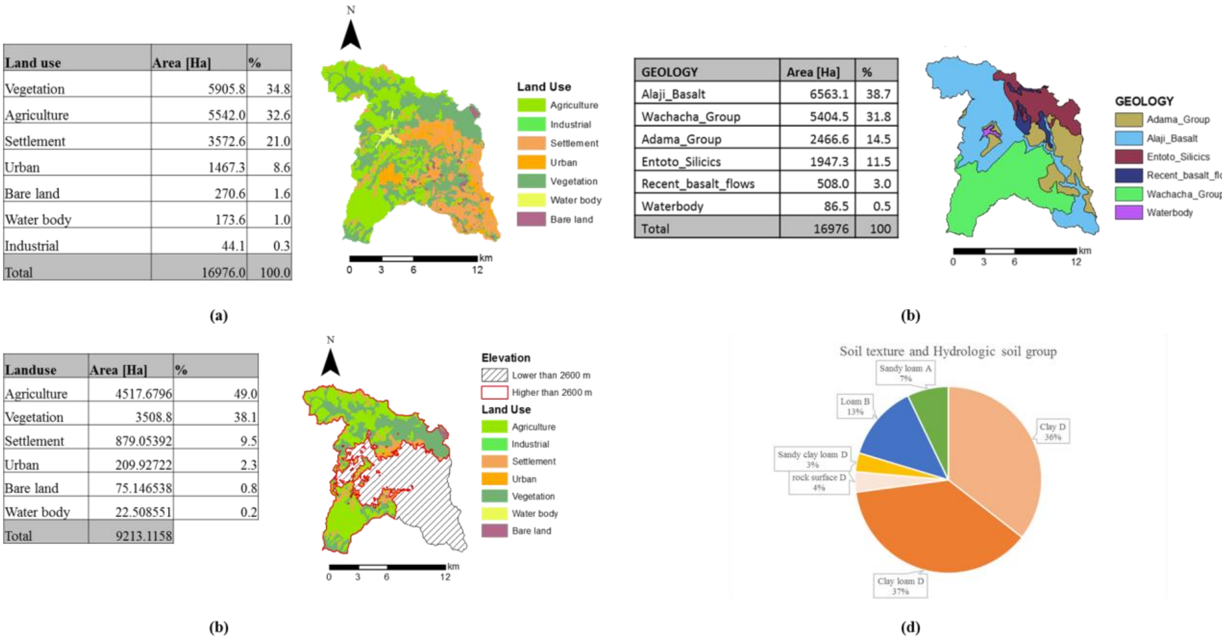
The difference of the settlement development between scenario 1 and scenario 2 was an increase of 37%. This would lead to an increase in the impermeable area in the subwatershed of the river being studied.

The densified area in both scenarios is the same (total 3519 ha) in which the CN curve for these areas were 87 (SCS manual Land cover of "Residential Areas: ¼") in 2011 and changed to 92 (SCS manual Land cover of "Residential Areas: ¼") in 2038 (both scenarios 2 and 3).

Flood modelling

<u>CN curve:</u>

Land use, geological types, elevation, soil texture and hydrologic groups in the research area (Figure 16) were used in order to determine the CN-curve numbers that were used in this application to produce the hydrographs for 2011. For the two scenarios in 2038, CN-curve numbers were determined to take into consideration the changes that would take place to the land use due to the settlement expansion.



Land use	Area [Ha]	%
Vegetation	5905.8	34.8
Agriculture	5542.0	32.6
Settlement	3572.6	21.0
Urban	1467.3	8.6
Bare land	270.6	1.6
Water body	173.6	1.0
Industrial	44.1	0.3
Total	16976.0	100.0

GEOLOGY	Area [Ha]	%
Alaji_Basalt	6563.1	38.7
Wachacha_Group	5404.5	31.8
Adama_Group	2466.6	14.5
Entoto_Silicics	1947.3	11.5
Recent_basalt_flows	508.0	3.0
Waterbody	86.5	0.5
Total	16976	100

Landuse	Area [Ha]	%
Agriculture	4517.6796	49.0
Vegetation	3508.8	38.1
Settlement	879.05392	9.5
Urban	209.92722	2.3
Bare land	75.146538	0.8
Water body	22.508551	0.2
Total	9213.1158	

Figure 18 CN curve input parameters: (a) Land use in the research area, (b) Geological types in the research area, (c) Elevation in the research area, (d) Soil texture and hydrologic groups in the research area

The settlement development in both scenario 1 and 2 was analysed and curve numbers for the year 2038 scenario 1 and 2038 scenario 2 were calculated based on the updated land use. The new settlement areas were considered as “Residential, 1/8 acre lots”. The settlement area densification that is planned by the city was also accounted for by changing the SCS land cover (increasing the CN) from "Residential 1/4 acre lots to 1/8 acre lots (92). Table 6 shows the CN curve numbers for 2011, 2038 scenario 1 (2038 S2) and scenario 2 (2038 S2)

Table 7 Curve Numbers (CN) for the research area in 2011 and 2038 (scenario 1 and 2)

2011			2038 S1			2038 S2		
CN	Cell	CN*count	CN	Cell	CN*count	CN value	Cell	CN*count
73	12052	879796	73	12052	879796	73	12052	879796
77	24832	1912064	77	20696	1593592	77	18072	1391544
79	59332	4687228	79	57525	4544475	79	55644	4395876
80	53848	4307840	80	51559	4124720	80	49749	3979920
84	237	19908	84	237	19908	84	237	19908
87	87989	7655043						
89	7876	700964	89	6794	604666	89	6746	600394
91	138519	12605229	91	124161	11298651	91	121686	11073426
92	2174	200008	92	113838	10473096	92	122680	11286560
93	10464	973152	93	10464	973152	93	10463	973059
95	11267	1070365	95	11267	1070365	95	11266	1070270
98	10166	996268	98	10163	995974	98	10161	995778
100	5643	564300	100	5643	564300	100	5643	564300
	424399	36572165		424399	37142695		424399	37230831
CN_II value			CN_II value			CN_II value		

The increase in CN curve for the research area between the present (2011) and the future (2038) for the two scenarios were 1.6% and 1.8% for scenario 1 and scenario 2 respectively. Although the increase is relatively small it will have an impact on the hydrograph and consequently the flood hazard area expansion (see the next sections). The impact of increasing the CN curve number due to densification is higher than the increase of the CN curve number due to the expansion of settlement located in new areas. This increase of the CN curve number between scenario 1 and scenario 2 is as low as 0.23%. The average increase in the CN value for 2038 (for both scenario 1 and 2) is largely due to the transformation of different land uses to Residential 1/8 acre lots rather than the increase due to the densification of already existing settlement.

Archydro:

The output from the Archydro analysis is shown in Figure 19. Using the digital elevation model (DEM), the Archydro was used to determine the little Akaki river (drainage line) and the subwatershed. The outlet point was identified and a domain area is delineated which would act as the analysis area in which the flood hazard would be mapped.

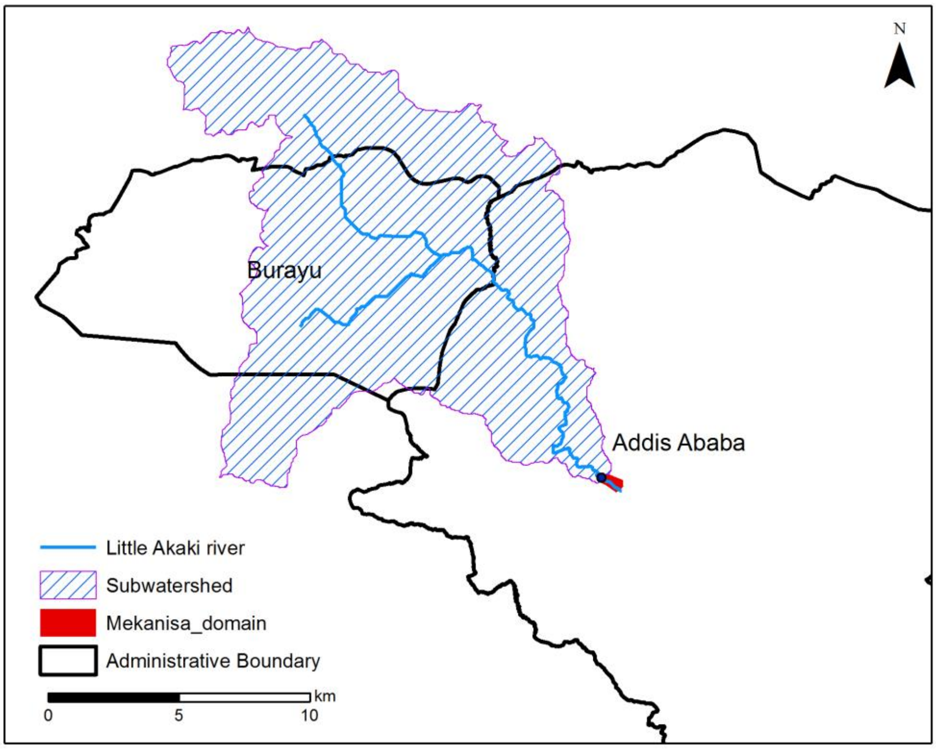


Figure 19 Output of Archydro analysis

Inflow hydrographs

As an output of the FLO-2d analysis, the inflow hydrographs for catchment corresponding to the various return periods considered are illustrated in Figure 20.

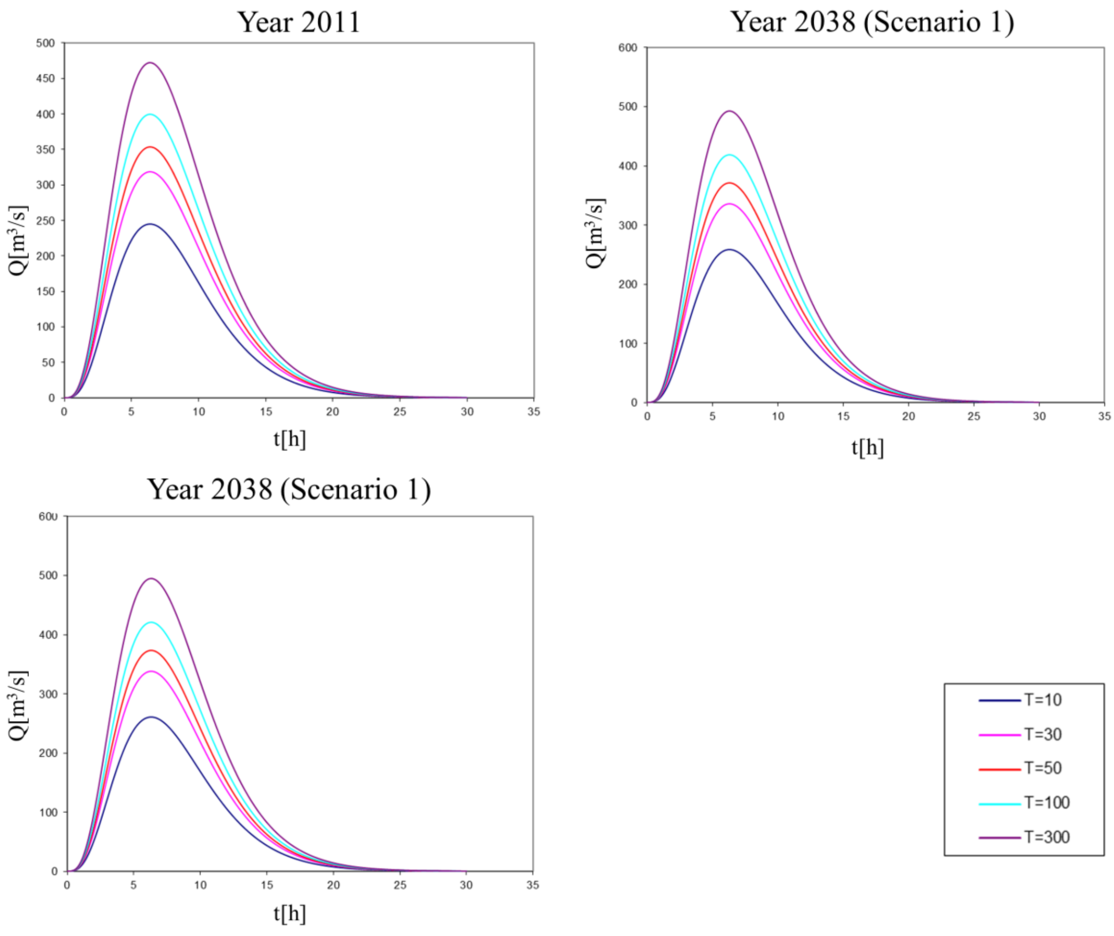


Figure 20 Inflow Hydrograph for the current situations 2011 (a) and for future 2038 (b).

There is an increment of the volume of about 7% for a 300 years return period although the average Curve Number difference between 2011 and 2038 is relatively low.

Hazard map for the domain area

Figure 21 shows that the new scenarios lead to an increment of the inundation maximum intensity in correspondence of the bridge (for a fixed return period). The outcome of the flood propagation is illustrated in Figure 21, in terms of maximum flow depth (in meters), with reference to three considered return periods (10, 100 and 300 years), for the three analysed cases.

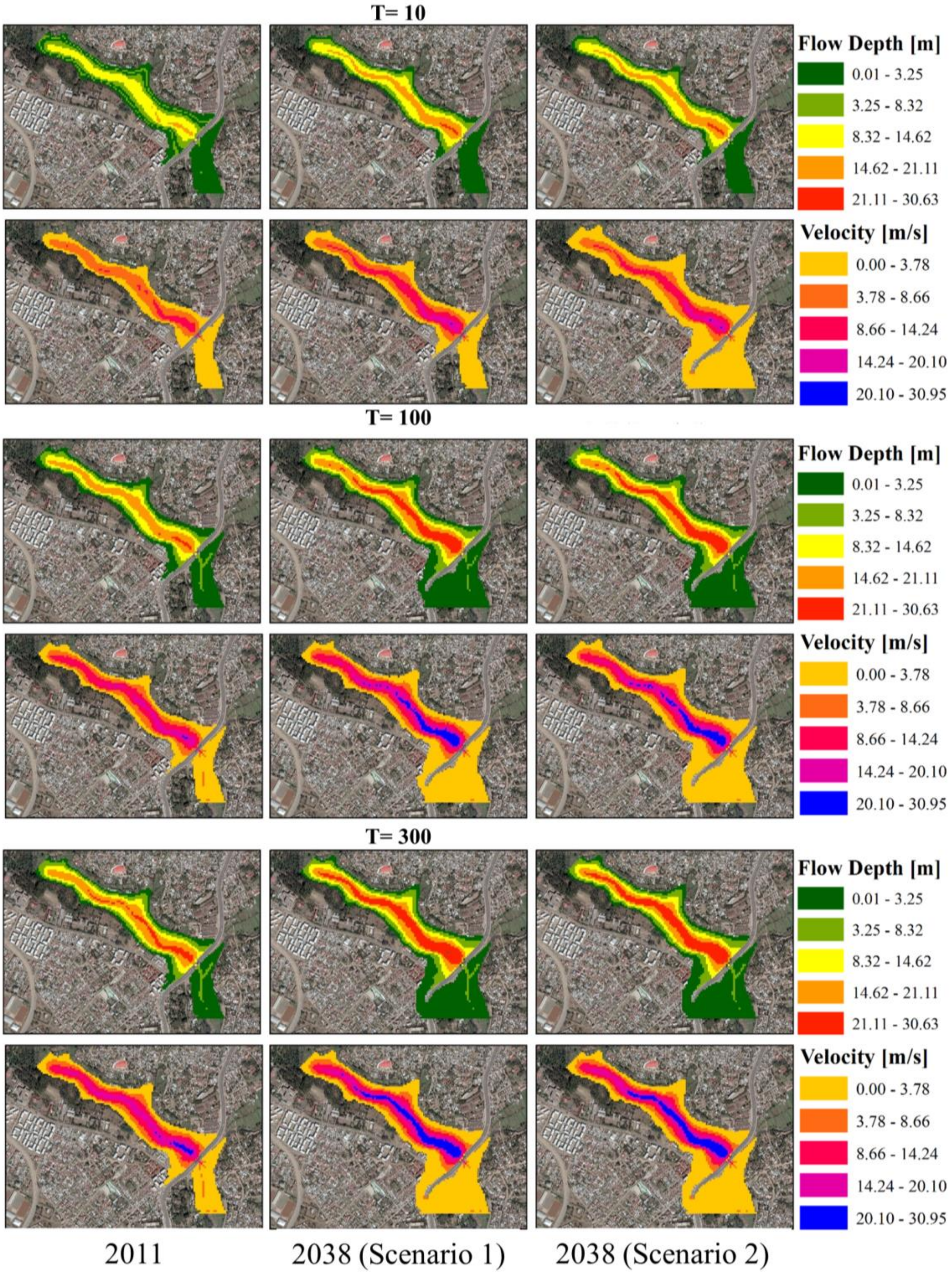


Figure 21 Hazard map: (flow depth and velocity) for 2011 and 2038 (SC1 and SC2) for T10, T100 and T300

The new scenarios lead to an increment of the inundation maximum intensity in correspondence of the bridge (for a fixed return period). In 2011, the maximum flow depth is approximately 25 m and the maximum velocity is 31 m/s (for T=300y) in 2011. For the same return period (T=300y), a maximum water depth of 31 m and a maximum velocity of 31 m/s

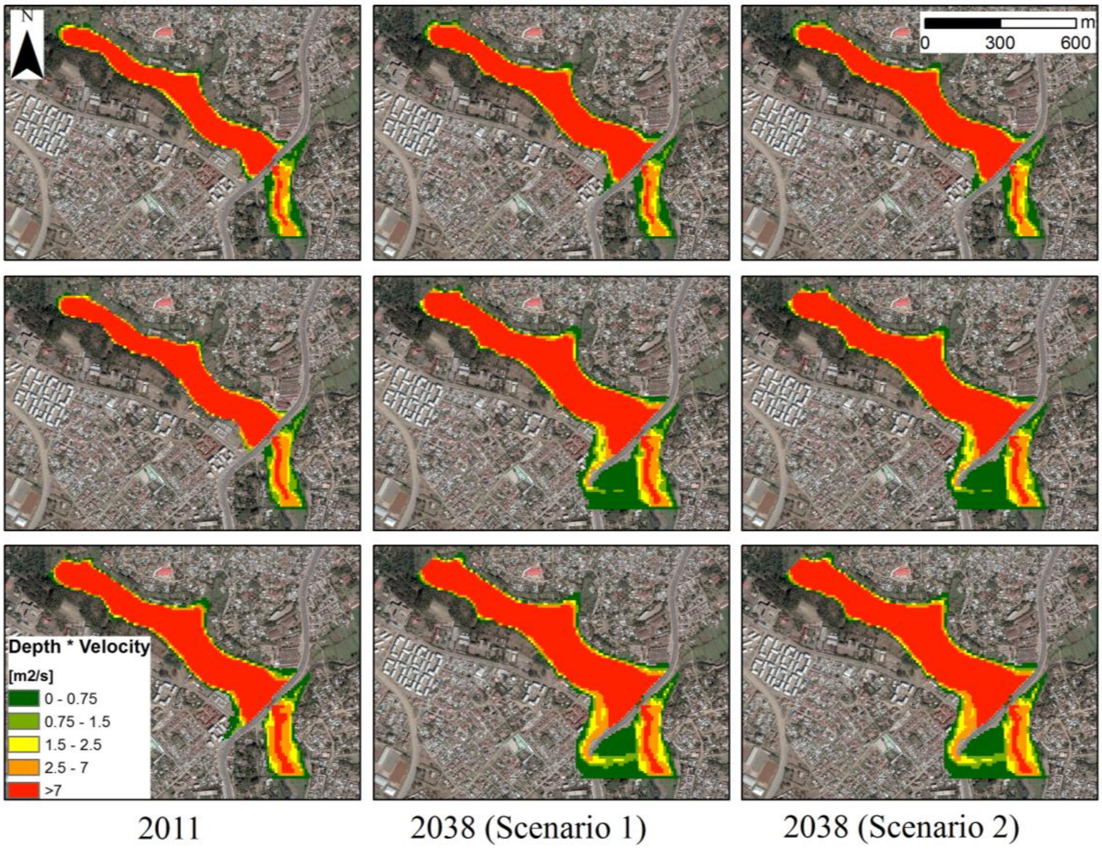


Figure 22 Flood hazard thresholds based on a combination of depth-velocity. Depth X Velocity [m2/sec] (threshold based on Priest et al., 2008)

were observed for the year 2038 in both scenarios. There were not a large difference in the values between scenario 1 and 2 in 2038. Furthermore, the presence of the obstruction caused by a road bridge causes strong lateral overflows that significantly increase the flooded area.In Figure 22, flood hazard maps are delineated by the multiplying the cellular values of flow depth and velocity. Thresholds defined based on Priest et al., 2008. In 2038, both scenarios would lead to an increased extent of the flood hazard area and the flood magnitude. Additionally the obstruction caused by the road bridge leads to a higher flood hazard due to the strong lateral overflows (for all return periods).

DISCUSSION

The results of the first two USSDM applications have demonstrated the influence of settlement density on the magnitude of losses of important components of green infrastructure and the vulnerability of the urban inhabitants to flooding. Food provisioning and flood regulation ecosystem services were addressed in this research. Both are important ecosystem services that support the urban inhabitants in Sub-Saharan African cities. The second application has investigated the impact of settlement expansion on the land suitable for agriculture and the potential reduction in food provisioning ecosystem services. The third USSDM application investigated the impact of settlement expansion in regional areas on flood regulating ecosystem services and the consequent increase of flood hazards in the domain area located inside the city. In the following sections, the influence of settlement density on green infrastructure, the potential impact of future settlement expansion on food provisioning and flood regulation and, finally, the spatial scenario approach used in this research are discussed

5.1 Settlement density and green infrastructure

Low-density development would lead to a general pattern of urban sprawl (Figure 10 a) and a horizontal development expansion in the peri-urban area (Figure 14 b), while adopting a high-density for new settlements would lead to a more compact city form (Figure 10 b) and clustered settlement developments around existing built-up area in the peri-urban region (Figure 14 a).

Farmland and other vegetated areas in the city will be continuously transformed into other land uses due to the increasing population growth and the subsequent expansion of settlements (Tan, Beckmann, van den Berg, & Qu, 2009). However, the extent of these losses would differ significantly depending on the settlement density. In the first two applications, the high-density development would reduce the losses of important green infrastructure components (such as agriculture land and other vegetated areas) by more than half when compared to low-density development (Figure 11, Figure 14). Settlements would supplant land used for cultivating field crops (such as grains, cereals and pulses), however, to different extents in both scenarios. Losses would be up to 40% of land for field crops in the low-density scenario but only 14% in the high-density scenario compared to the area in 2011(Figure 11). Vegetable farms would also suffer large losses due to settlement expansion (42% losses in the low-density and 21% in the high-density scenario compared to the area in 2011 as shown in Figure 11).

This seems to be a logical finding since if the settlement density is low, the future land required to be settled would be large and losses of the finite farmland inventory would be consequently higher. However, the first application of USSDM helped in providing a better understanding of the degree to which the two opposing growth patterns may affect farmland and provided a spatial distribution of these effects. Moreover, the modelled settlement development in the high-density scenario would be located closer to the existing built-up area rather than spreading into the open lands of the city, which is currently occupied by farmland.

In the first application of USSDM, without enforcing any controls that prohibit settlement development in flood-prone areas, the future settlement area in flood-prone areas have more than doubled in the low-density scenario and had an increase of around 50% in the high density when compared to 2011(Figure 12). However, in the high population density scenario, more people would be exposed to the risk of flooding. This shows the importance of controlling the organic development of settlements in the city in general but also the importance of adopting high-density settlement strategies. Adopting high-density settlements alone might lead to the risk of having more people settling in flood-prone areas. Therefore prohibiting settlement development in flood-prone areas, together with adopting high-density settlements for future settlement expansion would be needed.

Researchers as Jenks, Burton, & Williams (1996) consider compact urban form as a measure for achieving sustainable development while others (such as Neuman, 2005) question using urban form as an indicator of sustainable planning. They consider compactness of a city neither a necessary nor a sufficient measure for the sustainability of a city. They also highlight that using compact form strategies only might be counterproductive as it might lead to high losses and reduced quality of urban green space (Haaland & van den Bosch, 2015).

This part of the research contributes to the scientific literature by demonstrating the potential negative impact of maintaining the current low-density development patterns on valuable components of green infrastructure inside a city. It also contributes to one side of the ongoing debate concerning the use of urban form as a sustainable planning strategy. The findings support the adoption of high-density compact development, as it would particularly help to preserve green infrastructure from being lost to settlements. At the same time, negative effects that might arise from high-density settlements and densification have to be counteracted. Green and open space planning in the new settlement expansion areas, the strict prohibition of settlement development in flood-prone areas, and implementing socially accepted strategies to relocate the population residing in flood-prone areas are required. This research also promotes the use of settlement density rather than the population density of cities as an indicator for analysing urban growth of a city as it better relates to impacts on ecosystem services.

5.2 Settlement expansion and food provisioning

In the second application of USSDM, the future settlement expansion in the surrounding region of Addis Ababa was modelled (Figure 17) and overlaid on agricultural suitability maps, which served as spatial indicators of food provisioning ecosystem services. Crop suitability of land allowed the classification of areas where losses of suitable land for cultivating each crop were to be expected. The research has also indicated which areas had the lowest agricultural suitability. The land suitability levels have varied among different towns in the Oromia region. In the research area, some towns (Dukem-Gelan and Legetafo) have mostly land with marginal and very marginal suitability for cultivating the selected crops while other towns (Sabata, Sululta and Burayu-Menagesha) have relatively suitable land for agriculture (Figure 16). This indication would help planners in making decisions from the perspective of food provisioning, on where settlement development should be directed in order to limit losing valuable land that has higher agricultural suitability.

Preliminary results (first stage analysis) have shown that most of the settlement expansion (an average of 76% of the future settlements) would be located on the land of relatively low agricultural suitability (marginal and very marginal suitability). This might show a contradiction to the idea that urban expansion is mostly happening on fertile land (Alphan, 2003; Morello et al., 2000; Satterthwaite, McGranahan, & Tacoli, 2010). However, this is due to the fact that the areas with low suitability dominate the study area (Figure 16). The scarcity of land that is moderately suitable for cultivation gives it an even higher importance due to its potential to produce with higher productivity (Radcliffe & Bechtold, 1989). More than half of all crops (16 out of 30 crops) cultivated in the area would be threatened by the future settlement development (Figure 17as more than 50% of the future settlement development would be located in suitable land for cultivating them (Figure 15). Among these threatened are the four high value crops selected in the second stage analysis. (Figure 15). The selected crops were vegetables (cabbage), cereal crops (teff and bread wheat) and oilseeds (nigerseed) (Table 4).

Vegetable production located in the peri-urban regions are valuable due to their proximity to cities and consequently, transport costs are relatively lower when compared to rural areas (Smit, Nasr & Ratta, 2001). In cases of high food price crises or rise in oil prices, the role of vegetable production becomes more valuable. Moreover, vegetables constitute important components of a balanced diet. The modelled settlement expansion has occurred on land suitable for vegetables that are important for local consumption, and provide economic support for urban farmers (Duressa, 2007).

Land suitable for cultivating cereal crops has suffered the highest losses among all analysed crops (for more details check paper 2 in the appendix). In many cases, cereals are considered as a staple crop in many Sub-Saharan African countries. For the case of Addis Ababa, Teff, produced for own consumption mostly in Ethiopia and Eritrea (OWWDSE, 2011), which is used to make Enjera, the main traditional dish (OWWDSE, 2011). Wheat is the top import-substituting product of the country (FAOSTAT, 2011).

Finally, losses for land that is suitable for cultivating niger seed would range from 5 to 8% in scenario 1 and 12–20% in scenario 2. Oil crops have high export potential comprising approximately 24% of the total export products of Ethiopia in 2015 (Workman, 2016). Niger seed, as an example, is the second most widely produced oil crop in Ethiopia and accounts for approximately 44% of total oil production (FAS, 2016).

Research conducted on other cities in developing countries have indicated that local food supply is highly important both to secure nutrition as well as to contribute to the local economy, particularly in times of economic crisis (Pribadi & Pauleit, 2015). Urban inhabitants usually rely on a combination of food acquisition modalities, including the peri-urban food production as a response to insufficient, unreliable and, especially unaffordable food supplies from rural and foreign sources (Mougeot, 1999).

To this end, this research contributes to the scientific literature by providing evidence for the negative impact of settlement expansion and the consequent transformation of agricultural land on the food provisioning services that benefit urban inhabitants. It introduces the innovative use of agricultural suitability maps as spatial indicators to represent the food provisioning ecosystem services. Using the agricultural suitability maps, the research investigated the value of available land for agriculture not only in terms of area losses but also according to the land's capability to produce crops providing an additional level of information on these land losses. Additionally, the research highlights the importance of studying settlement growth beyond the city's limits adopting a regional perspective to support a more sustainable urban planning and development. This is important as the growth of (Sub-Saharan African) cities goes beyond cities' administrative boundaries.

5.3 Settlement expansion and flood regulation

In the third application of USSDM, both the settlement expansion and the further densification of the already settled area in the region surrounding Addis Ababa have led to a growth of the flood hazard areas inside the city. The modelled settlement expansion in the subwatershed of the river Little Akaki (Figure 17) has led to a general increase of the of the flood hazard area's stretch in the domain area of Mekanisa (Figure 21). The main reason for this is that the growth of the settlement area has led to a reduction of the total pervious areas in the subwatershed which in turn reduced the overall retention capacity of land in the subwatershed. The replacement of natural soil with built-up areas (settlements, roads and pavements) results in water moving to rivers more rapidly than it did under natural conditions and increased the flow depth and velocity runoff water in the domain area.

Both the volume and the velocity cellular values have generally increased (Figure 21) which would lead to the existence of a higher risk of flood in the domain area due to the settlement growth and the densification of existing settlements in the subwatershed area. However, the difference between the 2 scenarios for 2038 was not significantly large (both in the CN values for the subwatershed and the inflow hydrographs at the inlet). This shows that the transformation of other land uses to settlements (regardless of the density) has a lower impact than the densification of the already existing settlements. This, however, is only valid in the current research area being investigated in this paper, as the assumptions made were that most of the urban population growth would be accommodated in already existing settlement areas (through urban renewal) which might not be the case in other areas where the settlement areas could not be heavily densified.

According to the result of this research, the settlement expansion that takes place in a specific area in the region has led to an increase in flood hazard (and consequently higher vulnerability) in an area inside the city that is located kilometres away. Planning of regional areas should take into consideration the hydrological characteristics of the whole ecosystem. Controlling urban sprawl and promoting a more densified form of development would help in reducing natural land cover losses, which act as natural channels where floodwaters normally go. It would also minimise the increased vulnerability that would be caused due to the systematic change in permeability caused by the settlement expansion.

Potential trends of settlement growth in the regional area of Addis Ababa would have an impact not only on the regional area but also on the flood hazard and the increased vulnerability in zones located inside the city.

This dissertation also contributes to the areas of urban growth and environmental modelling. Specifically, it introduces a novel approach that combines a spatial scenario modelling approach with a flood model that has a hydrologic module and a two-dimensional hydraulic module. It also introduced an interesting case that investigates the evolution of land cover and flooding patterns on two different urban scales. The settlement growth modelling was performed at a regional level (subwatershed) and the change in flood hazard due to this growth was investigated in an urban area that is located inside the city. Results clearly demonstrate the close interconnections between the urban landscape and and confirms how the planning of cities should not be limited to the boundaries of the city but rather consider other ecological and physical boundaries of the different ecosystems in which cities are located.

5.4 Discussion of the modelling approach

USSDM provides a tool for urban planners and other potential users (city managers, researchers and city developers) to model settlement development in the different spatial scales of a city and its surrounding region. Modelling future settlement expansion provides a framework for decision-makers to evaluate different urban planning strategies and their consequences on the surrounding environment. The interaction between settlement expansion and the surrounding environment could also be investigated by analysing the model output with other indicators and models that represent important ecosystem services present in the area being studied. The output of USSDM provides a platform for urban planners to test certain hypotheses and to answer “what if?” questions by modelling settlement expansion using different parameters and scenarios.

In contrast to other models developed and applied for other cities in Africa (Sietchiping, 2004; Barredo et al., 2004; Hill, 2010; Abebe, 2011; Linard et al., 2103), USSDM offers flexibility in adding different influencing factors as inputs to the model depending on the context of the area under study. It is also considered as a living model whose data input can be continuously updated when new datasets are available. In the context of Sub-Saharan Africa, the input data are not too demanding as multi-temporal remotely sensed data for assessment of land use dynamics are mostly available due to the technological advancement in geospatial data capturing.

USSDM also has a great potential in improving the communication between scientists, planners, policymakers and the public. It also facilitates the integration of different stakeholders in the planning process which highly influences the quality of decisions being made through participatory planning (Reed, 2008). Due to the relative simplicity of the model's "white box" structure, its transparency in showing primary assumptions, and the possibility to run the simulations in a workshop environment, it offers new possibilities for stakeholder integration and enhances participatory urban planning and decision making. The modelling outputs from the different applications stimulated lively debates among experts consulted in this research about the different urban development patterns. These experts contributed to the definition and validation of the factors that influence settlement growth within the city and the surrounding region highlighted in this research. They also identified possible measures and strategies that could help in directing the future growth of the city in order to minimize the impact on ecosystem services. These stakeholders have appreciated the model and confirmed its capability in modelling urban growth and assessing the consequences of this growth on the changes of the city. The involvement of experts from different planning domains (urban, transport and environmental planners) allowed integrating both local and scientific knowledge that is recommended for the success of participatory planning (Reed, 2008).

USSDM fulfils the need to develop models that can be easily integrated into urban planning processes and applied in a real-world context. In this research, USSDM has been used for evaluating Addis Ababa's master plan review. The findings have shown that the small remaining areas of productive farmland would be lost if the areas designated for residential use in the proposed master plan were to be settled. Similarly, USSDM could be used in the process of preparing the master plans in order to determine the effect on the natural and semi-natural ecosystems and help planners in designating the new zones to be settled.

Some limitations of the modelling approach used in this research are related to the modelling concept itself (USSDM development) and other limitations that are related to the applications used in this research (USSDM application)

USSDM development:

USSDM is a single type model, whereas it can only model a single type (in this research, the settlement land use type). Due to the cellular structure of the model, the USSDM cannot model more than one type at the same time. However, the relationship between the settlement type and other land use types can be statistically assessed from the model results.

USSDM is developed, edited and run in ArcGIS Model builder environment and using features from the Spatial Analyst extension. ArcGIS requires a paid license which might limit the use of the model. Open source GIS software programs (such as GRASS) have their own modelbuilder feature however this was not tried within the scope of this research.

USSDM application:

In the different USSDM applications, selected factors were used as the main factors that influence settlement growth. These factors were derived from literature and validated by the different stakeholders involved in this research. However, there are other factors that might be considered to also influence settlement expansion and could be further added to other applications of USSDM, such as social and cultural factors and effects of major infrastructure projects. Social, behavioural and cultural studies could be used in order to investigate these factors. The challenge here would be to develop suitable spatial indicators that could be input to the model and represent these factors.

Future land demand is the main driver of USSDM, which is calculated exogenously to the model. The more accurate and detailed the future land demand is, the more precise the model outputs are. In the first application of the model, the future land demand was estimated directly from the projected population growth (according to the latest census). However, in the second and third application, information on the number of units per area and the difference between land demand calculation in vacant land and the land required for densification was used.

Except for the first USSDM application, the master plan has set the framework for the model, in which new settlement development was strictly limited to the designated residential areas defined by the master plan. This assumes that the settlement growth would follow a formal pattern and that the settlement development would be restricted to the designated residential areas in the proposed master plan. The large expansion of the settlement area projected to take place in the coming years would be derived mostly by formal planning, large-scale housing projects and industrial development planned in the region. However, the second and third USSDM applications did not consider the informal settlement development, which might be the case in reality as the number of slum dwellers in sub-Saharan Africa, has grown in lockstep with the increase in the region’s urban population (UN-Habitat, 2016). Although the regional government is aiming to strictly implement formally planned settlements and pledges to demolish any informal settlements built after a certain year (1995 in the case of Addis Ababa) (Kassahun, 2011), the emergence of informal settlements should be expected (especially in the peripheral areas of the towns). Due to the lack of studies that investigate the formation and characteristics of informal settlements in the region of Addis Ababa, and due to this research focusing on the master plan, informal settlements were not considered in the model.

CONCLUSION

6.1 Summary of key results

In this research, Urban Spatial Scenario Design Model (USSDM), one of the few models in Africa that is designed towards application by urban planners and other urban stakeholders is used as a tool for evaluating the impact of urban growth on the urban environment. USSDM is a conceptual and methodological framework for urban research in sub-Saharan Africa to support the planning of a more sustainable urban growth. Planners should have an in-depth understanding of the impact of the settlement area development and the consequences that would take place in the surrounding environment due to its expansion. Using the model, future processes of urbanisation in settled areas in sub-Saharan Africa cities are analysed highlighting the interactions between urbanisation and the surrounding environment in sub-Saharan African cities. USSDM was also used in evaluating master plans and land use zoning by estimating the impact of their implementation not only on food provisioning but also on the ecosystem service of flood regulation.

Three applications of USSDM were conducted to model settlement expansion and development using the case study of Addis Ababa and its surrounding region. The losses of farmland and the potential exposure of urban inhabitants to flood-prone hazards were estimated. Furthermore, settlement expansion in the peri-urban areas of Addis Ababa was modelled to assess its impact on suitable farmland that would be potentially lost. Finally, settlement area expansion in the sub-watershed of the little Akaki River (regional area of Addis Ababa) was modelled to analyse the consequent changes in flood patterns inside the city with the use of hydrological and hydraulic models.

6.2 Implications for urban planning

The expansion of settlement area in the different spatial scales of the urban area under investigation (the case study of Addis Ababa) has resulted in high losses of farmland and other vegetated areas, land use transformation of suitable agricultural land for cultivating important crops and an increased flood hazard inside the city. All these consequences negatively impact the livelihood, quality of life, security of the urban inhabitants and the overall sustainability of urban and rural development. Urban planning has to act in order to promote the resilience of cities and to achieve environmental sustainability in order to meet up with the challenges of urban transition caused by settlement expansion (Dyachia, Permana, Ho, Baba & Agboola, 2017).

The findings of this research support densification measures in the existing built-up area and a high-density settlement expansion for the newly developed settlements in the city and the surrounding region. Despite the existence of challenges from applying densification measures to other African cities, evidence from South Africa shows that densification and the more effective use of both vertical and horizontal space in a city are feasible (Pieterse & Fataar, 2016). Authorities in South Africa promote densification programmes in residential areas that are accessible to employment opportunities with the aim of improving urban sustainability and integration after apartheid (Williams, 2000).

However, densification and high-density settlement development strategies have to be complemented by other measures that promote green and open space development inside the new expansion areas and give considerable weight to preserving and managing urban green spaces (Pauleit et al., 2005). This is important in order to alleviate other negative effects that could result from high-density settlements such as air pollution, reduced quality of life, reduced urban resilience and reduction of open space areas (Haaland & van den Bosch, 2015).

The research also indicates that developing high-density settlement areas should not be only limited to the inner city (where land price is usually high). Horizontal development in regional areas would lead to large losses of suitable farmland in peri-urban areas as well as reduce the permeability of land that might drastically change flooding patterns in the region.

Master plans should identify areas to be protected, areas to be cultivated and areas to be used for building settlements, and so forth. Using spatial indicators and supply models for the different ecosystem along with modelling future settlement development could substantially help planners in identifying these areas.

Taking food provisioning service as an example, the importance of some areas has been determined using spatial indicators (such as agricultural suitability maps) depending on their varying suitability for cultivating specific crops of high value for food security (such as vegetables and cereals) due to being important components of the local diet (such as teff), having high export value (such as oil crops) or import substitution potential (such as bread wheat) and contributing to the livelihood of the inhabitants as income-generating activities (such as vegetables). Once these important areas are determined, strict land use zoning could be set in order to save these lands from being settled and direct the settlement expansion to the land of no or of the lowest suitability.

Products obtained from farmland is especially important for the poorest households who are the first ones affected by food price shocks (Conceição, Levine, Lipton, & Warren-Rodríguez, 2016). Moreover, Farming activities provide sources of income for those dependent on urban and peri-urban agriculture of the population (Egziabber, 1994). Given the increasing population growth and the high amount of poor people depending on the informal economy, this situation is not expected to change any time soon.

According to Wibberley (1959), economic evaluation of directing urban growth away from productive farmland might indicate that it would be more costly to avoid transforming productive farmland into settlements than locating the urban expansion elsewhere. Therefore, further arguments are needed to better protect and integrate farmland into urban regions. Such as its capacity to perform multiple functions that address other urban priorities such as recreation, social cohesion waste management and flood protection (Mougeot, 2015; Pauleit et al., 2013). These additional functions need to be also considered in the evaluation to support the development of multifunctional farming in peri-urban landscapes (Zasada, 2011).

For the case of flood regulation service, increasing urban density in cities would minimize the losses of natural and semi-natural vegetated areas due to a smaller overall land demand for new settlements. Once these vegetated areas, which act as natural channels for flood water passing, are replaced by impervious surfaces due to urban growth flood patterns increase and flood-prone areas expand together with the intensity of floods (increased flow depth and velocity). Moreover, increasing settlement density reduces its expansion into flood-prone areas, hence less population would be exposed to flood hazards. However, increasing the population density of newly expanded areas without the strict prohibition of building settlements in flood-prone areas might lead to increased vulnerability of urban inhabitants.

For settlement expansion into regional areas, preceding studies have to be conducted in order to investigate the impact of this expansion on a watershed level to include potential consequences not only in the region but also other areas that might be affected as shown in this research.

Tools such as USSDM have a high potential in providing platforms for scientists, planners, policymakers and the public to communicate through which would facilitate the integration of different stakeholders and enhances participatory urban planning and decision making. Local communities and stakeholders should be directly involved in the development and implementation of land use plans, and they must have a sense of ownership and clear and legally recognized rights to natural resources. This would act as an incentive for them to manage and conserve these natural resources. (Cleaver & Schreiber 1994).

6.3 Concluding Remarks

The research has shown that there is a need to adopt a new model for compact urban development which protects and integrates green infrastructure and farmland to increase urban resilience and food security. Densification of existing settlement areas and promoting high-density settlement strategies for newly developed settlements would lead to lower losses of Green Infrastructure and lower exposure of people to flood-prone hazard. Controlling urban sprawl and promoting a more densified form of development would help in reducing natural land cover losses, which act as natural channels where floodwaters normally go. It would also minimise the increased vulnerability that would be caused due to the systematic change in permeability caused by the settlement expansion. According to the result of this research, the settlement expansion that takes place in a specific area in the region has led to an increase in flood hazard (and consequently higher vulnerability) in an area inside the city that is located kilometres away. Planning of regional areas should take into consideration the hydrological characteristics of the ecosystem as a whole.

Assessment of ecosystem services provided by the environment should be an important step that precedes the allocation of future residential areas. Managing the environment of the peri-urban interface has significant consequences for the livelihoods, quality of life of the inhabitants and the sustainability of urban and rural development. Both the approach introduced and the specific results of this research can provide useful information for local administrations and decision makers to scientifically develop land use policies or planning, which would be in favour of reducing the adverse effects of urban growth on the environment.

6.4 Outlook and future research

The raster-based model introduced in this research could be integrated with agent-based models to enhance the incorporation of factors and agents that influence the urban settlement dynamics within a single modelling package. The integration of cell-based model, GIS and agent-based modelling (such as the work done in Dar es Salaam by Augustijn-Beckers, Flacke, & Retsios; 2011). Simulating informal settlement growth in Dar es Salaam, Tanzania: An agent-based housing model. Computers, Environment and Urban Systems, 35(2), 93-103. of in south Africa) would introduce new potentials for interlinking the different factors and agents involved in defining the urban settlement dynamics and to better understand the complexities of their interrelationships (Sietchiping. 2004).

Further investigation of the factors that influence settlement expansion would help improve the modelling output. This includes finding further factors or analyse the different magnitudes of this influence which could be translated into assigning different weights for each factor. In this research, a logistic regression approach was used to analyse the historical growth of the different research areas and different weights were assigned to the factors in the second and the third applications contrary to the first application where equal weights were given to all influencing factors.

Further research should investigate slums and informal settlement development in and around cities and use the results of this investigation to model both informal and formal settlement growth and assess the impact of both types of growth on the surrounding ecosystems.

In this research, USSDM was integrated with other spatial indicators (food provisioning ecosystem service) and hydraulic-hydrological models (flood regulation ecosystem services). USSDM could be integrated with other environmental models and datasets to investigate the impact of urban growth on the surrounding environment and analyse different environmental challenges that face urban areas (such as urban heat Island effect (UHI), pollution and climate regulation).

The impact of urban growth usually extends beyond the administrative boundaries of cities. As seen in this research, it is important to set the research's geographical focus in a wider perspective and not to be confined by the administrative boundaries of cities. More studies should conduct investigations beyond cities' limits and analyse the settlement development in the surrounding regions. The different spatial scales of cities would support a more sustainable urban growth that is not confined by the conventional city perspective.

DATASET KEY

Code	Dataset	Description	Use in research	Source
DS1.1	UMT maps	UMT maps for the years 2006 and 2011 for Addis Ababa were produced by the Ethiopian Institute of Architecture, Building Construction and City Development (EIABC), through digitising the orthorectified aerial photographs (ground sampling resolution of 0.2 m and Orthophoto Scale of 1:2000).	Application 1 Define the settlement area and farmland located in Addis Ababa. Additionally to prepare the neighbourhood influencing factor	CLUVA EU FP7 Research project Project ID: 265137 http://www.cluva.eu
DS1.2	Road network	Road network of Addis Ababa in 2011	Application 1: Prepare road proximity influencing factor	Addis Ababa Urban Planning Institute
DS1.3	Sub city markets	Waypoint Sub-city markets in 2011	Application 1: Prepare centrality influencing factor	Addis Ababa urban planning institute (2011)
DS1.4	Elevation	5 m interval contour input dataset for 2011	Application 1: Prepare slope influencing factor	Addis Ababa urban planning institute
DS1.5	Land use maps	The land use dataset for the year 2013	Application 2 and 3: Define the settlement area and farmland located in Addis Ababa.	(AAOIDP , 2013)
DS1.6	Facilities	The facilities and services dataset that include educational facilities, hospitals and markets (Waypoints)	Application 2 and 3: Prepare proximity to facilities influencing factor	(OWWDSE, 2011)
DS1.7	Land us 2008 and 2013	Historical built-up area Historical built-up area datasets for the years 2008 and 2013 in the whole area	Application 2 and 3: Conduct change detection Analysis for influencing factors weights	(OWWDSE, 2011)
DS1.8	Road network	Road network 2013	Application 2 and 3 Prepare proximity to roads influencing factor	(AAOIDP , 2013)
DS1.9	Elevation	20 m interval contour	Application 2: Prepare slope influencing factor	(AAOIDP , 2013)
DS1.10	Agricultural suitability maps	Agricultural Suitability maps for 30 agricultural crops according to a set of biophysical variables including soil characteristics, altitude and climate	Application 2: Spatial indicators for food provisioning ecosystem services	(OWWDSE, 2011)
DS1.11	Elevation	5 m interval contour	Application 3: Delineate subwatershed, drainage line (little Akaki river)m outlet and inlet points	(AAOIDP, 2013)
DS1.12	Soil and geological maps	Soil and geological maps for the subwatershed	Application 3: Calculate Curve Numbers (CN) for the research area	(OWWDSE, 2011)
DS1.13	Orthophoto	Aerial photograph (ground sampling resolution of 0.2 m and Orthophoto Scale of 1:2000).	Application 3 Base map for Domain area	CLUVA EU FP7 Research project Project ID: 265137 http://www.cluva.eu

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APPENDIX – PUBLISHED AND SUBMITTED ARTICLES

Appendix A: Paper 1 (published)

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Research Paper

The use of urban spatial scenario design model as a strategic planning tool for Addis Ababa

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ABSTRACT

Urban population growth and expansion of settlement areas are among the major challenges that African cities are facing. Addis Ababa's settlement area has been expanding into the city's peripheral area at the expense of losing green infrastructure (GI) of farmland and vegetated areas. The protection of GI is impeded by the lack of foresight information and tools to support urban planning. Therefore, a GIS-based urban spatial scenario design model (USSDM) was applied for modelling the settlement expansion in Addis Ababa. A business as usual scenario (BAU) and a densification scenario (DENS) were modelled to evaluate the impact of population density on the green infrastructure and the implications of excluding settlement development from flood prone areas. Training and workshops were conducted on the use of USSDM in the Addis Ababa master plan review. The results of our study indicated that increasing population density from 166 to 350 inhabitants per hectare would almost halve the losses of the green infrastructure. Moreover, the settlement development in the densification scenario would be located closer to the vicinity of the built-up area rather than spreading along the eastern part of the city, which is currently occupied by farmland in the case of BAU. Densification would also slow down expansion of settlements in river corridors but might expose more inhabitants to flood hazards. USSDM is one of few models in Africa that is designed towards application by urban planners as a tool of assessing the impact of urban development strategies on the surrounding environment.

1. Introduction

1.1. Background

The urban population in Africa is expected to triple by 2050 to reach 1.3 billion (UNDESA, 2014). Urbanisation is mostly taking place in the context of inadequate governance mechanisms, low urban institutional capacities and high levels of poverty (Parnell & Walawege, 2011; UN-HABITAT 2014; Vedeld et al., 2015). Accordingly, urban growth and expansion typically occur as the development of informal settlements, which often lack basic facilities and infrastructure and thus qualify as slums (UN-HABITAT, 2009).

The uncontrolled and often "leapfrogging" outward low-density settlement development causes huge losses in green infrastructure, directly influencing the provision of ecosystem services (e.g. food and timber provision, nutrient cycling, climate regulation and cultural identity) (Arku, 2009; Foley et al., 2005). Green infrastructure has been defined as an 'interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations' (Benedict and McMahon, 2006 Lovell and Taylor, 2013). However, in an African context, very few studies (such as Cilliers et al., 2017; Shackleton et al., 2017; Van der Walt, Cilliers, Du Toit, & Kellner, 2015) adopted the concept of green infrastructure for urban areas (Schäffler & Swilling, 2013). Farmland (vegetable farms and field crops) and other vegetated areas (plantation forest, mixed forest, riverine, and grasslands) are considered critical components of green infrastructure that reduce the vulnerability of the rapidly developing cities in sub-Saharan Africa (Lindley et al., 2015). In particular, agriculture in urban and peri-urban areas of African cities has an important role in the food supply for the urban inhabitants and for income generation (FAO, 2012; Halloran & Magid, 2013). Zezza and Tasciotti (2010) concluded that, in contrast to other continents, urban agriculture is a significant source of livelihoods for urban households on the African continent. Drechsel and Dongus (2010) have also considered urban vegetable production in sub-Saharan Africa as one of few stable income sources for farmers with limited qualifications, highlighting its

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importance even if their numbers might be small compared to the total urban population. In the case of Addis Ababa, Gebrekidan (2015) showed the importance of urban vegetable farming in terms of creating employment opportunities, income generation and improving food availability. Official statistics show that more than 50% of the field crops and 70% of the vegetable production within Addis Ababa is used for household consumption (CSA, 2002a).

Urban development and consequent loss of green infrastructure also increase the risk of flooding in cities due to the replacement of vegetation by impervious surfaces, changes in stream morphology and poor drainage systems (Huong & Pathirana, 2013). Encroachment of informal settlements onto flood-prone areas such as river valleys increases the risk of major disasters (Doberstein & Stager, 2013; UNISDR, 2009).

Prevailing approaches to comprehensive master planning need to be rethought as current urban population growth rates were not anticipated when the master plans for many African cities were developed (Watson & Agbola, 2013). With rapid population growth, plans are frequently dated by the time of their adoption and are thus impossible to implement. Planning capacity needs to be significantly strengthened to address these challenges. A shift towards more strategic planning approaches that target key interventions to make a real impact on urban development has been advocated (Herslund et al., 2015). The development of such approaches needs to be supported with information, tools and instruments tailored to the specific sub-Saharan Africa conditions such as low data availability and limited resources. An extensive set of information is required, such as:

1. Current land use patterns.
2. Future settlement expansion patterns in a city and their influence on:
   a The decline of ecosystem services due to the loss of green infrastructure.
   b The vulnerability of city inhabitants that might settle in hazard-prone areas (Printz, Abo-El-Wafa, Buchta, & Pauleit, 2015).

Haase and Schwarz (2009) distinguish four broad classes of land use models: spatial economic/econometric models, system dynamics models, cellular automata and agent-based models. Of these classes, cellular automata (CAs) have been frequently used (Barredo et al., 2003; Batty, Xie, & Sun, 1999; Ward & Murray, 2000) because of their simplicity, intuitiveness, flexibility, and their particular ability to integrate both the spatial and temporal dimensions of urbanisation processes (Batty et al., 1999; Santé, García, Miranda, & Crecente, 2010). CA is applied as a modelling framework in several applications where the spatial relationships between cells represent real-world relationships. These applications include traffic modelling, structural design, and urban growth (Yuen & Kay, 2009). In an urban development context, CAs are based on the assumption that cities are self-organising systems in which specific constraints and controls affect local decision-making processes producing macroscopic urban patterns (Ward & Murray, 2000). Although CA models do not explicitly include socio-economic systems and the behaviour of various agents in decision-making on land use, the probability of land use changes can be derived from historical land use data (Haase & Schwarz, 2009). Previously developed models are demanding in input data (e.g. Urbansim and Tranus), customised and limited to specific cities (e.g. LandSIM 1.0), require complex programming skills (e.g. SWARM model), or the source code may not be accessible (e.g. PCraster and SimLand) (Sietchiping, 2004).

In previous urban growth models, several factors of spatial nature that influence land use change have been used, including environmental constraints such as steep slopes and flood areas (Braimoh & Onishi, 2007; Burchfield, Overman, Puga, & Turner, 2006), proximity to existing settlement areas, neighbourhood effect (Braimoh & Onishi, 2007; Burchfield et al., 2006; Caruso, Rounsevell, & Cojocaru, 2005; White, Engelen, Uljee, Lavalle, & Ehrlich, 2000), proximity to transport networks and services (Barredo & Demicheli, 2003; White et al., 2000), and urban planning policies (Barredo & Demicheli, 2003; Braimoh & Onishi, 2007). Other factors would be attributed to economic development, socio-economic and political systems and individual preferences. Modelling of these factors would require the integration of spatial models with other types, such as system dynamics, economic and agent-based models to account for both local level factors as well as regional socio-economic factors and governance (Güneralp, Reilly, & Seto, 2012).

Despite the limited data availability modelling growth of African cities using cellular automata has been done for Yaoundé, Cameroon (Sietchiping, 2004), and Lagos, Nigeria (Barredo, Demicheli, Lavalle, Kasanko, & McCormick, 2004). Linard, Tatem, and Gilbert (2103) modelled growth of 20 large cities across Africa, while Seto, Güneralp, and Hutyra (2012) addressed the issue of urban growth on a global scale. None of the above models, however, were strongly integrated into urban planning processes (that included the participation of stakeholders/planners). Hence, the need to develop models that can be easily integrated into urban planning processes and applied in a real world context is relevant. Such models must be transparent, easy to use and flexible. They should enable users to change the model parameters and customise the model to meet the needs of the stakeholders. The model should visualise general urban growth patterns but not be a complex tool whose goal is to forecast urban growth. Moreover, models should be able to accommodate updates whenever new information is available.

The Urban Spatial Scenario Design Model (USSDM), a GIS-based model designed on CA principles, first developed and applied within the framework of the Climate change and Urban Vulnerability in Africa (CLUVA), a European union FP7 project. USSDM was applied to the cities of Dar es Salaam and Addis Ababa as a participatory design modelling tool for urban planners. In this paper, the application of USSDM in Addis Ababa is presented along with a comparison to Dar es Salaam's application (Printz et al., 2015). This comparison is to demonstrate the applicability of USSDM to cities in developing countries with different local conditions and urban planning schemes.

The objectives of the paper are to:

1. Examine the potential and limitations of USSDM as a tool to support urban planning in sub-Saharan cities. Addis Ababa, one of Africa's 10 fastest growing large cities (UN-HABITAT, 2010) serves as a case study.
2. Analyse the role of high-density settlements in the future urban development of Addis Ababa by assessing the potential impact of settlement growth under different urban population density scenarios on the loss of important green infrastructure components of farmland and other vegetated areas as well as flood vulnerability of the urban inhabitants.
3. Demonstrate the capability of USSDM to be applied in different cities in developing countries by comparing the USSDM applications in Addis Ababa to Dar es Salaam.

2. Methods

2.1. Case study area

Addis Ababa is the capital city of Ethiopia and one of the most rapidly growing cities in Africa (UN-HABITAT, 2014). It covers an area of approximately 520 km^2 and its population in the year 2012 was 3 million inhabitants (CSA, 2012). The city's population is projected to be almost 6 million inhabitants in 2030 at an average annual growth rate of 4% (UNDESA, 2014).

Urban growth has exposed the city to critical challenges such as high unemployment rates, housing shortages and environmental deterioration (UN-Habitat, 2008). Green spaces are being converted to other land uses such as housing and industrial development (Horst, 2006).

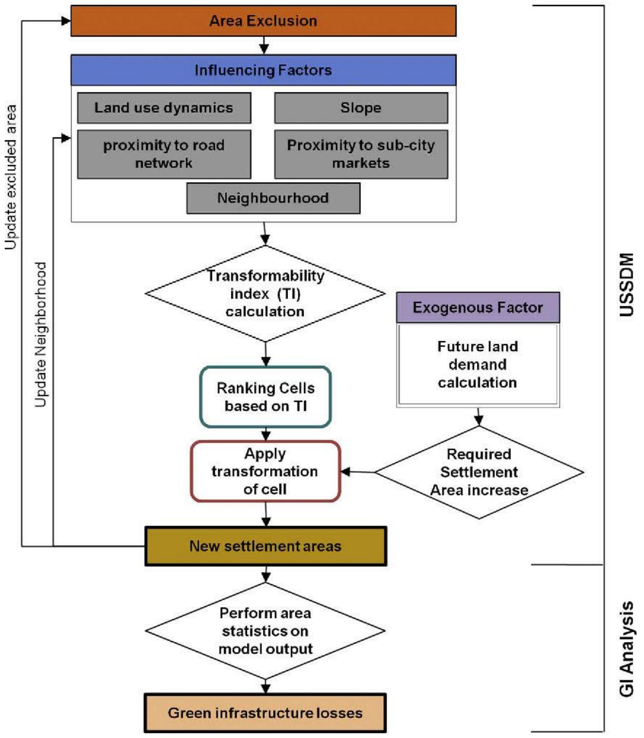

Fig. 1. USSDM in Addis Ababa: Conceptual Diagram.

The share of publicly accessible green spaces within the city's administrative boundaries is less than 1 m^2 per capita (AAOIDPP, 2013) compared to a 9 m^2 per capita recommendation by WHO (Edwards & Tsouros, 2006). In the period of 2006–2011, high losses of farmland (−24%) and an increase of residential areas (21%) occurred (Woldegerima, Yeshitela, & Lindley, 2016).

On the other hand, significant efforts have been made to plan for growth and the city administration has adopted strategic measures such as the development of a light rail transit (LRT) system and construction of multi-storey settlements (Condominium housing) at the fringe of the city (Wubneh, 2013). Addis Ababa faces challenges of rapid urbanisation similar to those in other African cities. At the same time, Addis Ababa is an interesting case for the application of USSDM as the city administration makes efforts to adopt a strategic planning of the city.

The physical expansion of Addis Ababa has occurred mainly horizontally into the city's peripheral area with more than 90% of the houses in the city being one storey (AAOIDPP, 2013). Although the Ethiopian government's interest in influencing the spatial development of the city dates back to the 1950s, scaled up organised responses to the enormous housing and infrastructure problems were not present until the beginning of the 21st century (Haregewoin, 2007a, 2007b). Though informal settlement development is still occurring, current urban development in Addis Ababa is dominated by formally planned settlements at a large scale, where slum areas in the city centre are cleared through the Integrated Housing Development Programme (IHDP) (UN Habitat, 2010; Wubneh, 2013). Consequently, thousands of settlers from the densely built neighbourhoods in the city centre have been relocated to newly built, large-scale condominium housing, mostly located in the peripheral areas of the city (Wubneh, 2013).

Addis Ababa has a pronounced rainfall peak during the summer (July–August) and exhibits a rainfall minimum during the winter (December–February) (CSIR, CMCC, 2013). Results from climate change modelling suggest that the seasonality of rainfall will not change but the frequency of high precipitation events will increase (Giugni et al., 2015). In conjunction with the modification of floodplains due to urbanisation, flood risks will rise (Nirupama & Simonovic, 2007).

The frequency and severity of damage caused by flooding have greatly increased recently (Gebremichael et al., 2014). Flooding is caused by the physical alteration of the catchment areas due to the expanding cover of impervious areas, alteration of stream morphology, and development of informal settlements in the flood-prone areas in the central parts of the city, including most of the riverbanks (Belete, 2011; Mazihindu et al., 2010). While regulations prohibit settlements in buffer zones along the river streams, they are rarely enforced (Achamyeleh, 2003). As a result, the riverbanks of Addis Ababa, which are acting as the only green corridors in the city's "green network", are increasingly occupied by settlements and industries. Consequently, an ever-increasing population is exposed to the risks from flooding. Rivers are heavily polluted by the discharge of both solid and liquid wastes (AAOIDPP, 2013).

2.2. Urban morphology type (UMT) mapping

Lack of spatial data in most developing countries and especially for African cities is considered a major obstacle in modelling urban growth dynamics (Barredo et al., 2004). For this study, accurate information on urban spatial structure and dynamics was available from urban

Table 1
Specific parametersfor applying USSDM to Addis Ababa.

S/N	Parameter		Description
1	Spatial scope		Administrative boundary of Addis Ababa. 520 km^2 represented by 207,764 raster cells (50 m by 50 m cells). Input Dataset: Administrative boundary[a]
2	Temporal scope		2011–2025 with modelling periods 2015, 2020, 2025 (based on the input population data)
3	Excluded area		All UMT's except bare land, agriculture, vegetation, and areas near airport. Input dataset: UMT maps[b]
4.1	Influencing factors (Fig. 2)	Road proximity	Proximity (Euclidean distance) to road network Input Dataset: Road network in 2011[a]
4.2		Centrality	Proximity (Euclidean distance) sub-city markets Input dataset: Sub-city markets in 2011[a]
4.3		Land use dynamics	Ranking the UMT's based on area statistics of the change detection analysis between 2006 and 2011 UMT maps based on Input Dataset: UMT maps [2006, 2011][b]
4.4		Neighbourhood	Focal Statistics of 4 × 4 cell array using SUM statistic of neighbouring cells (value of 1 for settled and 0 for non-settled cells) Input Dataset: UMT maps in 2011[b]
4.5		Slope	Calculated slope using a 5 m interval contour input dataset[a]

[a] Data Source: Addis Ababa Urban Planning institute.
[b] Data Source: CLUVA project, EIABC.

morphology type (UMT) mapping (Cavan et al., 2012). The UMT approach has been repeatedly applied in Europe (Gill et al., 2008; Pauleit & Duhme, 2000) and further adapted and applied in CLUVA to selected African cities, including Addis Ababa, to produce green infrastructure maps (Cavan et al., 2012). In UMT, geographical units, which are functional in terms of their physical structure and biophysical processes, are delineated. UMT maps provide a detailed overview of the spatial distribution of, for instance, main settlement types, infrastructure, agricultural and forest areas, urban green spaces, and natural ecosystems. UMT maps for Addis Ababa were produced by the Ethiopian Institute of Architecture, Building Construction and City Development (EIABC), through digitising the ortho-rectified aerial photographs (ground sampling resolution of 0.2 m and Orthophoto Scale of 1:2000). UMT maps for the years 2006 and 2011 were verified through field assessments and communicating with local stakeholders (Woldegerima et al., 2016). Overall, the UMT map for Addis Ababa has 11 aggregated urban morphology units that are further detailed to 36 urban morphology types (Appendix A).

2.3. *Urban spatial scenario design model (USSDM)*

USSDM is a raster based GIS model developed in the ArcGIS 10.1 modelbuilder whose input and output parameters are raster files. As shown in Fig. 1, USSDM starts by excluding all cells that will not be processed by the model (defined by the user). USSDM then calculates a transformability index based on specific influencing factors (input by the user). The cells are then ranked in a descending order according to the transformability index and the cells with the highest transformability index transform into settlements meeting the future land demand. A raster file is produced, indicating settlement area development during the model's temporal scope. The excluded areas and the neighbourhood factor are continuously updated to include the new modelled settlement areas.

In USSDM, all influencing factors are represented by score maps that are normalised from 0 to 100 using a feature scaling method. As a simplifying assumption, the future demand for urban areas is estimated exogenously to cellular models (White, Engelen, & Uljee, 1997) where it is assumed that this demand is not directly related to the local spatial dynamics, but by the demographic growth of a city (Barredo et al., 2003).

2.4. *USSDM in Addis Ababa*

2.4.1. *Stakeholder participation*

In this work, 15 experts involved in Addis Ababa's urban planning contributed to the application of USSDM for the city. This group included researchers from the EIABC, city officials, urban planners from the city administration, and team members of the master plan review project. In the context of Addis Ababa, the local stakeholders contributed to defining:

1. The factors that influence the transformation of land into settlements.
2. The settlement densities to be used for each scenario.
3. The excluded areas that are not likely to transform into settlements within the modelling period.
4. The scoring classes that were used to represent the proximity influencing factors.

Stakeholder participation was through 2 joint workshops, semi-structured interviews, and a training session (Appendix B). The first workshop was conducted with representatives from urban, transport and environmental planning departments of the city's administration. The workshop's objective was to explain USSDM and introduce its possible applications. In this workshop, the input parameters were discussed with different experts. A second workshop took place in the master plan review office with the attendance of the master plan team leaders. The training session was delivered to the city's GIS specialists to enable them to apply the model.

2.4.2. *Modelling scenarios*

Two scenarios were developed to assess the consequences of different urban population densities on land conversion. The first scenario simulates an overall densification strategy (densification scenario (DENS)) and the second represents the business as usual scenario (BAU). BAU assumed the continuation of Addis Ababa's current average settlement population density of 166 inhabitants per ha, while DENS assumed a high settlement population density of 350 inhabitants per ha. The high population density (350 inhabitants/ha) was agreed with the local researchers and planners to be a realistic value for multi-storey settlements as they are currently developed at the fringe of Addis. The scope was to model these two extreme scenarios and not to forecast how the city would look like in the future.

The influencing factors were identified based on previous urban growth modelling studies (Linard et al., 2013; Barredo et al., 2003) and local experts input through interviews and workshops. Table 1 shows the specific parameters for applying USSDM to the case of Addis Ababa. The input datasets were acquired from the EIABC and Addis Ababa urban planning institute.

Table 2 shows the estimated future land demand for Addis Ababa.

2.4.3. *Analysis of USSDM output*

In the green infrastructure analysis (GI), output of USSDM in both scenarios was used to quantify the losses of the farmland and other vegetated UMT's that would be expected to take place (Fig. 1). It was also used to identify future settlements that might be located in flood-prone areas. Flood-prone areas used in this research were delineated by the study of Jalayer et al. (2014) using the topographic wetness index

Table 2
Future land demand calculation.

Year	Projected population (UNDESA, 2011)	Population increment	Required Settlement Cells	
			BAU (166 inh./ha)	DENS (350 inh./ha)
2011	3,041,002			
2015	3,343,730	302,728	7277	3459
2020	3,946,425	602,694	14,487	6887
2025	4,766,903	820,478	19,723	9376

(TWI) in order to perform an analysis of urban flooding risk hotspots in Addis Ababa.

3. Results

3.1. Settlement development in the period 2011–2025

3.1.1. Scenario 1: BAU

In the BAU scenario, a total area of 10,371 ha would be transformed into settlement area by 2025. This expansion would lead to a total settlement area of 28,644 ha which represents 55% of Addis Ababa's administrative area (Fig. 3(a)). Settlement clusters would develop both in the eastern and southwestern parts of the city, namely in Bole sub-city, Yeka sub-city (east), Niffas Silk Lafto and Akaki Kality sub-cities (south-western). This is because these areas are characterised by having a low slope, major roads and their proximity to central markets and neighbouring settlements as shown in the influencing factors maps (Fig. 2). Most of these settlement clusters would develop in the eastern parts of the city where farmland (mainly field crops) is currently located. The south-eastern corner would show a lower settlement development despite being in a low slope area due to its location away from the road network, central markets and other settlement areas. Settlement activity would be very limited in the north mainly due to the steep slopes in this area, which act as a natural barrier to settlement development.

3.1.2. Scenario 2: DENS

In the DENS scenario, 4930 ha would be transformed to settlement area by 2025. This expansion would lead to a total settlement area of 23,203 ha which represents 45% of Addis Ababa's administrative area (Fig. 3(b)).

The spatial pattern of urban growth would be nearly the same in scenario 2 while in scenario 1, however, the settlement clusters in the eastern would remain much smaller and the settlement development in the south-western part would be negligible. This shows that the eastern sub-cities (Bole and Yeka) are the coming hubs for built-up area development in Addis Ababa. Compared to the BAU scenario, the majority of the modelled settlement area are located closer to the existing built-up area. Generally, Addis Ababa would witness much less spatial growth when compared to the BAU scenario whereby an area of 5441 ha would be saved from being transformed into settlement area.

3.2. Green infrastructure losses

3.2.1. BAU

From 2011 to 2025, in the BAU scenario, 39.9% of the farmland (field crops and vegetables) is estimated to be lost and 25.8% of the

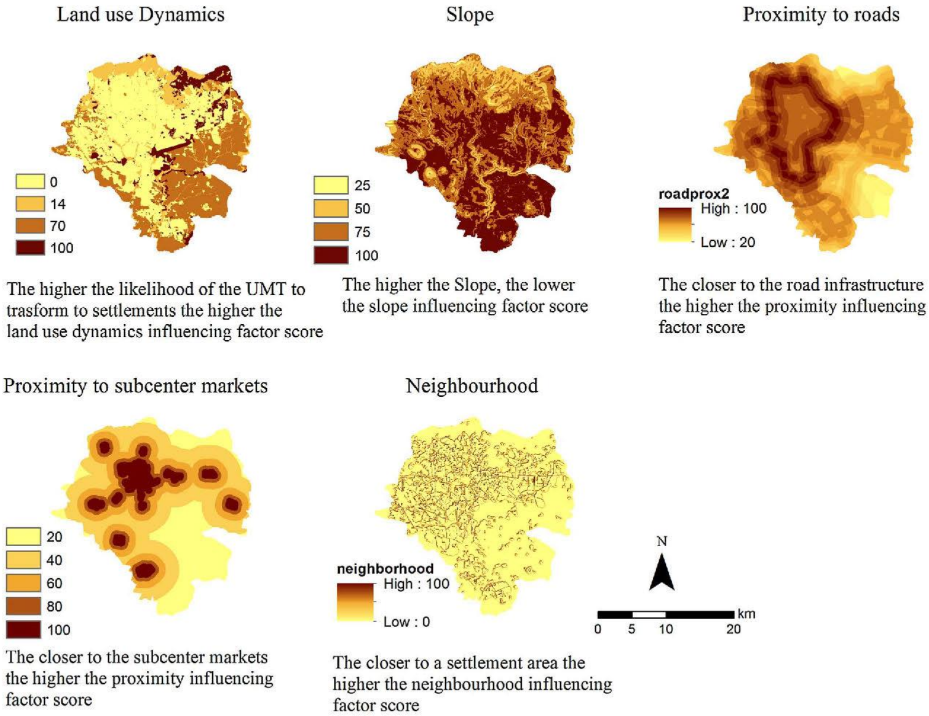

Fig. 2. USSDM Influencing factors for Addis Ababa (Data Source: EiABC and urban planning institute).

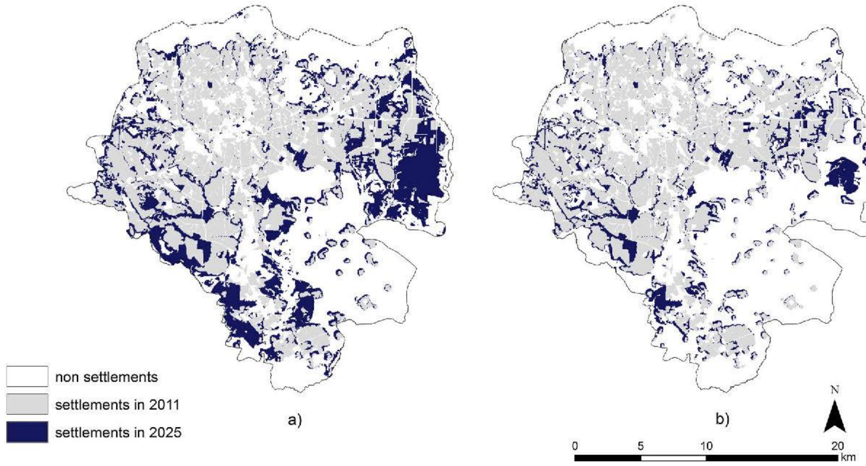

Fig. 3. Settlement development USSDM output 2011–2025 for a) BAU and b) DENS.

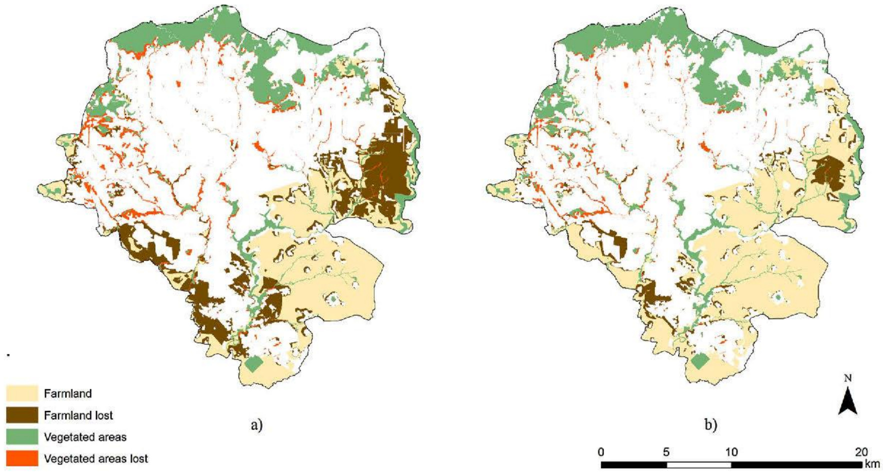

Fig. 4. Farmland and other vegetated area loss in a) BAU and b) DENS.

combined area of other vegetated areas. During this period, the proportion of the farmland within the administrative area of Addis Ababa would decrease from 28.8% in 2011 to 17.2% in 2025, while the proportion of other vegetated areas would decrease from 14.5% in 2011 to 10.7% in 2025. Detailed losses of farmland and other vegetated areas are shown in Table 2 and their spatial distribution in Fig. 4(a).

3.2.2. DENS

From 2011 to 2025, in the DENS scenario, 14.7% of the farmland is estimated to be lost and 15.7% of the other vegetated areas. During this period, the proportion of the farmland within Addis Ababa's administrative area would decrease from 28.8% to 24.5%, while the proportion of other vegetated areas would decrease from 14.5% to 12.2%. Detailed losses of farmland and other vegetated areas are shown in Table 2 and their spatial distribution in Fig. 4(b).

Table 3 shows the losses of different types of farmland and other vegetated areas in both scenarios, field crops would suffer the largest

Table 3
Farmland and other vegetated area loss in BAU and DENS.

UMT	Business as usual (BAU)		Densification (DENS)	
	Losses in 2025 (ha)	Losses relative to 2011 area (%)	Losses in 2025 (ha)	Losses relative to 2011 area (%)
Field crops	5817	40	2127	14
Vegetable farm	146	42	73	21
Total Agriculture UMT's	5963	39.9%	2200	14.7%
Plantation	231	7	76	2.2
mixed forest	509	31	240	15
Riverine	570	34	389	23
Grassland	632	76	478	58
Total other vegetated areas UMT's	1942	25.8%	1183	15.7%

losses in both BAU and DENS.

While losses of farmland will be inevitable due to urban expansion, the amount of such losses would differ dramatically depending on the density of urban development. Controlling urban sprawl by densification as suggested in the DENS scenario would almost halve the losses of farmland and other vegetated areas when compared to the BAU scenario. Moreover, the settlement development in the DENS scenario would be located closer to the vicinity of the built-up area rather than spreading along the eastern part of the city, which is currently occupied by farmland in the case of BAU.

Field crops (such as cereals, pulses and oilseeds) would be converted the most to settlements in both scenarios (losses of 40% in the BAU and 14% in DENS compared to the area in 2011). Vegetable farms would also suffer large losses due to expanding settlements in particular in the flood plain areas. Again, these losses would be much smaller under the high-density scenario where "only" 21% of its surface area would be built over in comparison to 42% under the BAU scenario.

3.3. Settlement development in flood-prone areas

In 2011, there were 882 ha of existing settlements located in high flood risk areas (Fig. 5 (b)). In the BAU scenario, additional settlement area that is located in flood-prone areas (990 ha) would more than double from 2011 to 2025 (+882 ha). In the DENS scenario, the settlement area located in flood-prone areas would increase by only 574 ha (42% less than in the BAU scenario). According to the estimated density, there would be a larger number of people exposed to floods in DENS (200,900 inhabitants) as compared to BAU (164,340 inhabitants).

4. Discussion and conclusions

4.1. Potential of USSDM to support urban planning

The application of USSDM in Addis Ababa showed that it could be applied by urban planners and other users (non-modelling experts) due to the relative simplicity of the model's structure, its transparency concerning underlying assumptions and operations, and the possibility to run the simulations in a workshop environment.

Data requirements regarding influencing factors in the model are not too demanding as multi-temporal remotely sensed data for assessment of land use dynamics should be mostly available. Involvement of local experts is important though to confirm the factors that influence the growth of settlements. As highlighted by Reed (2008), the quality of decisions made through participatory planning is highly dependent on the process put in place for stakeholder participation. Workshop attendees in Addis Ababa appreciated the model and agreed on its capability in modelling urban growth and evaluating the consequences of this growth on the structural changes of the city. The involvement of experts from different planning domains (urban, transport and environmental planners) allowed integrating both local and scientific knowledge that is recommended for the success of participatory planning (Reed, 2008). The outputs from the different scenarios incited lively debates about the different patterns of development. Stakeholders started identifying together possible measures that can help control and direct the future growth of the city and minimise the impact on green infrastructure and its ecosystem services. The use of USSDM during the process of the master plan review also highlighted its potential in enhancing the communication process between scientists, planners, policy makers and the public, providing new possibilities for participatory planning and decision making. The information generated in this study had not been available to urban planners and other stakeholders in Addis Ababa before.

4.2. High-density vs. low-density urban growth

Results showed the vast difference in terms of urban expansion depending on the population density strategy adopted. Under low-density development, the city of Addis Ababa would continue to sprawl while adopting a higher density for new settlements contributes to forming a more compact city. In addition to the densification of a city through urban regeneration of areas that are already settled, promoting dense settlement expansion leads to the overall densification of the city. Using densification as a measure for achieving sustainable development of cities in both the developed and the developing world has been debated in the literature (Jenks, Burton, & Williams, 1996). Other work such as Neuman (2005) questions the use of urban form as an indicator of sustainable planning, maintaining that compactness of a city is neither a necessary nor a sufficient condition for a city to be sustainable and that the attempt to make cities more sustainable only by using

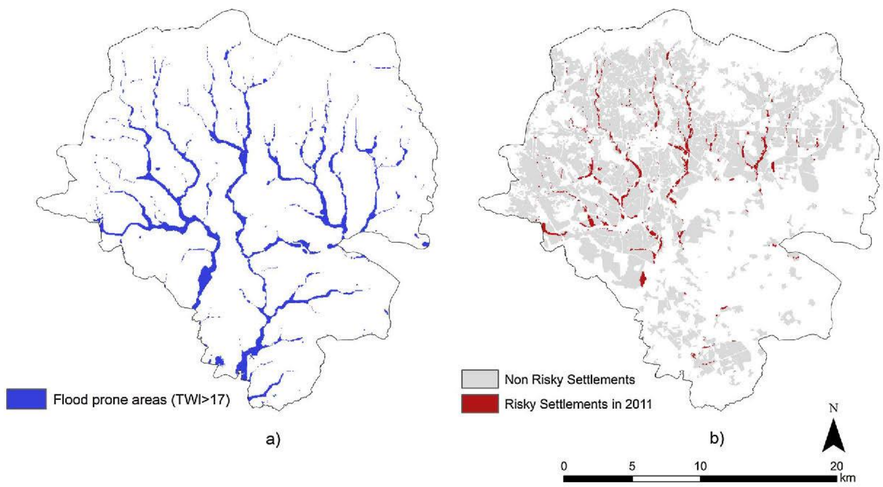

Fig. 5. a) Flood-prone areas in Addis Ababa, b) Settlement UMT located in flood-prone areas in 2011.

urban form strategies might be counterproductive. Moreover, densification may have a negative impact leading to reduction of open spaces inside the built-up area, increase pollution and loss of urban quality (Haaland & van den Bosch, 2015).

Findings of this study suggest that the adoption of high-density development would particularly help to preserve GI from being lost to settlements and on the vulnerability of the population to flooding if prohibiting settlement development in flood-prone areas is enforced.

4.2.1. *Losses of green infrastructure*

Loss of almost 40% of field cropland and vegetable farms in the BAU scenario would affect the food supply of the agricultural households in Addis Ababa which was estimated to be 148,575 inhabitants in 2003 (CSA, 2002b). This loss would, in turn, endanger their food security and abandon an income generating activity that contributes to their livelihood. According to Egziabher (1994), urban agriculture in Addis Ababa acts as a survival strategy for the low-income urban population and helps to create full-time and part-time employment opportunities. In Addis Ababa, the inhabitants adjust the types of staple crops (wheat, sorghum and maize) they use and rely on other crops (green maize, potato and cabbage) as coping mechanisms against poverty and food shortages (Tolossa, 2010). Research elsewhere showed that urban agriculture can play an important role in helping the poor to survive in times of economic crisis (Mlozi, 1996; Pribadi & Pauleit, 2015). By contrast, losses would only be 15% in the high-density scenario.

Another issue is the displacement of farmers in the city. Agricultural communities on the periphery of the city are moved and compensated for their land as the government retains the right to take land for public use with payment of compensation to the displaced people as per Proclamation 455/2005 (Federal Negarit Gazeta, 2005). Farmers – who only possess farming skills – are then expected to invest the relatively small amount of compensation into new livelihoods and homes. In addition to the decrease of supply of freshly produced crops, causing prices and food insecurity to increase, this process might lead to an increase in the unemployed population who are at stake of being homeless (Gittleman, 2009).

Urban agriculture has a major role in rapidly expanding city regions in sub-Saharan Africa in providing inhabitants with food and sources of livelihood (Egziabher et al., 1994; FAO, 2012; Nyapendi, Best, Ferris, & Jagwe, 2010). While the government is making marked efforts to accommodate the rapidly growing population in a denser and more functional urban form, the preservation of farmland at the urban fringe has not been considered a priority yet.

4.2.2. *Flood vulnerability*

Implementing high-density urban development would help in reducing losses of vegetated areas due to a smaller overall land demand for new settlements in flood-prone areas. Increasing urban density would also reduce the expansion of settlements into flood-prone areas. However, in a high population density scenario, more people would be exposed to the risk of flooding. Therefore, densification has to go in hand with a strict enforcement of settlement prohibition in flood-prone areas along with the development of green and open space development in these areas. At the same time, strategies should be developed to relocate the population already living in these flood-prone areas in socially acceptable ways. Learning from other surrounding African countries where resettlement has taken place (Mozambique and South Africa), resettlements should be done to new surroundings where natural, economic and social resources that provide opportunities for income diversification are available. This would avoid resettlers from returning to their original location (Arnall, Thomas, Twyman, & Liverman, 2013).

4.3. *USSDM in other cities*

Comparing the application of USSDM in the case studies of Addis Ababa and Dar es Salaam (Printz et al., 2015) demonstrates the capability of USSDM to be used in different cities in developing countries. USSDM has been applied for cities of different population sizes however the higher the city growth rate the better the USSDM grasps the general patterns of growth and lower the error factors within the model output. As shown in this paper, USSDM can incorporate natural barriers to urban growth as nature-based influencing factors (e.g. slope in the case of Addis Ababa). USSDM was successful in simulating the growth in both cities, however one may be inclined to conclude that USSDM's output better grasps the growth in cities that employ large-scale housing projects (Addis Ababa) as an urban growth strategy due to the nearly constant density across the city that USSDM assumes. Therefore, USSDM's application for the case of Addis Ababa only focused on modelling the expansion of newly developed settlement areas on non-built-up areas within the periphery zone of the city or in inner city areas and did not consider infill densification of existing settlement areas as in the case of the Dar es Salaam study. Both cities were in the process of revising their master plans, however Addis Ababa had a strong involvement of local planners and experts – who have shown a high degree of interest and ownership of the model- in contrast to the case of Dar es Salaam where the planning was mainly outsourced to foreign consultants (Herslund et al., 2015; Hossain, Scholz, & Baumgart, 2015). The high level of engagement from local planners in the USSDM application for a city would ensure that the input parameters are more accurate and the quality of results would be higher.

4.4. *Scope for further development*

A limitation of USSDM is that only settlement vs non-settlement land uses are modelled and that different population densities of newly developed areas were not considered. In addition, other factors that influence urban growth and transformation into settlement areas could be further added to the model, such as land-use zoning and major infrastructure projects. Equal weights were given to all influencing factors. In a further step, different weights should be defined for the influencing factors based on a calibration of the historical growth.

USSDM can be coupled to environmental models so that impact of different spatial scenarios on the provision of ecosystem services can be assessed. Further investigation is needed to analyse the value of available land for urban agriculture in terms of food provisioning and not only in terms of area losses using spatial indicators and land evaluation datasets. Since the growth of cities spills over its administrative boundary, is necessary to analyse the settlement growth beyond the city's limits. Adopting a regional perspective of large African cities would support a more sustainable urban growth in the region.

4.5. *Concluding remark*

The increase of urban density and the integration of green infrastructure in urban areas are crucial to further the resilience of expanding cities. High-density settlement expansion needs to be coupled with the promotion of urban agriculture and green spaces as major elements of the green infrastructure. Protection of the most productive farmland and the strict enforcement of settlement development prohibition in flood-prone areas should be a priority for city planners and officials.

Further work on a systematic integration of stakeholders' input into tailoring city-specific modelling scenarios that feed into an integrated approach of sub-Saharan African city planning is needed.

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Appendix A. Urban Morphology types for Addis Ababa

1. AGRICULTURE
   1.1 Field crops
   1.2 Vegetable Farm
2. VEGETATION
   2.1 Plantation
   2.2 Mixed forest
   2.3 Riverine
   2.4 Grassland
3. MINERALS
   3.1 Mineral workings and quarries
4. RECREATION
   4.1 Parks
   4.2 Stadium and festival sites
5. TRANSPORT
   5.1 Major road corridors (> =15 m width)
   5.2 Bus terminals
   5.3 Rail way
   5.4 Train station
   5.5 Airports
6. UTILITITES AND INFRASTRUCTURE
   6.1 Energy distribution
   6.2 Water treatment
   6.3 Refuse disposal, including landfill
   6.4 Cemeteries
7. RESIDENTIAL
   7.1 Condominium & multi-storey
   7.2 Villa & single storey stone/concrete
   7.3 Mud/wood construction
   7.4 Mixed
8. COMMUNITY SERVICES
   8.1 Education
   8.2 Medical
   8.3 Religion
9. RETAIL
   9.1 Formal shopping area
   9.2 Open markets
   9.3 Mixed formal and open
10. INDUSTRY & BUSINESS
    10.1 Manufacturing
    10.2 Offices
    10.3 Palace
    10.4 Hotel
    10.5 Storage and distribution
    10.6 Garages
    10.7 Mixed
11. BARE LAND

Source: Cavan et al. (2012).

Appendix B. Questions to stakeholders in workshops and interviews

1. Please select out of the following factors, the ones that (in your opinion) influence the transformation of land into settlements/of the urban area.
   a. Centrality (proximity to subcenter markets)
   b. Electricity (proximity to electrical grid)
   c. Infrastructure project (proximity to infrastructure (e.g. LRT))
   d. Land use zoning (designated as mixed residential zone in the masterplan)
   e. Neighbourhood (proximity to existing settlement areas)
   f. Road proximity (proximity to asphalt road network)
   g. Slope (steepness of the slope)
   h. Water network (proximity to the water network)
2. Please make an estimate of the settlement densities of the following settlement types:
   a. Condominium and multi-storey
   b. Villa and single storey
3. Please select in your opinion the areas that are NOT expected to transform into settlements in the coming 15 years.

1. AGRICULTURE
   1.1 Field crops
   1.2 Vegetable Farm
2. VEGETATION
   2.1 Plantation
   2.2 Mixed forest
   2.3 Riverine
   2.4 Grassland
3. MINERALS
   3.1 Mineral workings and quarries
4. RECREATION
   4.1 Parks
   4.2 Stadium and festival sites
5. TRANSPORT
   5.1 Major road corridors (> =15 m width)
   5.2 Bus terminals
   5.3 Rail way
   5.4 Train station
   5.5 Airports
6. UTILITITES AND INFRASTRUCTURE
   6.4 Cemeteries
7. RESIDENTIAL
   7.1 Condominium & multi-storey
   7.2 Villa & single storey stone/concrete
   7.3 Mud/wood construction
   7.4 Mixed
8. COMMUNITY SERVICES
   8.1 Education
   8.2 Medical
   8.3 Religion
9. RETAIL
   9.1 Formal shopping area
   9.2 Open markets
   9.3 Mixed formal and open
10. INDUSTRY & BUSINESS
    10.1 Manufacturing
    10.2 Offices
    10.3 Palace
    10.4 Hotel
    10.5 Storage and distribution

6.1 Energy distribution	10.6 Garages
6.2 Water treatment	10.7 Mixed
6.3 Refuse disposal, including landfill	11. BARE LAND

4. Please select from the following UMT's the most likely UMT's that would transform to settlements in the coming 15 years

UMT
1. AGRICULTURE
1.1 Field crops
1.2 Vegetable Farm
2. VEGETATION
2.1 Plantation
2.2 Mixed forest
2.3 Riverine
2.4 Grassland
11. BARE LAND

5. Please identify the distances that are best described by the following criteria

Criteria	Distance [m]
Direct proximity	?? m–?? m
Easily walkable distance	?? m–?? m
Distant areas however still accessible	?? m–?? m
Motorized means of transport is needed	?? m–?? m
Considered as a remote location	> ?? m

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Appendix B: Paper 2 (published)

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Exploring the future of rural–urban connections in sub-Saharan Africa: modelling urban expansion and its impact on food production in the Addis Ababa region

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ABSTRACT
The built-up area of Addis Ababa and its surrounding towns is expanding into the peri-urban region leading to high losses of farmland, directly influencing the food production for the urban population. This paper investigates the patterns of settlement growth in the region surrounding Addis Ababa and their impact on peri-urban agriculture using an urban spatial scenario design model. The effects of two population density scenarios are explored within the framework of a proposed master plan. The model output was used to estimate areas of different suitability levels that would be lost to the modelled settlement expansion. The settlement area in 2038 would represent 29% of the case study's total area in the low-density scenario but only 19% in the high-density scenario. Compared to the low-density scenario, the high-density scenario would only require a third of the agricultural land transformed into settlement areas. Settlement development would contribute to higher losses of land suitable for cultivating important export products, high nutritional value and import-substituting products. The scenario approach can support sustainable regional planning for settlement expansion that conserves valuable farmland in the peri-urban area and contributes to building capacity for strategic planning of the city regions of sub-Saharan Africa.

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Introduction

In 2040, the number of urban dwellers in east Africa, the world's least urbanized (urban dwellers: 23.3% of the population) is expected to be five times that of 2010 (UNDESA, 2014; UN-Habitat, 2014). Africa is thus the world's second fastest urbanizing region with an average annual rate of change of urban population for 2010–2020 of 4.13% (UN-Habitat, 2014). Urbanization in developing countries has been identified as the main driver affecting agricultural land conversion (Azadi, Ho, & Hasfiati, 2011; Dadi et al., 2016). Urban growth can have negative impact on the peri-urban areas where land use change is highly dynamic (Yankson & Gough, 1999). Among the negative consequences on the peri-urban areas are threats to biodiversity by habitat loss and fragmentation, loss and degradation of soils, decline of water quality (Foley et al., 2005) air pollution and traffic congestion (Simon, 2008). The loss of farmland and consequently a declining provision of ecosystem services such as the supply of food and timber (Metzger, Rounsevell, Acosta-Michlik, Leemans, & Schröter, 2006 is strongly related to urban form, which can range from compact to "sprawl" that is dependent on the population density in urban areas (Tsai, 2005).

Farmland in urban and peri-urban areas of African cities plays an important role in the food supply of the urban population and as income generating and entrepreneurial activities that support the urban population in a mostly informal economy (FAO, 2012; Smit, Nasr, & Ratta, 2001). Urban poor rely on the food production of urban and peri-urban agriculture as a response to inadequate and irregular access to food and lack of purchasing power as the costs of supplying and distributing food from rural areas to the urban areas, or to import food for the cities, are continuously rising (AAOIDP, 2013; Tolossa, 2010). In the context of developing countries, agriculture in peri-urban areas can thus reduce vulnerabilities of their regional food systems both for local consumption and for export (Pribadi & Pauleit, 2015; UN-Habitat, 2016).

Several studies have analysed the historical urban growth and its impact on agricultural land (Dutta, 2012; Kurucu & Chiristina, 2007; Pandey & Seto, 2015; Pribadi & Pauleit, 2015; Zhou & Wang, 2011). The current and historical trends suggest an increase in the conversion of agricultural land in the future (Pandey & Seto, 2015).

According to Friedman (2004, p. 56), strategic planning "is a way of probing the future in order to make more intelligent and informed decisions in the present". Hence,

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there is a need to provide strategic knowledge and tools for urban planning which encompasses detailed spatial information on how projected population growth rates translate into spatial patterns of expanding settlement areas in the future of a city along with the distribution of food provisioning . Moreover, it is important to know how food provisioning will decline due to loss of green areas, particularly farmland (Printz, Abo-El-Wafa, Buchta, & Pauleit, 2015).

Increasing the capacity for planned urban development is of high importance to reduce the negative impact of urban expansion and ensure a viable agriculture in the peri-urban areas (Printz et al., 2015). Monitoring and anticipating regional growth of emerging cities in Africa is a critical factor to enhancing planning capacity at the regional scale. However, this type of analysis requires spatial information that enables forecasting future urban expansion patterns (Weber & Puissant, 2003).

In spite of the limited availability of spatial data, work has been done on geospatial modelling to quantify, describe and map future urban growth and expansion in developing countries (Al-shalabi, Billa, Pradhan, Mansor, & Al-Sharif, 2012; Cheng & Masser, 2003; Herold, Goldstein, & Clarke, 2003; Weber & Puissant, 2003), as well as African cities (Linard, Tatem, & Gilbert, 2013), such as for Yaoundé, Cameroon (Sietchiping, 2004), Lagos, Nigeria (Barredo, Demicheli, Lavalle, Kasanko, & McCormick, 2004) and Dar es Salaam, Tanzania (Abeba, 2011; Hill & Lindner, 2010).

In order for these models to be easily integrated into urban planning processes, they need to be transparent and flexible, enabling users to quickly change different factors and adapt the model to the needs of planners and other stakeholders. Moreover, models should be able to incorporate updates whenever new information and data become available (Abo-El-Wafa, Yeshitela, & Pauleit, 2017).

However, very few studies combine the use of urban growth models with a detailed analysis of the impact on the agricultural land located in peri-urban areas. (Dutta, 2012; Yankson & Gough, 1999). This detailed analysis should go further than calculating the total losses in agricultural land due to settlement development towards understanding the value and quality of the land that would be lost along with the land's varying potential for growing specific crops and providing food for the inhabitants of urban regions (Pauleit et al., 2013), whereas maintaining the capacity of the highly productive land for agriculture is important for urban food security, especially in vulnerable regions, where the local population are depending on its produce (Fraser, Mabee, & Figge, 2005).

Land suitability evaluation is a well-established approach to assess the potential of land for the crop production (Bandyopadhyay, Jaiswal, Hegde, & Jayaraman, 2009). Applying this approach produces maps that show the suitability of each land-mapping unit for each crop type based on a standardized land suitability classification (FAO, 1976). Such information can provide a valuable input into land use planning (OWWDSE, 2011). Nevertheless, land suitability approach has not been applied to the assessment of future impact from urbanization in an African context.

The objectives of this paper are to (1) investigate potential future settlement growth patterns in the peri-urban interface of Addis Ababa using a spatial scenario modelling approach, (2) analyse the potential impact of settlement development on suitable farmland and it's utility to provide food to urban inhabitants and (3) provide policy and land use planning recommendations to support a more sustainable planning of the peri-urban area surrounding large cities in the process of urbanization.

Material and methods

Research area

The research area includes the neighbouring towns of Sululta, Burayu-Menagesha, Sebeta, Dukem-Gelan and Legetafo and their rural surroundings (Figure 1), which represents Addis Ababa's peri-urban area. It covers a total area of 755 km^2, almost 1.5 times the size of Addis Ababa (520 km^2) with a population of 202,980 inhabitants in 2013, whereas population of Addis Ababa was 3.5 Mio. (AAOIDP, 2013). It corresponds to the area covered by the structural plan of the 2012 Addis Ababa and the Surrounding Oromia Integrated Development Plan (AAOIDP). The city of Addis Ababa was not included in this study as the focus of this research was on the peri-urban region surrounding the city, not the city itself. In addition, the surrounding towns belong to a different administrative region (Oromia region) that acts as an independent planning body.

Addis Ababa, the capital of Ethiopia, has been chosen because it is one of the few cities whose initially proposed master plan had a regional focus, with the geographic coverage extending into the peri-urban area (The plan was cancelled in 2016 due to political reasons). In addition, it gives considerable attention to the environment within the urban planning framework (UN-Habitat, 2008; Wubneh, 2013). The city is developing large urban extensions in a multi-storey condominium style (Wubneh, 2013). This is extraordinary for sub-Saharan cities where more than 60% of urban development is informal and sprawling at low densities (UN-Habitat, 2015). Not only is Addis Ababa expanding at a rapid pace (approximately 4% p.a.), but growth is also taking place along the major outlets of the city into the surrounding region (Kassa, 2013). This growth is expected to translate into an expansion of settlements

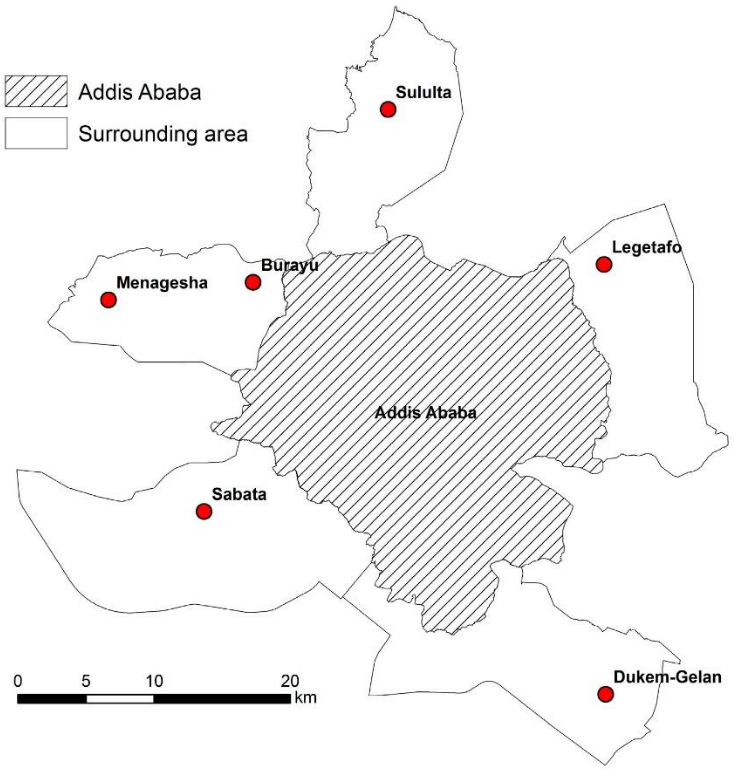

Figure 1. Research area: Addis Ababa surrounding region (Data source: AAOIDP, 2013).

in the city and into the surrounding areas. Consequently, farmland is expected to decline in the city's surrounding area as a result of urbanization and industrial development (AAOIDP, 2013).

In a previous study, a spatial scenario modelling approach was applied for the case of Addis Ababa (Abo-El-Wafa et al., 2017). A limitation of this study was that it was confined to the administrative boundaries of the city, whereas the growth expands into the adjacent municipalities. Therefore, the need to adopt a regional perspective to support a more sustainable urban growth in the region has emerged. According to the AAOIDP (2013), the population of the research area was projected to reach 1.1 Mio. in 2023 and 1.7 Mio. in 2038 (Table 1).

Agriculture is almost the sole means of livelihood in the zone's rural area where around 97% of the rural households practice agriculture as a primary or secondary source of income. The inhabitants of Addis Ababa depend on its surrounding area for various essential resources such as drinking water, fuelwood supply, construction materials and agricultural products (AAOIDP, 2013).

Table 1. Projected population growth in research area.

Towns	2013	2023	2038
Burayu-Menagesha	89,057	176,031	400,000
Sebeta	79,722	299,722	400,000
Sululta	10,563	58,563	100,000
Dukem-Gelan	14,401	264,401	400,000
Legetafo	9,237	259,237	400,000

Data source: AAOIDP, 2013.

Input data

Data for this study were acquired from the two main sources: "Finfinne (Addis Ababa) surrounding special zone of Oromia integrated land-use planning study project" (OWWDSE, 2011) and "Addis Ababa and the Surrounding

Table 2. USSDM's input data-sets and sources.

Data	Description	Use in study	Source
Land use	Land use data of the year 2013	Settlements in 2013 Farmland in 2013	(AAOIDP, 2013)
Facilities and services	Location of municipal facilities including schools, hospitals and markets	Proximity to facilities Influencing factor	(OWWDSE, 2011)
Historical built-up area	Historical built-up area datasets for the years 2008 and 2013 in the whole area	Change detection Analysis	(OWWDSE, 2011)
Road network	Road network 2013 Data-set	Proximity to roads influencing factor	(AAOIDP, 2013)
Elevation	20 m interval contour	Slope influencing factor	(AAOIDP, 2013)
Crop suitability maps	Suitability maps for 30 agricultural crops according to a set of biophysical variables including soil characteristics, altitude and climate	Agricultural suitability analysis	(OWWDSE, 2011)

Oromia Integrated Development Plan" (AAOIDP, 2013). Table 2 lists the input data-sets that were used in this study.

Urban spatial scenario design modelling

General information

The study used a spatial scenario modelling approach called USSDM (Urban Spatial Scenario Design Model). The model had already been applied to previous analysis of urban growth patterns in Addis Ababa (Abo-El-Wafa et al., 2017) and Dar es Salaam, Tanzania (Printz et al., 2015). It is a raster-based model developed in ArcGIS 10.3.3 model-builder, where the research area of 755 km^2 is represented by 1,887,500 raster cells of 20 m by 20 m in size. The temporal scope of the model was set to the period between 2013 and 2038, defined based on the available projected population data. The modelling starts by summing the weighted influencing factors to produce a "transformability index". USSDM then excludes all cells that are not expected to transform to settlements (defined by the user) within the model's temporal scope. The remaining cells are then ranked based on the transformability index. A specific number of cells corresponds to the future land demand transform to settlements. The final output is a raster file that indicates the modelled settlement area during the model's temporal scope. For a full description of USSDM, see Printz et al. (2015).

Influencing factors

In the USSDM application for the research area, the factors that influence the spatial distribution of urban growth were defined based on previous urban dynamics studies (Barredo et al., 2004; Linard et al., 2013) and local experts' input. The local experts included researchers from the Ethiopian institute of Architecture, Building Construction and City Development (EIABC), city officials, urban planners and team members of the Addis Ababa and surrounding Oromia Integrated Development Plan project. Their input was taken during the stakeholders' workshops occurring intermittently during the period of 2012–2014 and through interviews. In addition to defining the influencing factors, the experts have helped in setting the criteria for the crops selected in stage 2 of the agricultural suitability analysis.

The final list of influencing factors used in this study were slope, proximity to the road network, proximity to municipal facilities (schools, hospitals and markets) and neighbourhood (i.e. whether adjacent areas were already settled). Influencing factors were weighted through a logistic regression method using R software. The dependent variable is binary (whether the land use changed from 2008 to 2013). The binary map is an output of a change detection analysis that was performed for the research area between the years 2008 and 2013. The influencing factors are the independent variables. The function z is calculated as follows:

$$z = I - Ws \times \text{SLOPE} - Wr \times \text{ROAD} + Wc \times \text{CENTRA} + Wn \times \text{NEIGH} \quad (1)$$

where Z: built-up area change from 2008 to 2013; I is intercept; Ws: Weight for SLOPE; SLOPE: Slope influencing factor; Wr: Weight for the ROAD; ROAD: proximity to road influencing factor; Wc: Weight for CENTRA; CENTRA: proximity to facilities influencing factor; Wn: Weight for NEIGH; NEIGH: neighbourhood influencing factor.

Assuming formal urban growth and the successful enforcement of land use zoning, USSDM allowed settlement growth only in the proposed areas within each municipality designated for residential development according to the draft master plan (AAOIDP, 2013).

For this paper, two scenarios were designed in order to compare the consequences of two different settlement density patterns and their influence on the future urban form. The first scenario assumes a high-density scenario (settlement density of 82 housing units/ha) as proposed by the planners of the master plan review project (A. Workeneh, personal communication, November 14, 2014), which works out to a settlement density of 328 inhabitants/ha. The second scenario assumes that the designated areas for residential development would be completely converted to settlements at an average settlement density of 115 inhabitants/ha (corresponding to 29 housing units/ha).

Future land demand for settlements was calculated exogenously to the model based on the planned housing unit development to accommodate the projected population growth (Table 1), whereas the average household size for the peri-urban area in the region is four inhabitants/housing unit (AAOIDP, 2013). Only housing units on open land outside the current built-up area are considered (an estimate of 67% of the total housing units planned) with a housing density of 82 housing units/ha. (AAOIDP, 2013).

As the scope of work was to model growth scenarios showing extreme conditions of population density situations and not to forecast or predict how the city would look like, USSDM output was not validated. Limited data availability would have also made such validation inaccurate.

Finally, the farmland that would be lost due to modelled settlement development was calculated for both scenarios. In the following section, this farmland is analysed quantitatively according to its agricultural suitability.

Agricultural suitability

The crop suitability maps (OWWDSE, 2011) were produced using a method for land evaluation based on a framework proposed by FAO (1976) and existing local studies (OWWDSE, 2011). This method was employed by a group of experienced professionals compiling existing data from various sources (previous land use planning studies, Ethiopian Institute of Agricultural Research, regional research institutes and field experience) during an agronomic assessment. (OWWDSE, 2011).

The level of suitability level classes ranged from highly suitable (S1) to very marginally suitable (S4) to not suitable (N). According to Radcliffe and Bechtold (1989), these classes could be used indicators for the sustained performance of the land that is represented as percentages of the maximum attainable yield (e.g. S1 signifies 80–100% of the maximum attainable yield), while S4 signifies 20–40%. In the first stage of the methodology, these classes were collapsed into 2 classes, not suitable (N) and suitable (S1, S2, S3, S4) producing a binary suitable/non suitable map for each crop. Using area statistics, the USSDM output was overlaid on the binary crop suitability maps for all 30 crops cultivated in the area. This estimates the amount of land of varying agriculture suitability that would be lost due to the modelled settlement expansion. The proportion of modelled settlement development located in suitable farmland is used as an indicator for identifying the crops most vulnerable to be lost due to settlement development.

In the second stage, a list of the highly valued crops was selected for further analysis to estimate the losses at all suitability levels (S1, S2, S3 and S4) due to settlement development. The criteria for selecting these crops were the following:

(1) Crop group they belong to (cereals, vegetables and oil-seeds).
(2) High vulnerability due to modelled settlement development (identified in the first stage).
(3) Relevance to the local population manifested in:
    (a) Importance for local consumption (being a major constituent in the local dietary).
    (b) Role in the economic support for urban farmers.
    (c) High potential for import substitution.

Using area statistics, a land inventory analysis of land suitability to cultivate highly valued crops was performed to identify the land that is susceptible to settlement transformation. The USSDM output was then overlaid on the detailed suitability maps for the highly valued crops cultivated in the area. Similar to the first stage, this estimates the areas of different agriculture suitability that would be lost due to the modelled settlement expansion but at a more detailed level (all suitability levels).

Results

The change detection analysis showed that an area of 2015 ha has been transformed into built-up area in the period between 2008 and 2013. The binary map (Figure 2) has been used as the dependent variable in the logistic regression approach to indicate the weights of the different influencing factors (independent variables).

The result of the logistic regression is presented in Table 3 which shows the weights for all influencing factors for the surrounding towns (all results are significant at $p < 0.01$).

The future land demand is shown in Table 4 for the year 2038.

Settlement development

In 2013, the settlement area was estimated to be 10,170 ha. In scenario 1, a total area of 4199 ha of land would be transformed into settlement area by 2038 (average annual rate of change of 168 ha/year). This expansion would result in a total settlement area of 14,370 ha, which represents 19% of the case study's area. In scenario 2, 11,942 ha would be transformed to settlement area by 2038 (average annual rate of change of 477 ha/year). This expansion would add up to a total settlement area of 22,113 ha which represents 29% of the case study's area. Table 5 shows the settlement development in the research area for scenarios 1 and 2 for the years 2013–2038 and the losses of farmland.

Figure 3 shows the spatial distribution of settlement development and the lost farmland in the research area.

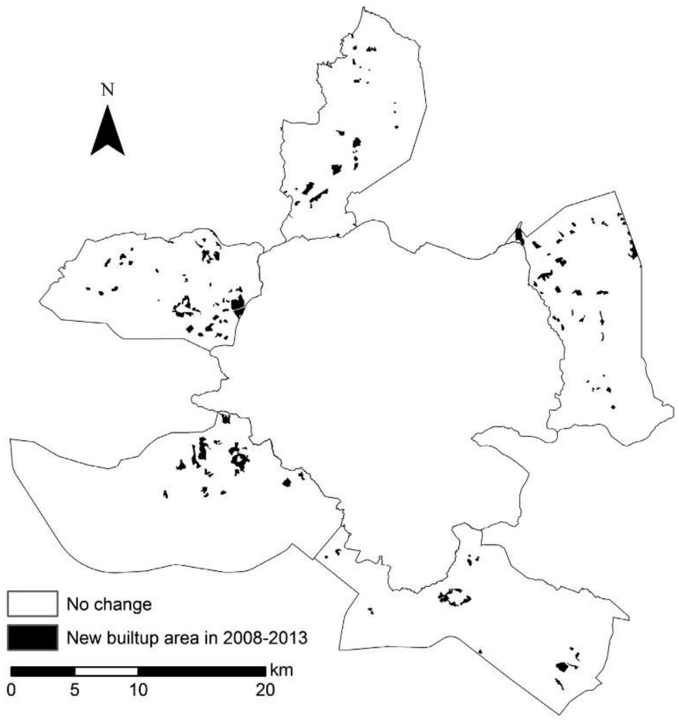

Figure 2. Change detection analysis output: built-up area change (2008–2013) (Data source: AAOIDP, 2013).

Table 3. Influencing factor weights according to the logistic regression analysis.

Parameter	Sululta	Burayu-Menagesha	Dukem-Gelan	Legetafo	Sabata
I	−3.19E+00	−2.36E+00	−2.81E+00	−3.63E+00	−3.66E+00
Ws	3.60E-03	−5.40E-02	−1.42E-01	−3.57E-02	1.73E-02
Wr	−2.36E-03	−2.65E-03	−1.33E-03	−4.93E-04	−3.00E-03
Wc	2.35E-04	3.55E-04	−3.04E-04	3.43E-04	4.32E-04
Wn	1.23E-01	4.47E-02	1.67E-01	1.56E-01	1.04E-01

Table 4. Future land demand for the year 2038 in all towns (scenario 1).

Town	Total housing units	Housing units in open land	Required area [ha]	Number of cells (20*20)
Burayu-Mena	116,504	77,669	947	23,680
Sebeta	115,000	76,667	935	23,374
Sululta	30,735	20,490	250	6,247
Dukem-Gelan	130,013	86,675	1057	26,425
Legetafo	124,314	82,876	1011	25,267

It should be noted that the farmland that would be lost due to the modelled settlement development in scenario 2 is approximately 270% of the farmland lost in scenario 1.

Agricultural suitability

In the low-density scenario, overlaying the USSDM output on the crop suitability maps of all 30 crops revealed that most of the settlement development (an average of 76%) that would occur within the temporal scope of the model would be located in areas that have low or no suitability in terms of crop production. On the other hand, when analysing suitable farmland for cultivating important grain crops (e.g. teff, wheat and barley), it was found that they are the most vulnerable to settlement development as more than 75% of the modelled settlement development would be located on this land in the low-density scenario.

Table 5. Settlement development in the research area for scenarios 1 and 2.

	Scenario 1	Scenario 2
New settlement area in 2013–2038 [ha]	4199	11,942
Settlement area in 2038 [ha]	14,370	22,113
Proportion of settlement area in 2038 [%]	19	29
Average annual rate of change [ha/year]	168	477
Loss of farmland	3230	8750

The list of highly valued crops in the research area (circled in Figure 4), selected for the second stage of the analysis were:

(1) Cabbage, a vegetable, important product for local consumption, which also provides economic support for urban farmers. (Duressa, 2007).

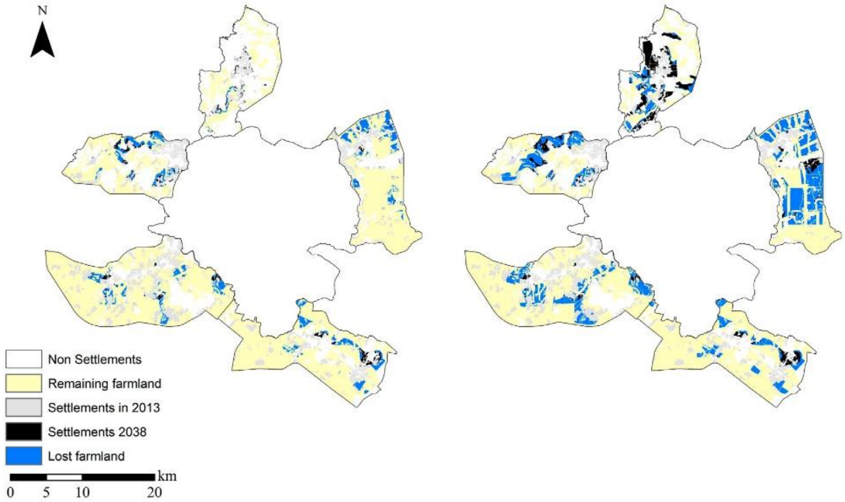

Figure 3. Modelled settlement development in 2038 for (a) scenario 1 and (b) scenario 2 and farmland losses (Data source: AAOIDP, 2013).

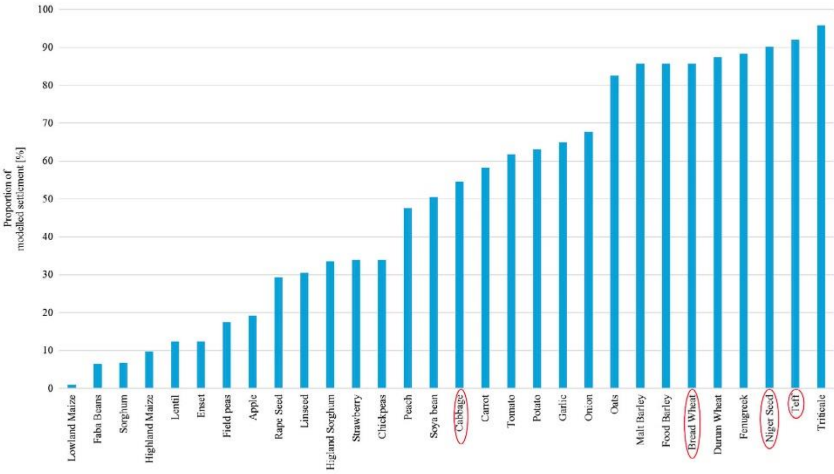

Figure 4. Proportion of the modelled settlement area located in suitable land for cultivating major crops. Highly valued crops are circled.

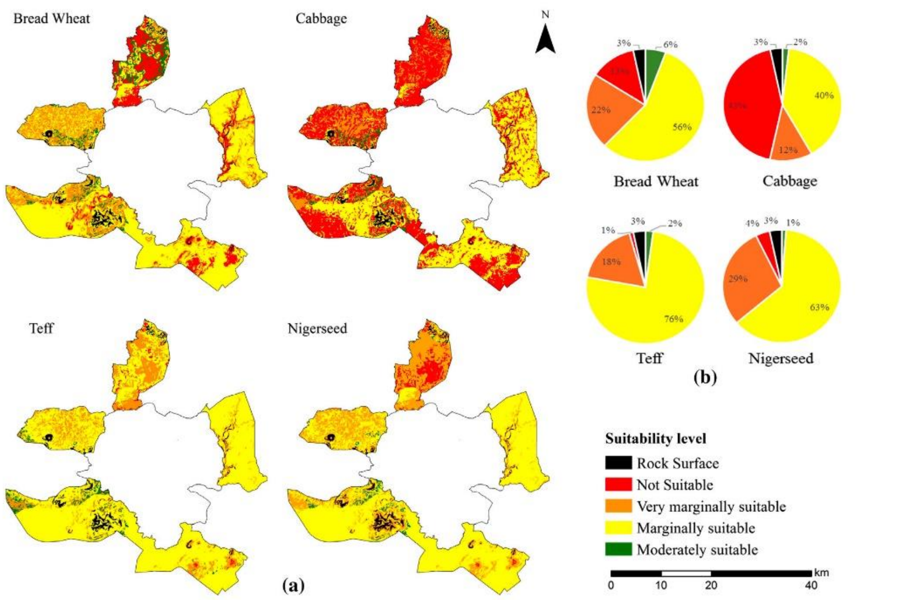

Figure 5. (a) Suitability maps for highly valued crops in the research area, (b) Land inventory analysis in 2013 for highly valued crops. (Data source: OWWDSE, 2011).

Table 6. Losses of land due to settlement development with varying suitability levels.

Scenario	Crop	Moderately suitable Area [ha]	Marginally suitable Area [ha]	Very marginally suitable Area [ha]
Scenario 1	Cabbage	92.1	2085.3	523.3
	Bread wheat	151	2690.1	1079.1
	Teff	28.7	3506.7	650.2
	Niger Seed	48.6	3140.4	963.4
Scenario 2	Cabbage	139.6	5677.6	1637.1
	Bread wheat	859.1	7207.6	2499.2
	Teff	78.6	9773.1	1993.5
	Niger Seed	90.3	7971.0	3381.6

(2) Niger seed, an oil-seed, providing economic support for urban farmers as an export product (FAS, 2016).
(3) Bread wheat, a staple that has high nutritional value and high potential for import substitution (Workman, 2016).
(4) Teff, a staple with high nutritional value mainly for domestic use (FAO, 2008).

Suitability levels for highly valued crops in the research area

According to the land inventory analysis (Figure 5(b)), a high proportion of land in the research area has a marginal suitability (40% in the case of cabbage and 76% in the case of teff), followed by the land of very marginal suitability (12% in the case of cabbage and 29% in the case of niger seed), while the smallest amount of land is moderately suitable (1% in the case of niger seed and 6% in the case of bread wheat). No land had the highest suitability level (highly suitable) for cultivating any of the highly valued crops. (Figure 5(b)).

The land that is moderately suitable for cultivating all four crops is located in the Sabata area (south-west of Addis), Burayu-Menagesha area (north-west) and Sululta area (north). Dukem-Gelan (south-east) and Legetafo (north-east) are comprised primarily by land that is marginally and very marginally suitable for cultivation of all four crops (Figure 5(a)).

Detailed losses due to modelled settlement development

For the four highly valued crops, the losses of the marginally and the very marginally suitable land would have an average increase in scenario 2 of 160% and 200%, respectively, compared to scenario 1 with small variation among the crops (standard deviation of 10% and 50%). Land moderately suitable for cultivating bread wheat and teff has suffered higher losses of 467 and 174%, respectively, compared to scenario 1. This shows the vulnerability of moderately suitable land for cultivating these two cereal crops when compared to cabbage and niger seed that would have a moderate increase of 50% and 80%, respectively (Table 6).

Discussion

The assessment of different urban growth patterns has become increasingly important for understanding the environmental impact of rapid urbanization. This assessment contributes to a more sustainable planning of today's growing cities (Han, Hayashi, Cao, & Imura, 2009). This is particularly the case in Africa's sub-Saharan cities where there is an urgent need to increase the capacity of urban planning to face the challenges of an almost explosive growth that is taking place in urban areas. (Binswanger-Mkhize & McCalla, 2010; Herslund et al., 2015).

In this research, a spatially explicit scenario modelling approach was employed for the assessment of the impact of settlement growth on agricultural land in the peri-urban area of Addis Ababa. Comparing urban population density scenarios, results have shown the difference in terms of settlement growth which depends on the pathway of development that is followed. The scope of work in this study was to model extreme population density scenarios (low and high) that correspond to the proposed urban planning strategies (condominium-based and plot-based strategies) and not to forecast or predict how the city would look like in the future. Although the results show a conservative picture of what is likely to happen, it improves the understanding of the potential impact of applying different settlement density strategies on the peri-urban area's farmland and consequently, on food production.

Urban growth patterns in the peri-urban interface

The change detection analysis indicates that the estimated amount of future land demand of the master plan that was used in scenario 1 is far from what would occur "in reality" if the development would follow a business as usual scenario. However, this measured land use transformation would be closer to the figures used in scenario 2. This shows the importance of planning intervention that should be carried out by the regional administration. According to the logistic regression approach, settlement development probability increased near already settled areas. In the case of road and slope influencing factors, the probability decreased with the increase in the distance to road network or the increase in slope.

Although the available data for the USSDM's calibration within a period of 5 years might be a bit short to model the growth until 2038, it is assumed that the future growth in the region would follow a similar pattern that occurred in this period.

Allowing low-density development for the future growth in the research area (scenario 2), as is currently the case, would lead to urban sprawl, whereas the high-density development (scenario 1) would contribute to developing a more compact form, which is regarded as promoting more sustainable human settlements in both the developed and the developing world (Jenks, 2002). High-density settlements would help to preserve natural resources, maintain food supply by land and increase the potential to service smaller areas with infrastructure. In economic terms, the expansion of the spatial extent of cities into the peri-urban area would raise the costs of fixed infrastructure such as roads, water supply, sewerage and drainage in addition to the higher cost of mobility and reduced access to employment and services. (UN-Habitat, 2016). This finding supports the condominium-based development (scenario 1) that is suggested by the planners of the "Addis Ababa and the Surrounding Oromia Integrated Development Plan". However, high-density settlement development has to go in hand with other strategies that adopt green and open space development in these areas. This is important in order to avoid other negative effects that might arise from high-density settlements such as reduced quality of life, reduced resilience of urban spaces, high rates of pollution and reduction of open space areas. (Haaland & van den Bosch, 2015).

The first stage analysis of USSDM output in the research area has shown that most of the settlement development (in the framework of the proposed master plan) that would occur within the temporal scope of the model would be located in areas of relatively low agricultural productivity that have marginal and very marginal suitability. This might be a contradiction to the common idea that urban growth usually takes place on fertile land that is highly suitable for agriculture (Alphan, 2003; Morello et al., 2000; Satterthwaite, McGranahan, & Tacoli, 2010). However, this is due to the fact that the areas with low suitability dominate the study area. The scarcity of land that is moderately suitable for cultivation gives it an even a higher importance due to its potential to produce with higher productivity (Radcliffe & Bechtold, 1989). The variability of land suitability levels among different towns surrounding Addis Ababa should also be taken into consideration. In this study, it was shown that Dukem-Gelan and Legetafo areas are dominated by land with marginal and very marginal suitability for cultivating the selected crops. Therefore, from the perspective of food provisioning, it would be advisable to direct more settlement development into the towns of Dukem-Gelan and Legetafo since Sabata, Sululta and Burayu-Menagesha areas contain valuable land for agriculture.

Potential impacts of master planning on peri-urban farmland and its food provisioning service

While losses of farmland will be unavoidable due to the increasing population growth and subsequently the expansion of settlement area (Tan, Beckmann, van den Berg, & Qu, 2009), the amount of losses in farmland would differ dramatically depending on the planned density of the settlement development. According to the results, controlling urban sprawl using high-density settlements in scenario 1 would lead to approximately one-third of the losses of farmland when compared to scenario 2 (low settlement density). Although this is only evident within the study's modelling environment and given the underlying assumptions and estimates are correct, this finding helps better understand the magnitude of the potential impact of the two opposing growth patterns. This result also highlights the benefit of developing high-density settlement areas for the regional area of Addis Ababa and for other African cities in terms of saving suitable farmland in peri-urban areas from being lost to settlements.

Information on crop suitability of land allowed the identification of areas where losses of suitable land for each crop are to be expected. Vegetable crops are widely cultivated in the research area due to their location proximity to the big market places mainly to Addis Ababa and other towns in the region (OWWDSE, 2011).

Vegetable crops production is important for both income generation and household consumption. (OWWDSE, 2011). Intensive vegetable production is frequently present in the peri-urban regions as transport costs are relatively lower when compared to rural areas due to the proximity to the city and towns (Smit et al., 2001). In addition, vegetables are important due to their contribution to the local food system. This importance becomes even higher in the cases of high food prices as in the 2007 food price crisis or in the case of rise in oil prices which would increase the value of local food supplies compared to its present value (Bon, Parrot, & Moustier, 2010).

The study area has relatively large suitable areas for the agriculture of cereal crops. However, these areas would suffer the highest losses among all selected crops. Most losses of suitable land would be among bread wheat, teff and barley. This is critical, as cereals, particularly teff and wheat, are the main staples in most parts of the country. Teff, produced for consumption purposes only in Ethiopia and Eritrea (OWWDSE, 2011) is used to make Enjera, the main traditional staple dish (OWWDSE, 2011). Wheat is also considered as an import-substituting product, which is among the top 10 import products of the country, with wheat being on the top of the list (FAOSTAT, 2011).

Finally, losses for land that is suitable for cultivating niger seed would range from 5 to 8% in scenario 1 and 12–20% in scenario 2. Oil crops have high export potential comprising approximately 24% of the total export products of Ethiopia in 2015 (Workman, 2016). Niger seed, as an example, is the second most widely produced oil crop in Ethiopia and accounts for approximately 44% of total oil production (FAS, 2016).

Planning recommendations for peri-urban areas

The findings of this paper support the high-density condominium-based development proposed by the planners of the master plan review project for the satellite towns of Oromia surrounding Addis Ababa. However, the small remaining areas of productive farmland would be lost if the designated areas for future residential use in the proposed master plan were to be implemented. There is a need to review the designated areas for residential development in order to protect productive farmland. The importance of these areas would be their suitability for cultivating specific crops of high value for food security (such as vegetables and cereals) due to them being important components of the local dietary, having high export (oil crops) or import substitution potential (cereals) and contributing to the livelihood of the inhabitants as income-generating activities (vegetables).

Therefore, planning should give more consideration to conserving and supporting farming near urban areas. Special measures should be put in place to protect high suitability farmland from land development. Farmland and farming activities provide important products that enhance the food security of the urban and peri-urban population, especially for the poorest households who are affected by food price shocks (Conceição, Levine, Lipton, & Warren-Rodríguez, 2016), and these activities also act as a source of income for parts of the population (Egziabber, 1994). Despite the lack of recent comprehensive studies to estimate current urban poor engagement in urban and peri-urban agriculture as a source of income, the proportion of those working directly in agriculture production in 2003 accounted for about 45% and those dependent on urban and peri-urban agriculture was still 55% (Gebremichael, 2014). Given the strong population growth and the high amount of poor people depending on the informal economy, it is unlikely that this situation will change any time soon. However, further arguments are needed to better protect and integrate farmland in urban regions. Therefore, its capacity to perform multiple functions that address other urban priorities such as social cohesion, recreation, waste management and flood protection (Mougeot, 2015; Pauleit et al., 2013) needs to be highlighted to support development of multifunctional farming in peri-urban landscapes (Zasada, 2011).

Although this aspect is not covered in the scope of this study, it is worth noting that improving the suitability of low-fertility areas would have a high impact on increasing the food supply since the majority of land has marginal and very marginal suitability for cultivating highly valued crops. An approach would be to revise the tenure agreements and provide more stable arrangements that encourage growers to invest in land improvements and productivity (Place, 2009).

Limitations

USSDM assumed the implementation of urban growth via formal planning and that the settlement development would be strictly limited to the designated areas for settlements in the proposed master plan. The large expansion of settlement area projected to take place in the coming years would be derived mostly by formal planning, large-scale housing projects and industrial development planned in the region. However, it did not consider the informal settlement development, which might be the case in reality as the number of slum dwellers in sub-Saharan Africa, has grown in lockstep with the increase in the region's urban population (UN-Habitat, 2016). Although the regional government is aiming to strictly implement formally planned settlements and pledges to demolish any informal settlements built after a certain year (1995 in the case of Addis Ababa) (Kassahun, 2011), the emergence of informal settlements should be expected (especially in the peripheral areas of the towns). Due to the lack of studies that investigate the formation and characteristics of informal settlements in the region of Addis Ababa, and due to this paper focusing on the master plan, informal settlements were not considered in the model.

Applicability and research outlook

USSDM could be applied in cities in different developing countries that are characterized by high growth rates, high dependence on agricultural land in the peri-urban areas and limited availability of data. USSDM could also play a role in evaluating master plans and land use zoning by estimating the impact of their implementation not only on food provisioning (as applied in this paper) but also on further ecosystem services such as climate regulation or flood control.

Further research should investigate the nature of informal settlements in the region and use the results of this investigation to model both informal and formal settlement growth and assess the impact of this growth on farmland. Furthermore, the economic value of lost farmland could be estimated in terms of monetary values of the agricultural products that would subsequently be lost.

Conclusion

This research examined recent trends in land use transformation taking place in the peri-urban areas of Addis Ababa, applying a spatial scenario modelling approach to support the planning of a more sustainable urban growth. It makes three main contributions to the current literature on agricultural land loss in peri-urban areas:

(1) Present a spatially explicit assessment of potential settlement area expansion in peri-urban areas
(2) Introduce an approach to evaluate the master plans and the designated future residential areas that they propose.
(3) Highlight the impact of settlement growth into peri-urban areas on the valuable agricultural land.

The study outcomes will not only be useful for local politicians in decision-making but also for researchers conducting work in this area, which is still highly understudied. Overall, it is concluded that the USSDM is a tool that can enhance the capacity for planning sustainable growth in this rapidly developing city region. The scenario approach via USSDM provides important information in support of more sustainable regional planning for settlement expansion that conserves valuable farmland in the peri-urban and thus contributes to food security and livelihood of the growing urban population. The novelty of the approach lies in the first-time use of a spatially explicit scenario model in the regional context of Addis Ababa and in providing detailed information on the impact of settlement growth on peri-urban agricultural land of varying suitability.

Due to the unprecedented growth of sub-Saharan African cities, the need to develop a sustainable model for city growth in Africa is emerging. This model should combine both the principles of the compact city (planning high-density settlements) with the classical garden city model. The adoption of this combined model would attempt to minimize the encroachment of impervious built-up area into natural and semi-natural land while integrating suitable green and open spaces into these areas.

The study recommends an integrated planning approach that is not only limited to the planning of residential and industrial development. Planners should have an in-depth understanding of the impact of settlement area development and the consequences for the surrounding environment due to its expansion. Assessing food production by agricultural land should be a crucial step preceding the allocation of future residential areas into neighbouring farmland. A high-density compact urban planning should be considered, as it would minimize the losses of farmland.

Although urban sprawl and loss of farmland relate to wider scales of food security from national and even regional perspectives, the role of local self-supply is highly important, especially in many southern urban food-supply systems (Mougeot, 1999). It has been proven in other cities of developing countries that local food supply is of great importance both to secure nutrition as well as to contribute to local economy, particularly in times of economic crisis (Pribadi & Pauleit, 2015). Urban inhabitants rely on a combination of food acquisition modalities, including the peri-urban food production as a response to unreliable, insufficient and, especially unaffordable food supplies from rural and foreign sources (Mougeot, 1999).

Moreover, the research has shown that there is an urgent need to adopt a new model for compact development, which protects and integrates agriculture into urban planning to increase food security and urban resilience.

Effective land use management in peri-urban areas is critical to minimize the impact of city expansion on food production (UN-Habitat, 2016). Managing the environment of the peri-urban interface has significant consequences for the livelihoods and quality of life of the inhabitants and the sustainability of urban and rural development. (Allen, 2003).

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No potential conflict of interest was reported by the authors.

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Appendix C: Paper 3 (submitted)

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MODELLING URBAN GROWTH AND FUTURE FLOOD HAZARD: THE CASE OF ADDIS ABABA

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Abstract: Urban growth increases the risk of flooding due to the replacement of vegetated areas by impervious surfaces and changes in stream morphology. This research models the settlement area expansion in the subwatershed of the little Akaki River (regional area of Addis Ababa) using an urban spatial scenario design model (USSDM). The consequent changes in flood patterns inside the city due to the modelled settlement expansion are simulated using a hydrological model. The model estimates the volume and the flow depth of water to delineate a hazard map for the years 2011 and 2038. The modelled settlement expansion in the subwatershed leads to an increase in the flood hazard area's extent within Mekanisa (domain area). Both the volume and the velocity cellular values generally increase, which contributes to a higher risk of flooding in the domain area. Incorporating urban growth models with hydrological and hydraulic models can help assess the impact of urbanization on the flood regulating ecosystem services provided by the natural and semi natural vegetative land cover. The output of such models would be useful in generating knowledge and empirically based evidence that assist in the sustainable planning of cities and their surrounding regions.

Keywords: Urban growth; modelling; spatial scenario; flood hazard; Africa; Addis Ababa

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INTRODUCTION

Flood-related disasters in Africa have increased in the past 40 years and almost half of the disasters recorded in Sub-Saharan Africa in the period 1981 - 2010 are floods (Tiepolo & Macchi 2014). Moreover, climate change projections show that flood risk will increase in the future due to higher frequency of extreme rainfalls. (World Bank, 2015). In cities of developing countries, low-income groups are usually forced to move to locations that are susceptible to natural hazards. Slums and informal settlements in particular, have four out of ten of non-permanent houses located in areas threatened by natural disasters such as landslides and floods (UN-Habitat, 2016).

The expansion of built-up areas leads to losses in green infrastructure. Green infrastructure has been defined as an "interconnected network of green space that conserves natural ecosystem values and functions and provides associated benefits to human populations" (Benedict and McMahon, 2006; Lovell and Taylor, 2013).

Continuous transformation of green infrastructure into built-up areas increase the risk of flooding in cities due to the replacement of vegetated areas by impervious surfaces, changes in stream morphology and poor drainage systems (Huong & Pathirana, 2013). Encroachment of settlements into flood-prone areas such as river valleys increases the risk of major disasters (Doberstein & Stager, 2013).

On one hand, climate change is the cause of significant alterations in rainfall regime and long periods of drought. On the other hand, the soil sealing, due to the continuous expansion of urban areas, causes increases in both flow rate and runoff volumes, exceeding the hydraulic capacity of the drainage network and the receiving water bodies. Moreover, the increased runoff velocity leads to the erosion of the soil. It has been shown that the excessive runoff, related to the increment of impervious surfaces, can lead to both uncontrolled flooding in urban areas and the deterioration of water quality in receiving water bodies (Khan et al., 2006; Dietz, 2007).

In natural catchments, i.e. in the presence of pervious surfaces, the runoff is significantly reduced since the hydrological losses (such as the evapotranspiration, the infiltration and the gradual saturation of the soil surface layers) are high. Hence, the flow tends to gradually reach the outlet points. This does not happen in the urban catchments, generally characterized by low permeability, where the water remains on the surface and in large quantities flows away. In fact, in urban surfaces the rainwater can accumulate in the available volumes, such as the depressions in the road surfaces or the roofs of buildings that are not inclined enough to let the water flow into the downpipes (De Paola et al., 2018).

In addition to heavy rainfall and extreme climatic events, dramatic changes in built-up area lead to continuous physical alteration of the catchment areas and an increase in impervious areas (Douglas et al., 2008). Urbanization tend to obstructs natural channels where floodwaters usually go by covering the ground with roads, pavements and roof areas, consequently, accumulating drains where water moves to rivers more rapidly than it did under natural conditions (Douglas et al., 2008). In addition, urbanization leads to changes in stream morphology, poor drainage systems and development of informal settlements in the flood-prone areas (Belete, 2011; Huong & Pathirana, 2013; Mazhindu, Gumbo & Gondo, 2010).

Urbanisation in floodplain areas exacerbates flooding risks due to increased peak discharge and volume and decreased time to peak (Campana and Tucci, 2001; Nirupama and Simonovic, 2007 and Saghafian, Farazjoo, Bozorgy & Yazdandoost, 2008). Encroachment of settlements into floodplain areas exposes them to a higher risk of flooding. Moreover, the change in the land use pattern due to urbanisation negatively affects the hydrological processes in a catchment. The increase in impervious areas disrupts the natural water balance. Reduced infiltration increases runoff and leads to higher flood peaks and volumes even for short duration low-intensity rainfall (Suriya & Mudgal, 2012).

Different studies have investigated the relationship between land use change and runoff response. Suriya, S., & Mudgal, 2012 have developed a flood hazard map using remote sensing and GIS techniques using a 1D mathematical model. However, this has not investigated the impact of future settlements and the modelled change in flood hazard maps.

The impact of future anthropogenic changes on the hydrology in watersheds can be assessed in terms of estimating flood peak after development to flood peak before development over different return periods (Kibler, Froelich & Aron, 2007). One of the main methods to assess flood hazard is by estimating the probability of different magnitudes of flooding such as the depth of inundation, duration of inundation and the velocity of moving water (National Research Council, 2015). Some studies (such as Miller et al., 2014) have investigated the changes in runoff resulting from the transformation of rural landscapes into peri-urban areas. Other studies (such as Du et al. 2012) have assessed the effects of future urbanisation on annual runoff and flood inside the urban area using hydrological models is still less covered.

The Objective of this research is to determine whether settlement growth in the peri-urban region increases the flooding hazard within the city and evaluate the consequent changes in flood patterns inside the city.

This research aims to model the settlement area expansion in the sub-watershed of the Akaki River (regional area of Addis Ababa) and analyses the consequent changes in flood patterns inside the city with the use of hydrological and hydraulic modelling approaches. The question that this paper contributes to answering is whether the modelled settlement growth in the regional area would lead to a change in the flooding hazard inside the city.

MATERIAL AND METHODS

Research Area

The research area is the sub-watershed of the Little Akaki river that flows from the northwestern town of Burayu (a surrounding town of Addis Ababa, the capital city of Ethiopia) into Mekanisa, the domain area. The subwatershed covers an area of 169 km2. The research area is based on the hydrological delineation of the little Akaki river's sub watershed. The majority of the research area (127 km2) is located in the Oromia region's administrative boundary, the largest region in Ethiopia while the rest of the research area and the domain area lie within the western part of Addis Ababa (**Fig. 1**). **Fig. 2** shows the domain Area, Mekanisa, which is located in the Niffasilk Lafto, one of the ten subcities of Addis Ababa. The domain area is vulnerable to flood risk and includes settlements, which poses a risk to both the inhabitants and to settlement structures (Habtemariam et al., 2018; Yeshitela et al., 2015).
Addis Ababa covers a total area of 520 km2 with a population of 3,553,682 in 2013 (AAOIDPP, 2013).

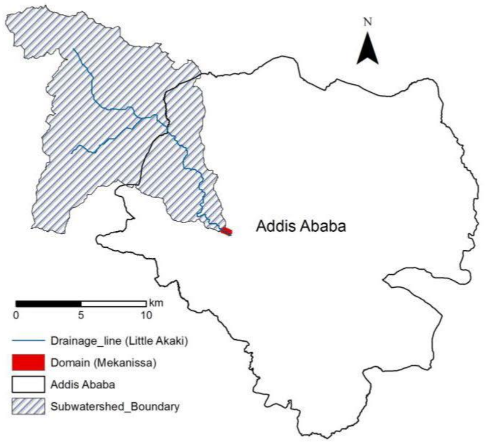

Fig. 1 Addis Ababa and Little Akaki subwatershed and domain area

Fig. 2 Mekanisa, the domain Area inside Addis Ababa (Data source: Cavan et al. 2012)

The population of the Burayu town is estimated to be 89057 inhabitants in the year 2013 and expected to reach 176,031 in 2023 and 400,000 in 2038 (AAOIDP, 2013). Within the research area, the new settlement area development would differ in the Oromia region from Addis Ababa.
In the part located in the Oromia region, most of the settlement expansion is expected to take place on green land (non built-up area) in addition to the densification of the town's existing built-up area. In the part located in Addis Ababa, densification of existing built-up area would be the major form of settlement development and settlement expansion on Greenland is negligible (AAOIDP, 2013).
Addis Ababa is vulnerable to riverine and flash floods due to river overflow caused by extreme rainfall events and river catchment activities that is intensified by the poor conditions of the drainage system (Birhanu, 2016). The vulnerability to flooding in Addis Ababa is linked to expansion of settlements near to riverbanks, weak housing material such as mud and wood, and poor drainage systems. Addis Ababa's topography and geographic location, in addition to the poor condition of the drainage system and road network exposes the city to street and riverine flooding (World Bank, 2015). Flooding is considered as a major development challenge that faces Addis Ababa in spite of the rapid economic growth and urbanization (Birhanu, 2016). The level of vulnerability to floods varies within the different neighbourhoods and communities in the city. This is due to the high variations in topography, access to services, poverty level, settlement patterns and quality of housing in these communities. (World Bank, 2015).

In this research, future settlement expansion in the subwatershed is simulated using Urban spatial Scenario Design Model (USSDM), a spatial scenario modelling approach (Abo-El-Wafa, 2017; Printz et al., 2015). A hydrological module is used to delineate and define the characteristics of the catchment and subwatershed and estimate the runoff. Finally, a 2D hydraulic model is used to calculate the maximum flow depth and velocity in the domain area to delineate a flood hazard map.

USSDM Spatial scenario modelling

USSDM is a raster-based model developed in ArcGIS's modelbuilder, which simulates the new settlement areas that are expected to be developed within specific temporal and spatial scopes defined by the user. The input parameters of the model are the influencing factors (factors that influence settlement expansion in the research area), exclusion areas (areas that are not expected to transform to settlements), and future land demand (the estimated area that will be settled). The final output is a raster file that indicates the modelled settlement area during the model's temporal scope. For a full description of USSDM, see Abo-El-Wafa et al. (2017) and Printz et al. (2015). The research area of 169 km2 is represented by 424399 raster cells of 20m by 20m in size. The temporal scope of the model was set to the period between 2013 and 2038 with two modelling periods of 2023 and 2038 (defined based on the population data availability for these two years). In the USSDM application for the research area, the factors that influence urban growth were defined based on previous urban dynamics studies (Barredo et al., 2014; Linard et al., 2013) and local experts input through semi structured interviews.
The influencing factors that drive settlement growth in this study were slope, proximity to road network, proximity to municipal facilities (schools, hospitals and markets), and neighbourhood (i.e. whether adjacent areas were already settled).
Influencing factors were weighted using a logistic regression using ArcGIS and R. The dependent variable is binary (whether the land use changed from 2008 to 2013) and independent variables are the influencing factors. The function z is calculated as follows:

$$z= I -Ws*S_i-Wr*R_i+ Wc* C_i +Wn*N_i \qquad (1)$$

In **Eq. 1**:
(a) z: built-up area change from 2008 to 2013
(b) I is intercept;
(c) Ws: Weight for S_i;
(d) S_i: Slope influencing factor
(e) Wr: Weight for the R_i
(f) R_i: proximity to road influencing factor
(g) Wc: Weight for C_i
(h) C_i: proximity to facilities influencing factor
(i) Wn: Weight for N_i
(j) N_i: neighbourhood influencing factor

Two different Land use datasets were used for characterising the land use types in the analysis area. Urban morphology types (UMT) dataset was used for the part of the research area that lies within the administrative area of Addis Ababa (Cavan et al., 2012). The land-use land-cover dataset from the Addis Ababa and the Surrounding Oromia Integrated Development Plan Project and from the Finfinne surrounding special zone of Oromia integrated land use planning study project were used for the part of research area that lies in Oromia region (OWWDSE, 2011). The land use types of both datasets were grouped into a uniform classification of the Soil Conservation Service manual 1975 (Appendix Table A1). Road network dataset was acquired from the Ethiopian institute of architecture, building construction and city planning (EiABC). Elevation data was acquired from the Addis Ababa and the Surrounding Oromia Integrated Development Plan Project in the form of 20 m interval contour for the whole area. Municipal facilities (Schools hospitals and markets) datasets were acquired from the Addis Ababa and the Surrounding Oromia Integrated Development Plan Project and from the Finfinne surrounding special zone of Oromia integrated land use planning study project. Soil data was acquired from the Finfinne surrounding special zone of Oromia integrated land use planning study project.

Fig. 3 shows the influencing factors that were used in this research.
Future land demand for settlements was calculated exogenously to the model based on the planned housing unit development to accommodate the projected population growth whereas the household size is 4 inhabitants/housing unit with a 2/3 proportion of new housing built on green land with a density of 82 housing unit/ha. (AAOIDP, 2013).
USSDM allowed settlement growth only in the proposed areas within each municipality designated for residential development according to the draft master plan assuming formal urban growth and the successful enforcement of land use zoning.
Two scenarios were designed in order to compare the consequences of a high-density development as proposed by the planners of the master plan review project (AAOIDP, 2013) with low-density plot based development which would totally cover the designated areas for residential.

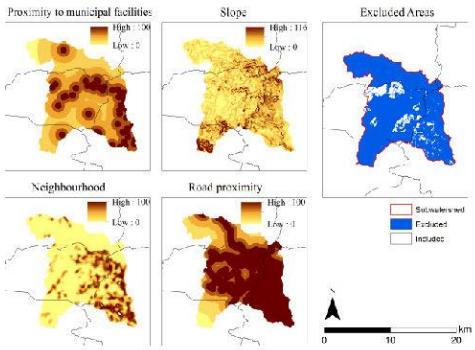

Fig. 3 USSDM Influencing factors for the subwatershed

Scenario 1 is a high-density scenario based on the Masterplan recommendation of housing density of 82 housing units/ha which yields a settlement density is 328 inhabitants/ha. This density was considered to be the Soil Conservation Service (SCS) manual's land cover of "Residential, 1/8 acre lots" (high-density residential) (SCS, 1975).

In scenario 2, the designated areas for residential development would be completely converted to settlements at an average settlement density of 115 inhabitants/ha (corresponding to 29 housing units/ha).

The settlement area densification that is planned by the city was also accounted for in both scenarios by changing the SCS land cover from "Residential 1/4 acre lots" to "Residential 1/8 acre lots".

Flood Modelling

The methodological framework used for the definition of the hazards maps consists of the following modules:

(a) A hydrologic module through which, extreme rainfalls, river catchment geological, and land use characteristics, the peak volume and the peak discharge corresponding to a fixed return period is assessed.

(b) A hydraulic two-dimensional module to delimit flood prone areas evaluating cell-by-cell flood characteristics in terms of maximum water depths, maximum velocity and flood duration.

Hydrological module The hydrological analysis and modelling on both the sub watershed and domain levels to determine the flood hazards in the domain for 2011 and 2038 were done using the following methods:

(a) Archydro is used to delineate the sub watershed and the drainage lines of the major rivers in the Addis Ababa and surrounding towns to be used in the analysis. The little Akaki river drainage line was extracted and used for further analysis.

(b) IDF curves for Addis Ababa in 2011 and 2038 were based on De Paola et al. 2014.

(c) Curve numbers: Land use geological and soil Analyses are conducted on the sub watershed of the Little Akaki river to calculate the hydrographs for the various return periods associated with the rainfall patterns. The hydrograph refers to the flow discharge as a function of time and constitutes the input for the hydraulic diffusion model

The Intensity Duration Frequency curves both for the 2011 and for the 2038 have been desumed from a precedent study (De Paola et al. 2014) in order to obtain the hyetograph for the case study river catchment. For the one referred to 2038 the CMCC projections with a downscale of 1 km are used. The IDF has the well-known form of i(t,T) = KT μt tn-1, in which i is the rainfall intensity, t the rainfall duration, T is the Return Period, μt and n the IDF parameters and KT is a growing factor associated to a return period T.

CN method

Once IDF has been estimated, a rainfall-runoff method could be applied in order to evaluate the hydrograph, which is the input for the hydraulic model. For drainage catchments where no runoff has been directly measured, the classic Curve Number Method (CNM) (developed by the Soil Conservation Service, 1972) could be successfully used.

CNM fundamental relationship is:

$$P_{net} = \frac{(P - I_a)^2}{P - I_a + S} \tag{2}$$

In **Eq. 2**:

(a) Pnet : accumulated runoff depth (mm);

(b) P: accumulative rainfall depth (mm);

(c) Ia: initial abstraction (mm), or the amount of water loss before runoff begins, such as infiltration, depression storage and rainfall interception by vegetation;

(d) - S: potential maximum soil moisture retention after runoff begins (mm).

Assuming Ia = 0.2S, yields (**Eq. 3**):

$$P_{net} = \frac{(P - 0.2 \cdot S)^2}{P + 0.8 \cdot S} \tag{3}$$

The runoff Curve Number, CN, is related to potential maximum soil moisture retention, S, **Eq. 4**:

$$S = \frac{1000}{CN} - 10 \tag{4}$$

As the potential maximum retention S can theoretically vary between zero and infinity, the Curve Number CN can range from 100 to zero.

Fig. 4 shows the graphical solution, indicating values of runoff depth Q (which corresponds to Pnet) as a function of rainfall depth P for selected values of Curve Number.

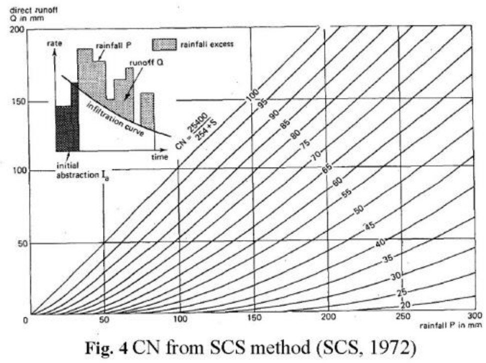

Fig. 4 CN from SCS method (SCS, 1972)

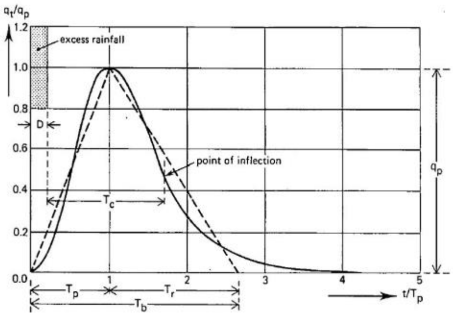

Fig. 5 Mockus Hydrograph (SCS, 1972)

For paved areas, for example, S will be zero and CN will be 100: all rainfall will become runoff. For highly permeable, flat-lying soils, S will go to infinity and CN to zero: all rainfall will infiltrate and there will be no runoff. In drainage catchments, the reality obviously will be somewhere in between.

Therefore, the Curve Number is a dimensionless parameter indicating the runoff response characteristics of a drainage basin. CN is related to land use, land treatment, hydrological condition, and hydrological soil group in the drainage catchment. Soil properties greatly influence the amount of runoff.

The soil moisture condition in the catchment before runoff occurs is another important factor influencing the final CN value, classified in three Antecedent Moisture Conditions (AMC):

(a) AMC I: the soils in the catchment are practically dry (i.e. the soil moisture content is at wilting point)
(b) AMC II: average condition
(c) AMC III: the soils in the catchment are practically saturated from antecedent rainfalls (i.e. the soil moisture content is at field capacity).

The characteristics of the discharge hydrograph - developed by Victor Mockus (SCS, 1972) - are indicated in **Fig. 5**.

The **Eqs (5), (6), (7)** and **(8)** are used to evaluate the hydrograph parameters are:

$$\frac{q_t}{q_p} = \left(\frac{t}{t_p}\right)^{3.5} \cdot e^{-3.5\left[\left(\frac{t}{t_p}\right)-1\right]} \quad (5)$$

$$t_p = 0{,}5D + t_l \quad (6)$$

Where:

(a) t : the time independent variable [h];
(b) qt : the discharge at time t [m3/s];
(c) qp : the peak discharge [m3/s];
(d) tp : the hydrograph peak time [h];
(e) D : the rainfall duration [h]
(f) tl : the catchment lag time, i.e. the time between the hydrograph centroid and the net rainfall centroid, equal to:

$$t_l = 0{,}342\frac{L^{0.8}}{s^{0.5}}\left(\frac{1000}{CN} - 9\right)^{0.7} \quad (7)$$

In which L is the length of the main channel [km] and s is the mean slope [%]:

$$q_p = 0.208\frac{VA}{t_p} \quad (8)$$

In which A [km2] is the catchment area and V = Pnet [mm] is the flood volume.

In order to calculate the curve numbers for the subwatershed, land use is an important factor both for the detection of the precipitation retention capacity and the formation of the water flow. Based on area statistics, the portion of the catchment at high elevations is covered mainly by vegetation (33% agriculture and 35% of other vegetated areas). For elevation higher than 2600 m, the same percentages are 38% and 49% So It is safe to say that at higher elevation the portion is mainly vegetation (87%)). The bottom part of catchments fall into a densely urbanized area. The soil dataset was used to determine the Hydrologic Soil group in the analysis area. Hydrologic soil group D was chosen for the whole area as approximately 70% of the area is classified as group D (Soil texture of clay, clay loam, rock surface, sandy clay loam.) (Berhanu et al. 2013).

The peak flow for the catchment was evaluated by the Curve Number method, with reference to five return periods (e.g., 10, 30, 50, 100, and 300 years). The choice of the condition of AMCIII is made because of safety condition. In this way, it is possible to maximize volumes and peak discharges. The assessed discharge hydrograph is the input for the delimitation of flood hazard areas in the hydraulic module.

Hydraulic module: In this module, the diffusion of the total discharge volume (area under the hydrograph) based on the general constitutive equations of continuity and fluid dynamics using a bi-dimensional diffusion model (using FLO2D software). The inundation profile can be used to delineate the inundated areas for a given return period, as those areas within the zones of interest where the inundation height is greater than zero.

FLO-2D software (O'Brien et al., 1993; FLO-2D, 2004) can be used as an effective tool for delineating flood hazard. To start a flood simulation, it is important obtaining the topographic database. As a first step, a digital terrain model (DTM) has to be overlaid with a grid system. Aerial photography, detailed topographic maps, orthographic photos and digitized mapping are necessary to locate important features with respect to the grid system, such as streets, buildings, bridges, culverts or other flood conveyance or storage structures. FLO-2D is a volume conservation model. The general constitutive fluid equations include the continuity equation and the motion equation (dynamic wave momentum equation, **Eqs (9)** and **(10)**:

$$\frac{\partial h}{\partial t} + \frac{\partial hV}{\partial x} = 0 \qquad (9)$$

$$S_f = S_0 - \frac{\partial h}{\partial x} - \frac{V}{g}\frac{\partial V}{\partial x} - \frac{1}{g}\frac{\partial V}{\partial t} \qquad (10)$$

In which h is the flow depth and V is the depth-averaged velocity in one of the eight flow directions considered (**Fig. 6**)

The friction slope component Sf is based on Manning's equation. The other terms include the bed slope So, pressure gradient and convective and local acceleration terms. The motion equation represents the one-dimensional depth averaged channel flow. For the floodplain, being FLO-2D a multi-direction flow model, the equations of motion are applied by computing the average flow velocity across a grid element boundary one direction at time.

The differential form of the continuity and momentum equations in the FLO-2D model is solved with a central, finite difference numerical scheme.

The solution domain in the FLO-2D model is discretized into uniform, square grid elements. The computational procedure for overland flow involves calculating the discharge across each of the boundaries in the eight potential flow directions and begins with a linear estimate of the flow depth at the grid element boundary. The estimated boundary flow depth is an average of the flow depths in the two grid elements that will be sharing discharge in one of the eight directions. To solve the equation for the flow velocity at a grid element boundary, initially the flow velocity is calculated with the diffusive wave equation using the average water surface slope (bed slope plus pressure head gradient).

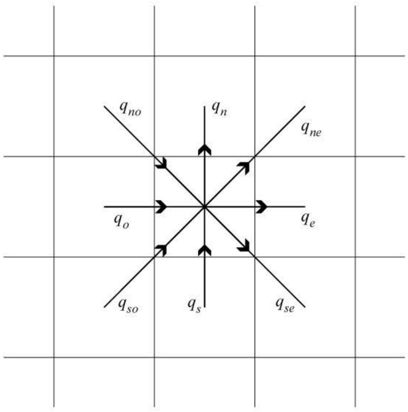

Fig. 6 Discharge Flux across Grid Element Boundaries (FLO-2D, 2004)

This velocity is then used as a first estimate (or a seed) in the second order Newton-Raphson tangent method to determine the roots of the full dynamic wave equation.

FLO-2D moreover has a variable time step depending on whether the numerical stability criteria are exceeded or not. The numerical stability criteria are checked for every grid element on every time step to ensure that the solution is stable. If the numerical stability criteria are exceeded, the time step is decreased and all previous hydraulic computations for that time step are discarded.

For the simulations, one or more flood hydrograph from an upstream catchment can be inflow either to the floodplain, channel or both. More than one grid element can have an inflow hydrograph.

The principal advantages in using a two-dimensional model are due to the possibility to analyse many particular hydraulic problems that a one-dimensional classical model cannot see, such as:

(a) unconfined flow or tributary flow
(b) very flat topography
(c) split flow (channel or floodplain)
(d) combined hydrologic and hydraulic modeling
(e) routing flood hydrograph
(f) Flood wave attenuation.

A digital elevation model (DEM), with 5 m resolution was used, assuming a 35 hours simulation time. The simulation time step is fixed to 1 minute, and a cell size of 10 m was considered. FLO-2D was selected as being a standard bi-dimensional hydraulic model for flood wave propagation since the US Federal Agency (FEMA) has validated it. It is widely used worldwide by both researchers and professional engineers.

RESULTS AND DISCUSSION

Settlement development

This section presents the simulated settlement area development in the sub watershed for the period 2013-2038. **Table 1** shows the future land demand that was used in this research to model the settlement expansion in 2038 for both scenarios.

The result of the logistic regression is presented in **Eq. 11** which shows the intercept and the weights for all influencing factors for the surrounding towns (all results are significant at $p < 0.01$).

$$z = -3.16e+00 - 5.29e-02*S_i - 2.29e-03*R_i - 1.12e-03*C_i + 7.72e-02*N_i \qquad (11)$$

Table 1 Future land demand for 2023 and 2038

Year	Total Housing units	Housing units in green land	Land demand (Ha)	Land demand (20m*20m) cells
2023	49,313	32,875	401	10,023
2038	67,191	44,794	546	13,657

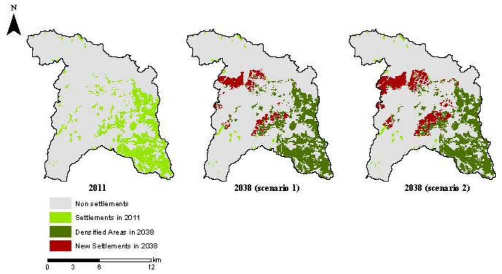

Fig. 7 the modelled settlement expansion in 2038

As shown in **Fig. 7**, in the first scenario, a total area of 947 ha of land would be transformed to settlement area by 2038. This expansion would lead to a total settlement area of 4,553 ha which represents 26% of the case study's area. In the second scenario, 1,300 ha would be transformed to settlement area by 2038. This expansion would lead to a total settlement area of 4,907 ha which represents 29% of the case study's area.

The difference of the settlement development between scenario 1 and scenario 2 was an increase of 37%. This would lead to increase in the impermeable area in the subwatershed of the river being studied.

The densified area in both scenarios is the same (total 3519 ha) in which the CN curve for these areas were 87 (SCS manual Land cover of "Residential Areas: ¼") in 2011 and changed to 92 (SCS manual Land cover of "Residential Areas: ¼") in 2038 (both scenarios 2 and 3).

Flood Hazard

Hydrologic module: The output from the Arc Hydro analysis is shown in Fig. 8. Using the digital elevation model, the Arc Hydro was used to determine the Akaki river (drainage line) and the sub watershed. The outlet point was identified and a domain area is delineated which would act as the analysis area in which the flood hazard would be mapped. The IDF parameters curve are shown in

Table 2.

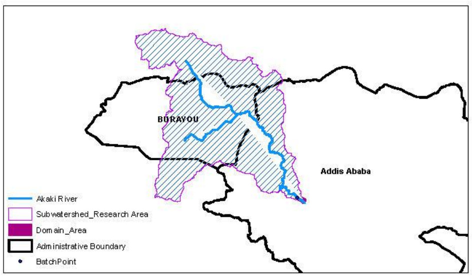

Fig. 8 Archydro output: Subwatershed, drainage line and domain area

Table 2 IDF parameters for Addis Ababa (De Paola et al. 2014).

2011 Historical Data		2038 CMCC 8.5, 1 km	
μ_t=25.06 n=0.23		μ_t=23.97 n=0.25	
T	K_T	T	K_T
10	1.50	10	1.51
30	1.84	30	1.86
50	2.00	50	2.02
100	2.21	100	2.23
300	2.54	300	2.56

The settlement development in both scenario 1 and 2 were analysed and curve numbers for the year 2011, 2038 scenario 1 and 2038 scenario 2 were calculated based on the updated land use. The new settlement areas are considered as "Residential, 1/8 acre lots". The settlement area densification that is planned by the city are also accounted for by changing the SCS land cover (increasing the CN) from "Residential 1/4 acre lots to 1/8 acre lots (92). The CN values in the subwatershed that correspond to the different land use types in 2011 and for both scenarios in 2038 were calculated (Appendix **Table A 2**). Using the output of Archydro and the CN parameters, the catchment characteristics are shown in **Table 3.**

The increase in CN curve for the research area between the present (2011) and the future (2038) for the two scenarios were 1.6% and 1.8% for scenario 1 and scenario 2 respectively. Although the increase is relatively small but it will have an impact on the hydrograph and consequently the flood hazard area (see the next sections). The impact of increasing the CN curve number due to densification is higher than the increase of the CN curve number due to expansion of settlement located in new areas. This increase of the CN curve number between scenario 1 and scenario 2 is as low as 0.23%. The average increase in the CN value for 2038 (for both scenario 1 and 2) is largely due to the transformation of different land uses to Residential 1/8 acre lots rather than the increase due to the densification of already existing settlement.

Table 3 Little Akaki catchment characteristics

Characteristics	Little Akaki River Catchment
Drainage area (km^2)	169.76
Main channel length (km)	~ 27
Average slope (%)	11.45
Average height (m.a.s.l.)	97.2
2011 CNIII	93.48
2038 CNIII sc1	94.16
2038 CNIII sc2	94.27
D (h)	8.33

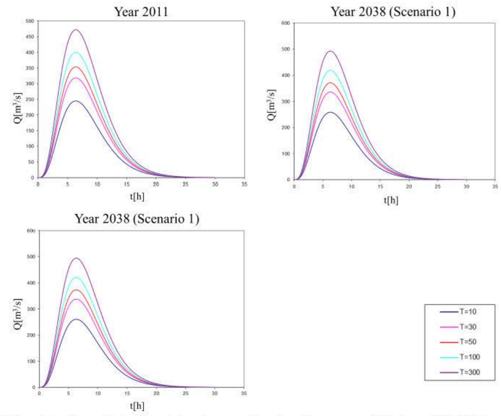

Fig. 9 Inflow (Mockus) hydrographs for the years 2011 and 2038 in different return periods

The inflow hydrographs for catchment in different return periods are illustrated in **Fig. 9.** There is an increment of the volume of about 7% for 300 years return period although the average Curve Number difference between the 2011 and 2038 is relatively low. Hydraulic 2D module As an output of the FLO-2d analysis, Fig. 10 shows the outcome of the flood propagation in terms of maximum flow depth (in meters) and maximum velocity (m/s), with reference to three considered return periods (10, 100 and 300 years),

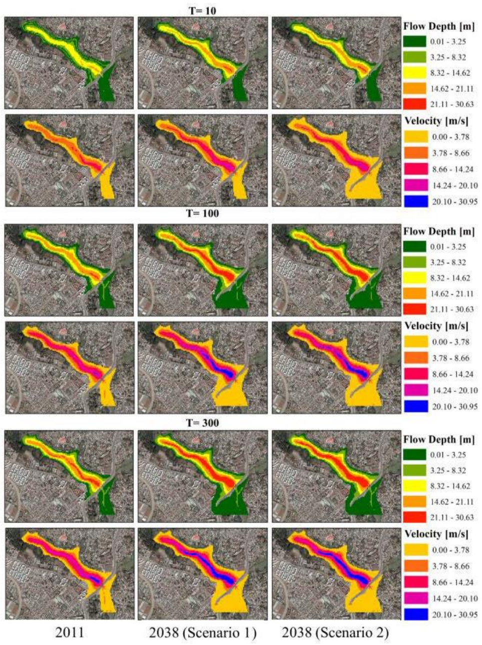

Fig. 10 Cellular values of Flow depth (m) and velocity (m/s) for 2011 and 2038

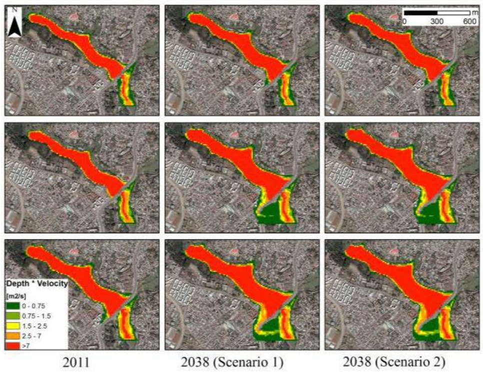

Fig. 11 Flood hazard thresholds based on a combination of depth-velocity. Depth X Velocity [m2/sec] (threshold based on Priest et al., 2008)

for the year 2011 and the 2 scenarios in year 2038. The new scenarios lead to an increment of the inundation maximum intensity in correspondence of the bridge (for a fixed return period). In 2011, the maximum flow depth is approximately 25 m and the maximum velocity is 31 m/s (for T=300y) in 2011. For the same return period (T=300y), a maximum water depth of 31 m and a maximum velocity of 31 m/s were observed for the year 2038 in both scenarios. There were not a large difference in the values between scenario 1 and 2 in 2038. Furthermore, the presence of the obstruction caused by a road bridge causes strong lateral overflows that significantly increase the flooded area. In Fig. 11, flood hazard maps are delineates by the multiplying the cellular values of flow depth and velocity. Thresholds defined based on Priest et al., 2008

In 2038, both scenarios would lead to an increased extent of the flood hazard area and the flood magnitude. Additionally the obstruction caused by the road bridge leads to a higher flood hazard due to the strong lateral overflows (for all return periods).

CONCLUSION

According to the results of this research, both climate change and urbanization would contribute to an increase of the flooding hazard in the domain area. The climate of Addis Ababa is forecasted to have an increase in precipitation variability and temperature. This will likely induce a wide range of hazards in the city including flooding and landslides in addition to droughts and fires, which have been the most common hazards in rural and urban areas. (World Bank, 2015).

USSDM's output has indicated that both the settlement area growth and the further densification of existing settlement areas have contributed to the growth of the flood hazard areas inside the city. This confirms what other studies (such as Douglas et al., 2008) have stated, where urbanization would obstruct the natural channels leading to the impermeability of the ground with roofs, roads and pavements, resulting in water moving to rivers more rapidly than it did under natural conditions.

Controlling urban sprawl and promoting a more densified form of development could improve the future situation. However, the difference between the 2 scenarios for 2038 was not significantly large (both in the CN values for the subwatershed and the inflow hydrographs at the inlet). This shows that the transformation of other land uses to settlements (regardless of the density) has a lower impact than the densification of the already existing settlements. This is only valid in the current research area being investigated in this paper, as the assumptions made were that most of the urban population growth would be accommodated in already existing settlement areas (through urban renewal) which might not be the case in other areas where the existing settlement areas could not be heavily densified. Moreover, limiting the growth of the settlement area in the sub watershed would reduce the increase in permeability, and consequently minimize the vulnerability of people settling in flood-prone areas (domain area).

Another finding of this research is that the settlement expansion that takes place in a specific area in the region would have an impact not only on the regional area but also on the flood hazard in zones located inside the city that is located kilometres away. This finding clearly demonstrates the close linkages between the urban and regional landscapes and confirms how the planning of cities and regional areas should take into consideration the hydrological characteristics of the whole ecosystem and should not be limited to the administrative boundaries but rather consider other ecological and physical boundaries of the different ecosystems in which cities are located.

Incorporating urban growth models with other environmental and hydrological models can assess the impact of urbanization on the flood regulating ecosystem services provided by the natural and semi natural vegetative land cover. The output of such models would greatly help for generating knowledge and empirically based evidence which serve into the sustainable planning of cities and their regional areas, namely in the preparation of land use plans to direct where settlement expansion should take place to achieve minimal negative impact on the surrounding environment.

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APPENDIX

Table A1 Land use types and corresponding SCS manual land cover types used in this research

S/N	Land_Use types	SCS manual Landcover	CN (D)	S/N	Land_Use types	SCS manual Landcover	CN (D
1	Bush shrub land, Riverine	Bush (good, >75% ground cover)	73	9	Bare land, Mineral workings and quarries, Open markets, Quarry	Streets and Roads: Dirt	89
2	Forest	Woods and Forests: Good (no grazing; brush covers ground)	77	10	Agriculture ,Crop Land ,Cultivated land ,Field crops ,Vegetable Farm	Cultivated (Agricultural Crop) Land Without conservation treatment (no terraces)	91
3	Plantation, Plantation Forest, Woodlot	Woods and Forests: Fair (grazing but not burned; some brush)	79	11	Condominium & multi-storey, Settlements2038	Residential Areas: 1/8 Acre lots, about 65% impervious	92
4	Mixed forest	Woods and Forests: Fair (grazing but not burned; some brush)	79	12	Airports, Industry, Manufacturing	Industrial Districts (72% impervious)	93
5	Cemetary, Parks, Religious site	Open Spaces (lawns, parks, golf courses, cemeteries, etc.): Good (grass covers >75% of area)	80	13	Commercial, Education, Education center, Formal shopping area, Health center, Hotel, Medical, Mixed formal and open, Municipal service, Office, Recreation Center, Social service, Storage, Storage and distribution	Commercial and Business Districts (85% impervious)	95
6	Grass land, Open grassland	Pasture or Range Land: Good (50-75% ground cover; not heavily grazed)	80	14	Bus terminals	Paved parking lots, roofs, driveways	98
7	Open Space, Stadium and festival sites, Terminal	Open Spaces (lawns, parks, golf courses, cemeteries, etc.): Fair (grass covers 50-75% of area)	84	15	Major road corridors, Road	Streets and Roads: Paved with curbs and storm sewers	98
8	Mixed, Mixed Use, Mud/wood construction, Residential, Settlement, Villa &", "& single storey stone/concrete	Residential Areas: 1/4 Acre lots, about 38% impervious	87	16	Dam, River, Water body(Dam), Water treatment	Water body	100

Table A 2 *CN values for the subwatershed according to land use types in 2011 and 2038*

2011			2038 (Scenario 1)			2038 (Scenario 2)		
CN value (D)	Cell count	CN*count	CN value (D)	Cell count	CN*count	CN value D	Cell count	CN*count
73	12052	879796	73	12052	879796	73	12052	879796
77	24832	1912064	77	20696	1593592	77	18072	1391544
79	59332	4687228	79	57525	4544475	79	55644	4395876
80	53848	4307840	80	51559	4124720	80	49749	3979920
84	237	19908	84	237	19908	84	237	19908
87	87989	7655043						
89	7876	700964	89	6794	604666	89	6746	600394
91	138519	12605229	91	124161	11298651	91	121686	11073426
92	2174	200008	92	113838	10473096	92	122680	11286560
93	10464	973152	93	10464	973152	93	10463	973059
95	11267	1070365	95	11267	1070365	95	11266	1070270
98	10166	996268	98	10163	995974	98	10161	995778
100	5643	564300	100	5643	564300	100	5643	564300
	424399	36572165		424399	37142695		424399	37230831
	CN_II value 86.1740131			CN_II value 87.5183377			CN_II value 87.7260102	