SEVENTH FRAMEWORK
PROGRAMME
THEME [ENV.2010.2.1.5-1]
[Assessing vulnerability of urban systems, populations and goods in relation to natural and man-made disasters in Africa]

Grant agreement no: **265137**
Project acronym: **CLUVA**
Project title: **"CLimate change and Urban Vulnerability in Africa"**

Deliverable reference number and title: D2.17 Report describing the developed methods and its possible relevance for planning and decision-making

Due date of deliverable: M36
Actual submission date: M36

Start date of project: 01/12/2010 Duration: 36 months

Organisation name of lead contractor for this deliverable: AMRA

Revision [1]

Project co-funded by the European Commission within the Sixth Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Note about contributors

The following organisations contributed to the work described in this deliverable:

Lead partner responsible for the deliverable:

[AMRA]

Deliverable prepared by: Fatemeh Jalayer, Raffaele De Risi, Lise Herslund, Alexander Garcia-Aristizabal, Stefano Carozza

Partner responsible for quality control:

[KU]

Deliverable reviewed by:
Gertrud Jørgensen

Other contributors:

[AMRA]
Fatemeh Jalayer
Raffaele De Risi
Alexander Garcia-Aristizabal
Stefano Carozza
Francesco De Paola

[EiABC]
Nebyou Yonas
Alemu Nebebe
Kumelachew Yeshitela

[ARDHI]
Deusdedit Kibassa
Riziki Shemdoe

[UFZ]
Nathalie Jean-Baptist

[TUM]
Stephan Pauleit

[UOM]
Sarah Lindley

SUMMARY

Vulnerability assessment remains central in global climatic change discourses and takes a more pertinent meaning considering that natural disasters continue to deeply affect human settlements. The challenge for many African nations is to absorb the social, economic and environmental impact caused by natural disasters while reducing poverty, developing infrastructure and providing livelihood opportunities in the continent. In recent years, severe weather-related events affected urban populations and challenged local institutions to adapt and to improve their coping and resilient capacities. Given the polyhedric and context-dependent nature of vulnerability, it is critical to adopt a conceptual framework that embraces alternative interpretations of vulnerability assessment. With special regard to climate-related vulnerability assessment, two main alternative methods can be distinguished. The two differing interpretations, conceptualized as outcome[1] vulnerability and contextual vulnerability, can be linked to scientific and social sciences frameworks, respectively. It can be expected that each framework is going to prioritize and emphasize different types of climate adaptation strategies and policy response implications. The out-come vulnerability focuses on the end point of sequence of climatic analysis and can be conceptualized as a linear and modular procedure starting from a suitable down-scaling of climate projections, to climate-related hazard assessment, to vulnerability and exposure assessment, and finally to an evaluation of the risk as the prediction of future impact on urban areas. The contextual vulnerability envisions vulnerability as a starting point for developing climate adaptation strategies. In this interpretation, vulnerability is seen as a multi-faceted concept that is a product of different realities and causes that include but are not limited to natural hazards. The CLUVA project employs both conceptual frameworks for vulnerability assessment. The *multi-dimensional vulnerability mapping* method is based on the contextual vulnerability framework and adopts various vulnerability indicators that are evaluated and verified based on stakeholders' participation. The *bi-level method for flooding risk assessment for the built environment* is based on the outcome vulnerability framework and provides quantified estimates of risk and vulnerability for the residential buildings and with specific reference to flooding hazard. Finally, the *multi-risk assessment* provides a powerful vehicle for integrating the risk and vulnerability information, in the out-come vulnerability framework, for different urban land classification types (e.g., buildings, green areas, roads, ..., etc.) and for different climate-related hazards (e.g., floods, wind, draughts, heat waves, ..., etc.). A multi-faceted outlook to vulnerability assessment emphasizes the importance of taking into account alternative interpretations in the adopted conceptual framework. Arguably, integrating the above two interpretations is going to lead to climate policies that address a comprehensive range of issues and concerns.

---

[1] It should be noted that within the scientific discipline this approach is not usually called by the name *outcome vulnerability*. Herein, we have adopted this terminology, which seems to be used more in the social sciences, in order to distinguish the two interpretations.

FOREWORD

Climate change is expected to present serious challenges for cities all over the world, and in particular in the least developed countries. The five CLUVA cities: Dar Es Salaam, Addis Ababa, Saint Louis, Douala and Ouagadougou are already challenged by severe effects such as flooding and drought. The cities need to become more resilient and adapt to present and future effects of climate change despite of many challenges. However, adapting can be overwhelming for a developing city struggling with a multitude of urban problems. A developing city might not be able to address all the issues which are important to create resilience, but they might be able to address a part of these issues; that is, the most important.

Strategic urban planning is characterized by focusing on a limited number of key issues that are considered most important. Strategic planning is selective and oriented to issues that really matter. As it is impossible to do everything that needs to be done, 'strategic' implies that some decisions and actions are considered more important than others and that much of the process lies in making the tough decisions about what is most important.

For climate change adaptation, this means on one hand that climate change needs to be considered a problem that really matters in order to be a subject for strategic planning of a city. And on the other hand, if climate change is in fact considered as an important challenge to address, neither all effects of climate change can be addressed nor all the possible measures can be taken. Strategy making then involves identifying and selecting which climate change issues are most important in a given city. In order to do so vulnerability assessments are of key importance when deciding on what needs most attention here and now.

Urban authorities have a key role to play in making cities more resilient to climate changes but the question is where to start when climate change adaptation tends to drown in more urgent urban development problems? Because of limited resources and deficits in governance systems it is not realistic that all relevant measures can be implemented in the CLUVA cities. It is therefore crucial to focus on the most important to identify what strategic measures should be taken.

City-level adaptation is a relatively new area within urban planning, and there are no standards for how to do it. This has to do with the complexity of the issue and a high context dependency. What works in one city may be infeasible or even irrelevant in another city. Thus, assessments of the particular context and vulnerabilities in the city in question are essential. While vulnerability assessments are essential, it is however important to be aware that climate change and adaptation is full of uncertainties and it is unlikely that assessments and the identification of options will ever reach a stage of finality and certainty. Therefore it is important that urban planning is flexible enough to allow for the discovery and incorporation of new knowledge and assessments and that final assessments need not necessarily be finished before any planning can occur.

In these years, many cities like the CLUVA cities, are realizing they need to adapt to climate changes and are struggling to get hold of the 'science' in their city and understanding the effects of climate change in order to put actions into place. Cities call for methods for assessing risks and vulnerabilities and their distribution in a comprehensive manner. As urban development dynamics is too complex a field to be covered by a single discipline – multi disciplinarily in vulnerability assessments are needed. Here, the methods for vulnerability assessment presented in this deliverable can serve as a catalogue of different relevant ways to assess the vulnerabilities in a city.

DISCLAIMER

The risk maps illustrated in Chapter 3 are not ready to use for urban planning purposes. They should be subjected to verification and updating as more data become available. Examples of the type of information that can help in providing more reliable maps are: laboratory tests for the materials used in the building construction, including tests that take into account the degradation of material properties in direct and elongated contact with water. Moreover, the results of the structural analyses need to be verified with both large or reduced-scale tests on prototype buildings in laboratory and also observed damage due to previous flooding events. The vulnerability evaluations need to be assisted with several sample field surveys in order to verify the resulting fragility curves. Nonetheless and arguably, these maps and the description of the methodology behind them, provide a useful perspective of the kind of information that can be passed on to the urban planner and policy-maker.

CONTENTS

List of figures

List of Tables

1 INTRODUCTION

Africa is probably the continent most vulnerable to climate change and its adverse effects, despite being the continent least responsible for global greenhouse gas emissions. The adverse effects of climate change in Africa may include, reduced agricultural production, worsening food security, the increased incidence of flooding and drought, spreading disease and an increased risk of conflict over scarce land and water resources. Therefore, it is clear that immediate action is needed in both reducing the global carbon emissions and adapting to the adverse effects of climate change (Downing et al., 1997). Hence, climate change and its associated impacts on the natural, physical and social systems asks for the integration of a forward-looking perspective into decision-making processes to ensure that climate change adaptation strategies are fully addressed. There is increasing evidence about correlation between the phenomenon of climate change and extreme climate-related events. As evidence of the link between climate change and extreme events, one can cite the increased frequency of heat waves, the increase in temperature maxima, increased likelihood of flash floods and draughts, change in rainfall patterns and intensity, increase in hurricane intensity, sea-level rise (CRED, 2012). The weather-related extreme events are transformed into natural disasters when they hit vulnerable areas. Therefore, assessment and prediction of the adverse effects of climate change and extreme weather-related events and identifying the vulnerable areas are undoubtedly important steps in an integrated climate change adaptation strategy.

Informal Settlements

Africa has the highest rate of urbanization around the world, equal to about 3.5% per year (UN-HABITAT, 2010). Around 40% of the African population currently lives in the urban areas (UN-HABITAT, 2010). This number by 2050 is going to increase to 61.8% of Africa's projected population (UN-HABITAT, 2010). However, the infrastructure development and economic growth in urban areas lag behind the rapidly-growing urbanization phenomenon. In simple terms, the cities develop too fast and there is not enough time margin left for being able to properly absorb its new inhabitants. This leads to high levels of unemployment, inadequate standards of housing and services, and impacts on human health and development. These are amongst the reasons why the urbanized areas are potentially vulnerable to weather-related extreme events. One of the most significant consequences of the rapid urbanization process is the phenomenon of the squatter settlements also known as the informal settlements, shanty towns, and slums. Although they defer slightly in their definitions, these denominations all refer to generally poor standards of living. General estimates indicate that about 60% of the urban population in Africa lives in informal settlements and shanty towns (UN-HABITAT, 2009). The Table below reports the proportion of the urban population living in slums in Africa in the last 20 years (UN-HABITAT, 2010).

Year	1990	1995	2000	2005	2007	2010
Percentage of urban population living in slums in Sub-Saharan Africa	70.0%	67.6%	65.0%	63.0%	62.4%	61.7%

Table 1 Proportion of urban population in the Sub-Saharan Africa living in slums (UN-HABITAT, 2010)

This emphasizes why the urban informal settlements are recognized as the potentially vulnerable areas to weather-related phenomena.

Urban eco-systems

Urban ecosystems provide a crucial ‘life-support’ for cities. They provide food and materials for urban populations; they regulate and support local urban environments for the benefit of residents; and they allow space for recreational and cultural activities. Many different types of vegetation and areas of water provide these services and they exist everywhere in the city, from street trees and vegetable patches through to municipal parks and river valleys. The climate adaptation potential provided by the ecosystems depends on the pressures that the structures face now and into the future. One important pressure is development related and layered onto this is the additional stress from climate. By all means, the urban eco-systems can be classified as areas particularly vulnerable to the undesirable effects of climate change and climate-related hazards.

The dual conceptual framework adopted in the CLUVA project

One of the points that distinguishes the CLUVA project is a multi-faceted interpretation of vulnerability.

Contextual vulnerability

The contextual interpretation of vulnerability is a polyhedric approach (see Figure 1) mainly based on the social sciences frameworks. In this conceptual framework, vulnerability is interpreted as a starting point for developing adaptation strategies (O'Brien et al., 2007). The contextual vulnerability is evaluated as a product of different realities and causes that might be external to natural hazards. Another aspect that distinguishes the contextual framework is that is examines current vulnerabilities and not prospective impacts.

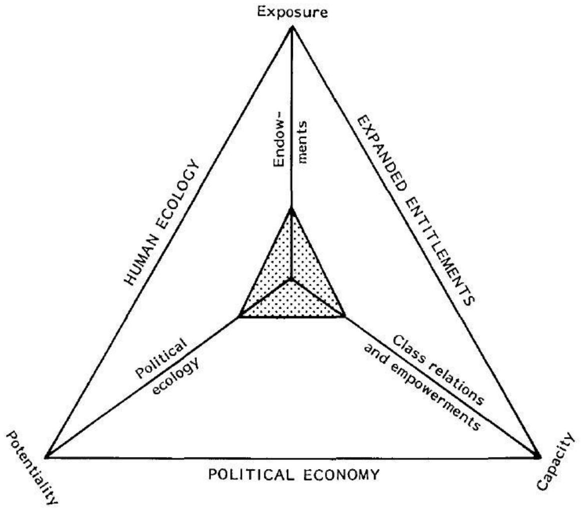


Figure 1 - Space of Vulnerability (Watts and Bohle, 1993)

Outcome vulnerability
The framework adopted in the CLUVA project for assessing the impact of climate-related hazards is based on strictly scientific principles. From the point of view of urban planning and policy-making, this approach can be classified as an *outcome vulnerability* framework, where global climate projection secnarios are downscaled in order to make hazard assessment for critical weather-related phenomena.

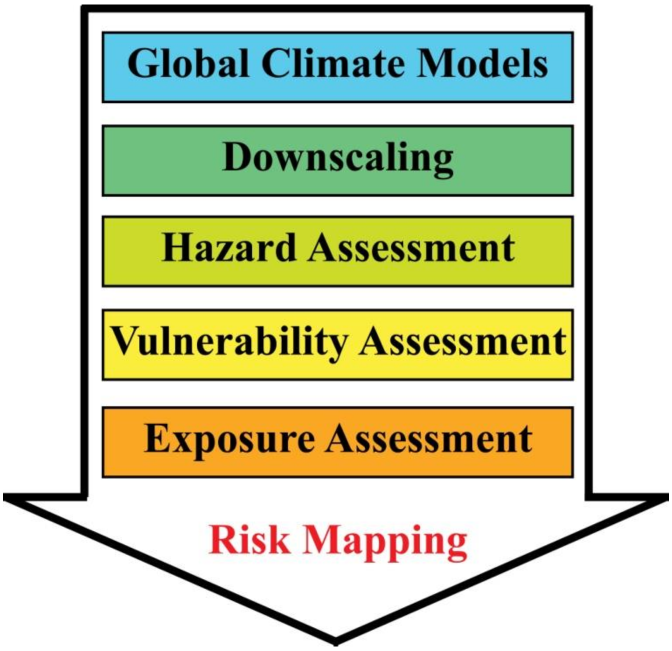


Figure 2 - A flow-chart representation of the outcome vulnerability conceptual framework.

The results of hazard assessment are then integrated together with quantified vulnerability calculations for various land classification categories and exposure in order to calculate risk. Arguably, risk mapping provides a technical support basis for the decision-maker in order to decide where and how to apply adaptation strategies. In such a framework, the multi-risk assessment consists of a state of the art procedure for integrating the impact of various weather-related phenomena and to consider the possible inter-relations between the objects for which the vulnerability is being assessed.

The integrated framework adopted by the CLUVA project

As mentioned before the integrated framework adopted by CLUVA is multi-faceted since it embodies alternative interpretations of the concept of vulnerability. Moreover, the methods adopted by CLUVA span different spatial scales and involve both up-scaling and downscaling techniques in various stages. The schematic diagram in Figure 2 illustrates integrated framework adopted in CLUVA. It can be observed how the two different vulnerability interpretations (outcome vulnerability and contextual vulnerability) are implemented in strategic climate adaptation decision-making.

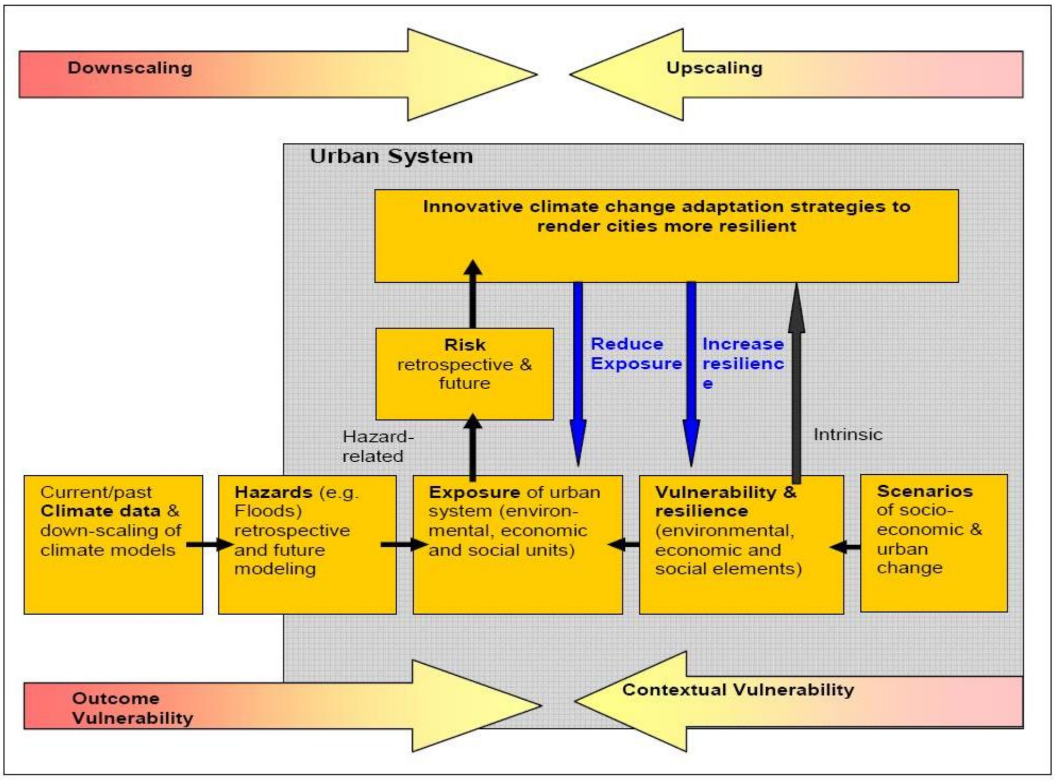


Figure 3 - The CLUVA research framework.

The structure of the deliverable

The *multi-dimensional vulnerability mapping* discussed in Chapter 2 is a method developed and implemented in Task 3.2 (land-use indicators) of the CLUVA project and is based on the contextual vulnerability framework elaborated by the Task 2.3 (assessing social vulnerability). The *bi-level method for flooding risk assessment for the built environment* discussed in Chapter 3 is a method developed and implemented in Task 2.1 (vulnerability of urban structures and lifelines). This method can be classified as an outcome vulnerability approach. This method implements the climate-related hazard scenarios and maps developed within Task 1.3 (Probabilistic scenarios of natural hazards). In this approach, the *urban morphology maps* developed within Task 2.2 (Vulnerability and adaptation potential associated with urban ecosystems) are employed in order to obtain the spatial delineation of various land cover categories within the urban system. The *multi-risk assessment* framework outlined in Chapter 4 is developed and implemented within Task 2.4 (Task 2.4 Multi-risk models) describes how the alternative vulnerability assessment approaches can be integrated in order to take into account both the different critical weather-related phenomena and also to take into account the inter-relations between various objects for which the vulnerability is being evaluated. In the overview of the methods presented herein, the attention is focused on describing the procedure that leads to results that are useful for urban planning and decision making.

2 MULTI-DIMENSIONAL VULNERABILITY MAPPING

To support cities in their climate change adaptation and urban planning, Task 3.2 has performed an approach to vulnerability assessment using geomatics and geographical indicators. Taking the standpoint in the multi-dimensional setup (a conceptual framework developed by CLUVA Task 2.3), the task explores in a step-by-step manner how to capture, measure and process spatial data of multiple dimensions and integrating them into a Geographical Information System (GIS).

The overall approach is a spatial multiple criteria evaluation (S-MCE) process, following a series of steps, whereby the most important multi-dimensional indicators of vulnerability to flooding are selected, measured and analyzed. Eventually the output is presented as a product in one, aggregated dimension; - a vulnerability map easy to comprehend for policy- and decision-makers and to be used in urban planning.

Spatial multi-criteria analysis

A multiple criteria evaluation may be one-dimensional, only taking into consideration variables relating to one aspect; for example, the physical nature of the environment (the slope of the terrain, land use features etc.). A multi-dimensional approach, however, means that input data are reflecting a wider variety of aspects of the reality we live in. What makes certain urban areas more vulnerable to climate change hazards like flooding is the combination of several factors. The combination of factors consist of both vulnerable land use and lack of infrastructure, but also most probably the socio-economic situation of the inhabitants, unclear governance structures, low awareness and undeveloped social networks among people. However, there exists no widely accepted set of multi-dimensional geographical indicators of vulnerability to environmental hazards. We are using variables from four dimensions – the Physical, Asset, Institutional and Attitudinal dimensions.

Stakeholder interaction

The work also presents how the stakeholders of a city are introduced to this process at an early stage, and how they as an expertise group, are providing with vital information and insight, that give the study relevance and are facilitating the subsequent steps of the methodology.

In Dar Es Salaam and Addis Ababa stakeholders from different levels of governance and across different sectors of the two cities, plus university staff and local people from vulnerable areas took part in sessions to select what they considered to be the most important factors making their city vulnerable to flooding. The selection procedure was followed by weighting of the selected indicators by the stakeholders. We used the widely adopted and straightforward analytical hierarchy process (AHP) developed by Saaty (Saaty, 1988). Another contribution from the stakeholders was to provide input on how to measure and capture data for the selected indicators in the case cities.

Detailed introductions are given to how all the indicators from the more GIS-related indicators, like mobility and low-lying areas, population density, as well as the more intangible indicators, like institutional capacity and trust, may be measured and mapped.

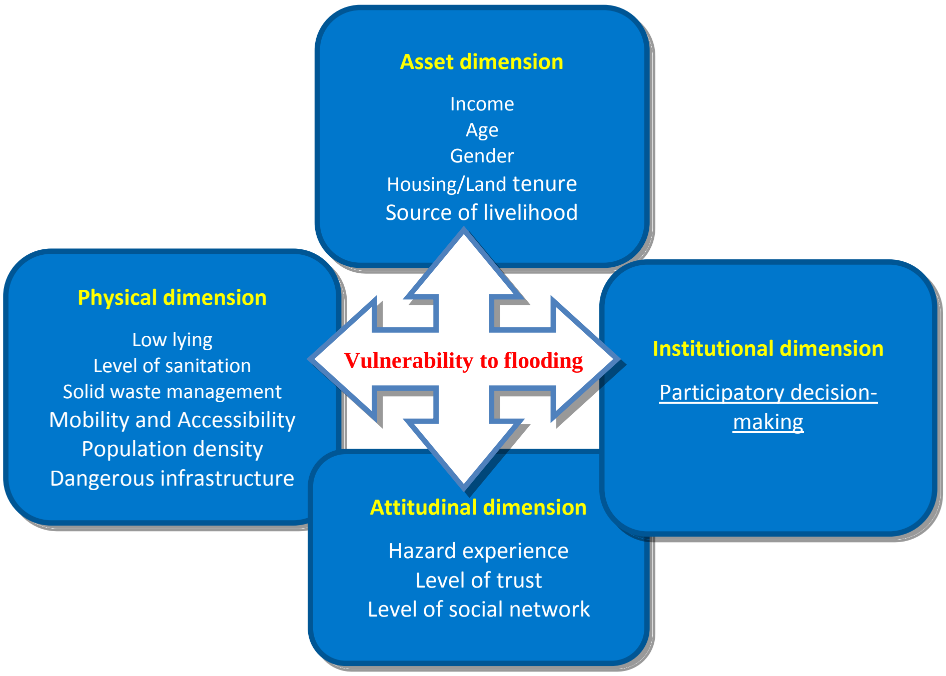


Figure 4 - The selected indicators to vulnerability of flooding by stakeholders in Dar Es Salaam

The results

A map of the vulnerability to flooding in Dar es Salaam at the resolution of the finest administrative level (the subward/mtaa; comprising approx. 5-15 000 residents) is developed. Overlaying a hydrological model, representing the areas of the city most likely to become flooded, the high-risk areas may be identified. That is, where the flood-prone areas coincide with the highly vulnerable subwards. The combined vulnerability and high-risk area map of Dar Es Salaam display a variation of vulnerability to flooding among subwards in Dar Es Salaam, and the high-risk areas are identified to be mainly the informal and unplanned areas. The map shows that it is the informal areas located to the west of the city center that are most vulnerable. However, the individual indicator maps also show that all informal settlements are not the same. For several indicators such as Age, Gender, Income and services such as Sanitation and to some extent Solid Waste Management, the most vulnerable subwards are located on the fringe of the studied area, in the south and the southwest direction from the city center. Here the dwellings are made up of the newer informal settlements where apparently there are less services and opportunities for income generation. These subwards are the new ‘expansion frontier’ of Dar Es Salaam, where the new urban in-migrants often are obliged to settle in absence of available or affordable housing closer to the city center, where job opportunities are greater. This may also be an indication that presumably poorer households with many children have no other option than to settle in the fringe areas where housing or available plots are more affordable. Thus, it is especially the vulnerability indicators of the ‘Asset dimension’ that are important in order to capture the vulnerability of such areas in Dar Es Salaam.

Among the informal areas west of the city center, on the other hand, it is the ‘Physical dimension’ of the indicators, like Low-lying areas, Dangerous industries and Population density that dominate the vulnerability to flooding. These areas are much more densely populated than the new informal settlements further out of the city. These patterns may be related to the attraction of the city center and the job opportunities found there. When living close to job opportunities people have to make do with the more compacted living conditions and take the risk of settling in the low-lying floodplains. As to the Mobility and the Accessibility indicators, it is evident that the large rivers in the studied area are taking the shape of 'screens' for the residents in many subwards. Commuters on the far side of the floodplains are effectively blocked from reaching the workplaces close to the city center unless they make significant detours during floods.

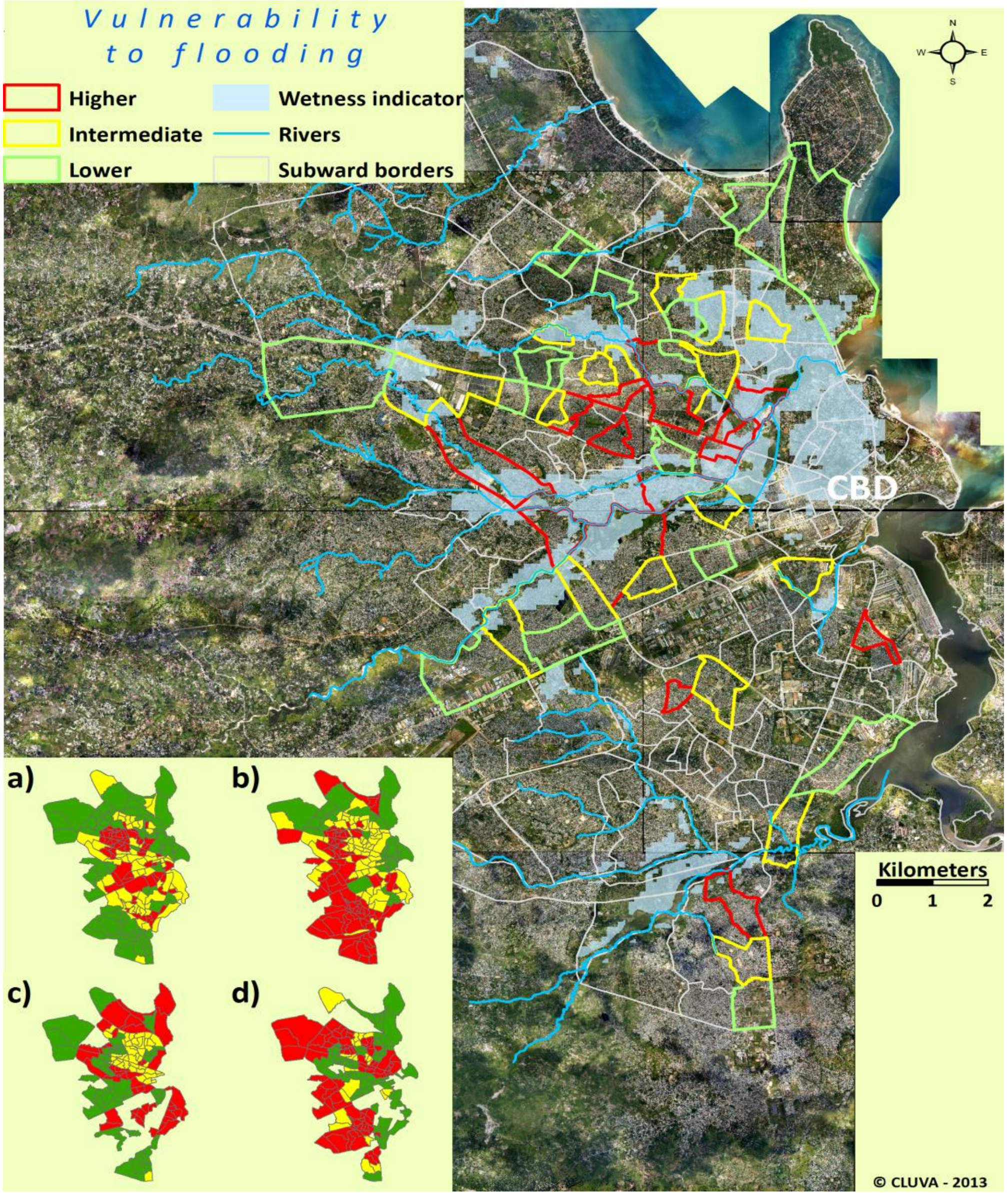


Figure 5 - The map of multi-dimensional vulnerability to flooding in Dar Es Salaam at the level of the subward administrative unit.

The map is a combination of 16 indicators selected and weighted by stakeholders (see Figure 4 above). The colouration of the individual subward borders is corresponding to the level of vulnerability. Characteristically, several highly vulnerable subwards, dominated by informal settlements, are located to the west of the Central Business District (CBD). The four minor maps depict a sample of individual vulnerability indicators, each representing a distinct dimension; a) Population density, b) Age, c) Participatory decision-making, and d) Level of Social Network[1]. The minor maps reveal that also other parts of the city may be vulnerable to flooding, but with respect to only one or a few individual vulnerability indicators. The light-blue areas in the main map are indications of where flooding is more likely to occur (according to a hydrological model using a topographical wetness index see (De Risi and Jalayer, 2013)). High-risk areas are where subwards highly vulnerable to flooding (red borders) are coinciding with areas more likely to become flooded.

Working with the more intangible vulnerability indicators (of the ‘Attitudinal’ and ‘Institutional’ dimensions) highlights that also formal and more affluent communities can be vulnerable in certain respects, like in lacking social networks and trust and participatory decision making. Interestingly, it that subwards with presumably wealthier residential land use classes (e.g. Villa area & Dispersed dwellings) were more vulnerable with respect to these indicators. The reason may naturally be that those areas are not particularly flood-prone, and that residents generally are more self-sufficient. All the same, this indicates that the preparedness may be low in those subwards if hazards of unexpected dimensions are expanding into new areas.

How to use in urban planning

The CLUVA partner cities are advised to engage in vulnerability mapping using geomatics, as it is a straightforward way to work with multi-dimensional vulnerability to the effects of climate change, and the output is easy to comprehend for planners, policy- and decision-makers. Vulnerability maps help to distinguish between areas of varying vulnerability and are an aid in understanding what particular indicators are important and where.

High-risk area maps (i.e. the overlay between vulnerability maps and hazard-likelihood maps) may be utilized to identify areas of immediate and particular concern. But also, the high-risk area maps may give indications on the ‘soon-to-become’ high-risk areas.

Vulnerability mapping should preferably take place at sufficiently large scale (i.e. high resolution) so as to give detailed information useful for planning and directed actions. In Dar es Salaam the lowest administrative level – the subward/mtaa – (equivalent to 5-15 000 residents) was agreed to be the most appropriate spatial scale.

---

[1] For a thorough introduction into mapping multi-dimensional indicators to vulnerability see wwww.cluva.eu. deliverable 3.4.

Stakeholder interaction is essential during several of the steps of the vulnerability mapping procedure. The stakeholder group ought to be represented by a wide variety of expertise and experiences (i.e. sector specialists, administrative levels, age, gender and background). The invitation of the local level stakeholders is of particular concern as they may contribute with first-hand experiences from the vulnerable areas.

A well-functioning (geo) data infrastructure is central to the success of any vulnerability mapping task. Cities should work to improve the data capture activities and the data storage of important elements of vulnerability, such as land use and orthophotos, elevation, demography, solid waste management, drainage, water provisioning, road network etc. Cities are advised to maintain a (geo)data stock (including metadata) with great details that is up-to-date. Ideally the (geo)data stock should be compiled and stored in one place and readily accessible to researchers and municipal employees.

Taking the flood-prone areas into account shows that the main high-risk areas (subwards) are located to the west of the city center. Yet again, looking at the individual vulnerability indicators, they reveal that there is no common subset of indicators explaining the vulnerability of the subwards in the high-risk areas. Consequently, the indicators relating to high vulnerability of one subward in the high-risk area, may not be the same in a nearby subward in the same flood-prone area.

Furthermore, there is a distinction between the vulnerable subwards in the peripheral areas compared to them closer to the city center. Among the subwards in the outskirts of the city the vulnerability is to a greater extent associated with a few of the Asset dimension indicators (e.g. Income and Age). Closer to the city center the vulnerable subwards are more linked to the indicators of the Physical dimension (e.g. Low-lying Areas, Population Density, Dangerous Infrastructure/Industry). These patterns may possibly be related to the attraction of the city center and the job opportunities found there. The greater job opportunities in the city center make it favourable to settle there. This produces a scarcity of available land to dwell on and generates a high population density. As a result, people with fewer resources are staying in the crowded settlements closer to the center, or are taking the risk of settling on the nearby flood-prone floodplains. The opposite alternative for people with fewer resources is to settle in the less dense peripheral areas and away from the low-lying areas, but there the job opportunities are fewer.

Interestingly, our results are indicating that with regard to formal and more affluent communities, the flooding vulnerability is explained by the indicators of the Institutional and Attitudinal dimensions (e.g. Participatory Decision-making, Level of Social Network).

3 A BI-LEVEL METHOD FOR FLOODING RISK ASSESSMENT FOR THE BUILT ENVIRONMENT

The CLUVA project adopts a bi-level approach in order to perform flood risk mapping for the urban residential areas. The final product is presented in terms of a *meso-scale* risk map for flooding of residential areas that is easily accessible for strategic and adaptive urban planning purposes. However, the risk maps are the final outcome of a series of calculations that are carried out in *micro-scale*.

3.1 Overview

The flood risk maps, which are developed as the final product of the bi-level method, are obtained by direct integration of hazard, vulnerability and exposure. This also implies that the *hazard* maps and *vulnerability* maps in meso-scale are by-products of this process. The maps of the *flood risk urban hotspots* (De Risi and Jalayer, 2013) are another by-product of this method. These maps can be used as quick screening tools by the decision-maker in order to spot the zones that are potentially high risk. The information provided by the maps of flood risk hotspots are employed in the context of the bi-scale method described herein in order to identify those areas where more detailed risk assessment in micro-scale can be performed. The hazard maps provided on the city level are basically maps of potentially flood-prone areas that are calibrated though a probabilistic procedure with respect to detailed calculations of the hydraulic profile in the micro-scale. Clearly, this implies that the meso-scale hazard maps have an indicative value and are not suitable for accurate and detailed risk calculations. The *urban morphology types (UMT,)* which is a land classification scheme proposed and implemented by Task 2.2, was adopted in order to both identify and spatially delineate the different housing categories/classes. For each category/class, the vulnerability was calculated by adopting a probabilistic approach applied in the micro-scale. This probabilistic approach takes into account the various sources of uncertainty including the building-to-building variability within each class/category (De Risi et al., 2012, Carozza et al., 2013). Figure 6 below outlines the bi-scale method outlined herein and how the meso-scale and micro-scale assessment procedures are inter-linked.

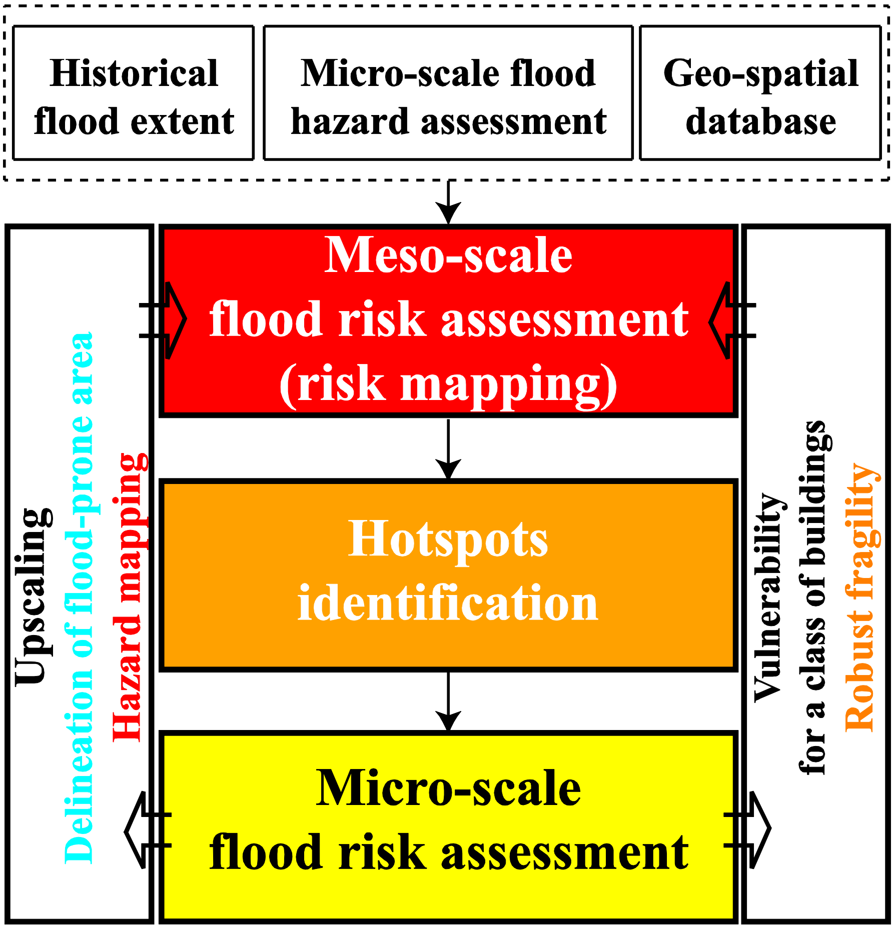


Figure 6 – A bi-scale method for flood risk assessment

3.2 Meso-scale risk maps

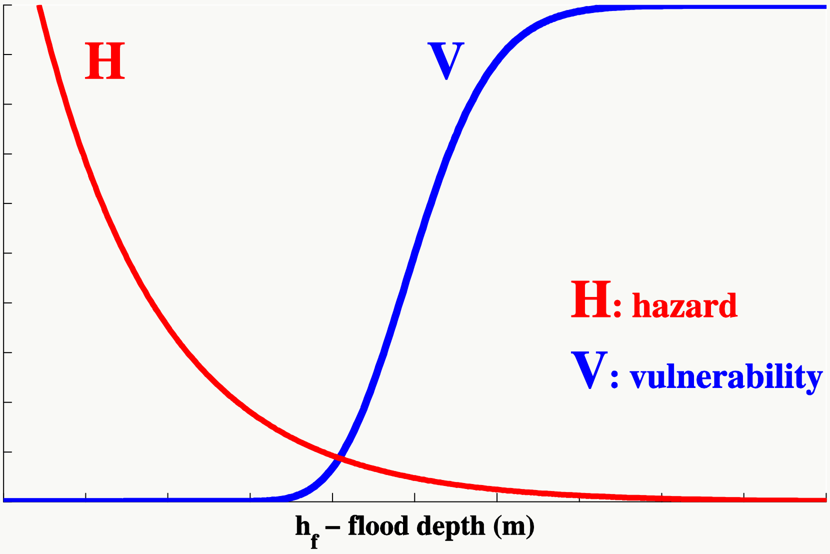
The flooding risk maps in the meso-scale are obtained through the direct integration of hazard, vulnerability and exposure. The flooding risk can be represented by adopting various metrics. One of these metrics is the annual frequency of exceeding a prescribed limit state (i.e., a certain threshold defined as a function of the building performance to flooding. Of course, the concept can be extended to other land classification categories, see the box below for more information on limit states). This risk metric can be obtained through direct integration of vulnerability and hazard (see the box below for a visual scheme of such integration for a given point within the area of interest). The flood hazard and vulnerability integration is performed by adopting the flood height as an interface variable (see the box below for more information). Another metric for risk assessment can be expressed in terms of the (expected value of) number of people in the residential areas potentially exposed to flooding risk. This metric is calculated by taking into account specific exposure data; for example, the population density datasets. The structural vulnerability herein is seen from the point of view of the effects of the natural phenomena on the physical integrity of the structure. Therefore, the calculations provide an estimate of the probability that the structure is going to lose a specific functionality due to a decrease in its physical integrity. In such a context, The fragility curves provide a visual and efficient way of representing the structural vulnerability. One of their characteristics is that they correspond to a specific structural limit state (see the box below). Formally, the flooding fragility can be defined as the probability of exceeding a specific limit state given a specific value of flood height. The flood hazard represents the frequency and the intensity of the flooding event. It is defined as the mean annual rate that a certain flood height value is exceeded. The hazard information on the meso-scale is represented as flood height values that are exceeded with a given *return period* (see the box below).

The return period:
The return period can be regarded as an alternative way of describing hazard. Formally, the return period is equal to one over the hazard. Thus, it has a dimension of time. It can also be defined as the mean time that passes between the occurrence of two flooding events of a certain intensity. The inhabitants of informal settlements sometimes use this concept to indicate the frequency and the intensity of a flood event. For example, they might say: "this kind of flooding occurs on average every two years".

Limit states:
The limit states mark various significant thresholds from the point of view of structural performance. For the problem of flood vulnerability assessment for informal settlements three limit states are considered (De Risi et al., 2013a, De Risi et al., 2013b); namely, serviceability (SE), life safety (LS), and structural collapse (CO). The limit state thresholds are expressed in terms of the critical flooding height. Serviceability is marked by the critical water beyond which the normal activities in the household is going to be interrupted, most probably due to water infiltration. For example, for an insufficiently water-tight building built on a raised foundation, the critical serviceability water height is equal to the height of raised foundation above the ground level. For buildings constructed according to flood-resistant criteria, the critical water height for limit state of serviceability is taken asymptotically equal to the critical height needed for exceeding collapse limit state assuming brittle failure modes. Collapse limit state is defined as the critical flooding height in which the most vulnerable section of the most vulnerable wall in the building is going to break. Life safety limit state defines the critical flooding height in which lives of the inhabitants is going to be in danger. This can be caused either due to the infiltration of water inside the building (with the increasing risk of drowning in water), or the structural collapse (defined in the same manner as the critical height for collapse limit state). The critical water height for structural collapse is calculated by employing structural analysis taking into account the various sources of uncertainties in geometry, material properties and construction details (see for example (Jonkman et al., 2008)). In this report, the vulnerability of typical informal building types is studied mostly for the ultimate limit state of collapse.

Flood height as an intermediate variable between hazard and vulnerability: For the bi-scale method application outlined herein, the flood height has been used as the intermediate variable (i.e., a flood intensity measure) linking the hydrographic basin analysis and flooding vulnerability assessment. This means that the hazard curves are represented in terms of the annual rate of exceeding different flood height values. On the vulnerability side, the critical flood height is used as a proxy for the flood resistant capacity of the structure. That is, the critical flood height for a given limit state is the threshold flood height value beyond which the structure no longer satisfies that limit state. For example, the critical water height for collapse is the flood height beyond which the structure collapses.

How to calculate risk? Integration of hazard curve and vulnerability curve (fragility).



3.2.1 *The required cartography:*

Geo-morphological spatial datasets (e.g., topographic maps, geology maps, land-use, ..., etc.) are fundamental data requirements in various stages of flood risk assessment. The datasets that are most critical for flood risk assessment are briefly outlined below.

Topography: The Digital Elevation Model

Topography plays an important role in flood modeling. It is demonstrated that there exists a correlation in macro-scale between the terrain elevation and the annual accumulated rainfall (Allamano et al., 2009). Moreover, topography plays a key role in the surface runoff and catchment response time (i.e. the time between the peak rainfall and the peak flow discharge). Steeper catchments have higher runoff coefficients and response time. In addition, mountain rivers flow much more quickly with respect to rivers in lowlands.

The typical instrument used to describe the topography of a generic hydrological domain is the Digitalized Elevation Model (*DEM*); that is, a 3D digital representation of terrain's surface. A typical *DEM* representation is shown in Figure 7 for the city of Addis Ababa, Ethiopia.

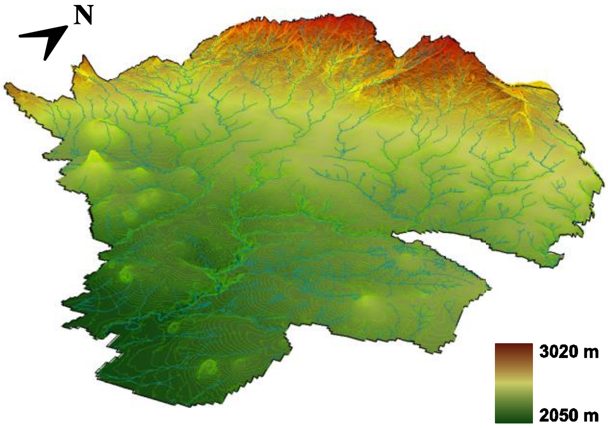


Figure 7- DEM of Addis Ababa (overlaid with the main water courses)

The DEM is used in this method for two specific purposes: a) evaluation of a meso-scale hazard indicator (Topographic Wetness Index); and b) flood diffusion/propagation by employing a classical hydraulic routine.

Land use maps

The runoff coefficient, the catchment discharge, and the catchment response time all depend on the land cover. In forest areas, tree roots increase the infiltration of water by channeling it deeply inside the soil layers down to the ground water. This effect is less pronounced in areas covered by shrubs and in pastures where the roots are much shallower.

In urbanized areas, and in particular in large cities, the large percentage of paved areas may increase the runoff coefficient significantly. This is because smooth surfaces like asphalt and concrete generally have very low infiltration capacity. This leads to larger flood discharge and lower response time in urban areas.

The land-use geo-spatial datasets can be found in GIS-based formats such as shape files and raster files. These land-use datasets/maps efficiently store the land cover type (e.g., green area, stone-paved, ..., etc.) for the spatial units considered. The resolution of the land-use maps may vary between 1:1000 to 1:100000.

UMT: Urban Morphology Types

Urban Morphology Types (UMTs) (Pauleit and Duhme, 2000, Cavan et al., 2012) form the foundation of a classification scheme which brings together facets of urban form and function. The UMT's are used to develop a geo-spatial dataset containing seamless polygons of UMT units. Each unit is associated with attribute information describing its class and its geometric properties. This geospatial layer provides complete and consistent coverage across the city having used an internally consistent process for unit delineation, data recording and coding. Linear features such as roads and rivers are usually used as the outline of UMT units, and they are matched with administrative units/zones whenever possible, e.g. for the boundary of the dataset, as shown in Figure 8.

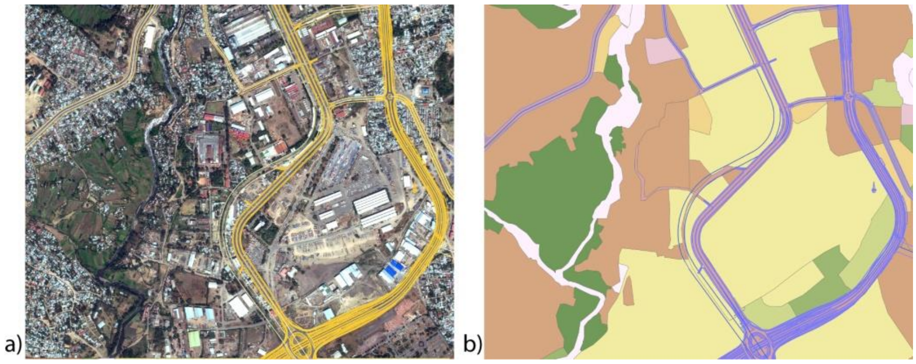


Figure 8 - Mapping UMT units (b) using ortho-rectified aerial photography (*source www.bing.it/maps*) (a), an example in Addis Ababa.

In order to build a UMT map, it is necessary to identify the various UMT classes for the specific urban area (e.g., farmland, transport, residential, etc.). The UMT classification is then subjected to a verification process in order to establish its suitability for the case-study area. The UMT classes can be detected through visual analysis of remote sensing data (ortho-rectified aerial photography) as primary method of applying the scheme (Gill et al., 2008, Pauleit and Duhme, 2000). Furthermore, for each UMT class, typical images can be captured and kept for reference with a description of its characteristics. Finally, the dataset is going to undergo field verification and approval. Once a complete UMT layer has been created through the process of digitization, it can be combined with other datasets to produce spatial indicators.

Census information

Geo-spatial data-sets having Census information are fundamental sources of information for the estimation of exposure. These datasets can be used to obtain demographic information such as population density. For example, the data used for estimating the exposure for Addis Ababa are obtained from the Central Statistical Authority of Ethiopia, and are related to the population census made in 2007. For Dar Es Salaam, the data are related to the population census made in 2007 realized by National Bureau of Statistics of the Ministry of Planning Economy and Empowerment.

3.2.2 The flood hazard zonation/mapping

The flood hazard maps in the meso scale are based on the topographic wetness index (TWI, (Giugni et al., 2012, De Risi and Jalayer, 2013)) map. This map identifies the potentially flood prone areas that have a topographic index higher than a certain threshold. The TWI maps are calibrated with respect to accurate hydraulic calculations in the micro-scale in order to perform hazard mapping differentiated by flood height for a given return period. In the context of the CLUVA project, a semi-probabilistic GIS-based methodology for hazard zoning of potentially flood-prone areas is developed. The output is presented as GIS-compatible maps of hazard zonation (by flood height) of the potentially flood prone urban areas at the meso-scale level. Upon necessary field verifications, these maps can be used as supplementary technical support for flood risk mitigation and emergency preparedness.

In Jalayer et al. (Jalayer et al., 2013a), it is demonstrated how the potentially flood-prone areas (i.e. areas identified as those with a topographic wetness index greater than a specific threshold) can be delineated through a Maximum likelihood estimation procedure applied to a spatial window in micro-scale. In De Risi et al. (De Risi et al., 2014), the concept of potentially flood-prone areas is extended in order to define a flood depth-dependent TWI threshold. Such a threshold marks the lower-bound TWI for areas with flood depth larger than a prescribed depth value given the return period. Maximum likelihood parameter estimation is then applied in order to obtain a probability distribution for the TWI threshold that corresponds to a prescribed flood depth and return period. This procedure, performed for different levels of flood depth, will help in characterizing the correlation between TWI threshold and flood depth, conditioned on a given return period. Up-scaling the results obtained for the spatial window at the micro scale level to the meso-scale, potentially flood-prone areas distinguished by flood depth larger than a specific value and conditioned on the return period can be delineated.

As an example, the procedure has been applied to the city of Addis Ababa, Ethiopia. In particular the maximum likelihood calibration of the TWI threshold for different values of flood depth has been performed on the area of Little Akaky, in the south of the city.

Hazard mapping for Addis Ababa

Figure 9 illustrates the hazards maps for the city of Addis Ababa, obtained based on the TWI maps and an up-scaling of hydraulic profile calculations in the micro-scale. The regression model developed in the methodology can be used in order to upscale the results to the meso-scale. In Figure 9 below are shown the results obtained for the whole city and for the return periods of 30 and 300 years.

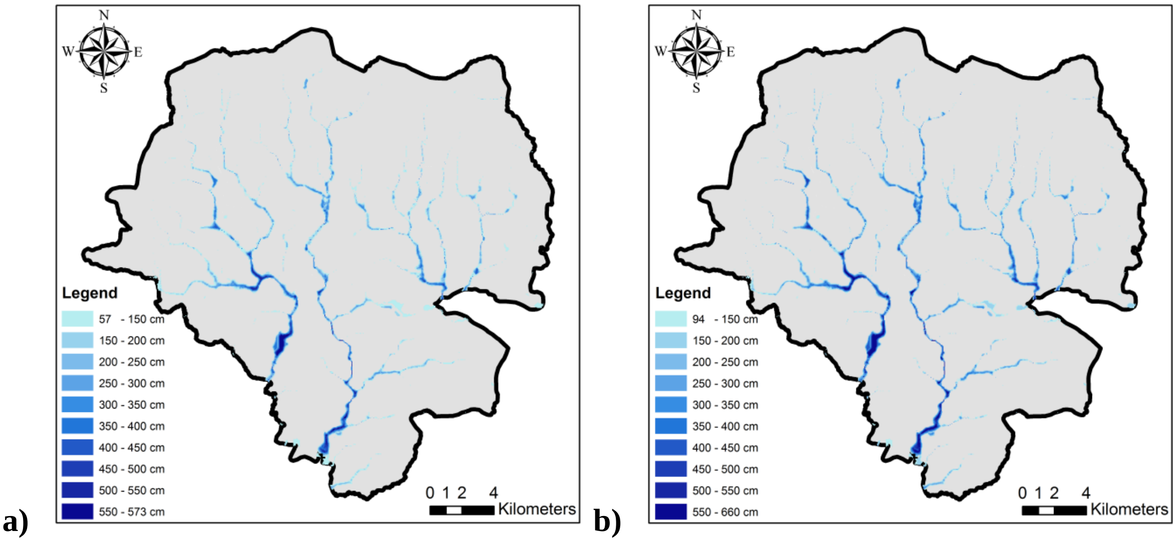


Figure 9 - Meso-scale hazard maps for a) T_R=30 Ys and b) T_R=300 Ys

Since the meso-scale hazard maps are obtained through an approximate up-scaling procedure, the resolution represented in Figure 9 is not justifiable. In fact, Figure 10 below illustrates an alternative hazard representation in which the resolution of the flood height discretization is reduced. In particular, The figure shows meso-scale hazard maps for return periods of 30 and 300 years, in which the hazard zonation thresholds are defined as follows: 0.0 – 1.0 m, 1.0 – 3.0 m, and larger than 3.0 m.

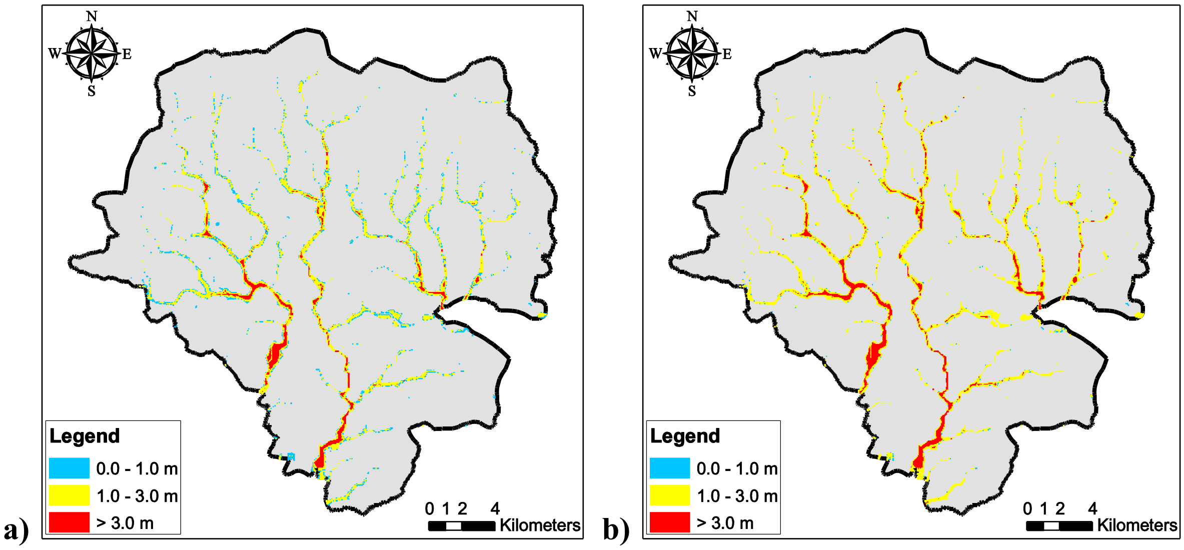


Figure 10 - Meso-scale flood hazard maps for a) T_R=30 Ys and b) T_R=300 Ys

3.2.3 The flood fragility curves for classes of structures

As mentioned before, the vulnerability of the buildings is represented by the fragility curves corresponding to prescribed limit states. The fragility curves for a specific class of buildings are calculated by employing a simulation-based analytic methodology (De Risi et al., 2013a, De Risi et al., 2013b). This methodology employs the Bayesian parameter estimation for calculating the structural fragility for a class of structures (see the box), by characterization of building-to-building variability and other sources of uncertainty based on a limited number of in-situ field surveys and remote-sensing. The following flooding actions are considered: hydrostatic pressure, hydrodynamic pressure and accidental debris impact.

The fragility assessment for a class of buildings:
The fragility curves derived herein correspond to the Collapse limit state, (CO) defined as the critical flooding height in which the most vulnerable section of the most vulnerable wall in the building is going to exceed the allowable stress requirements. The critical water height for structural collapse is calculated by employing structural analysis taking into account the various sources of uncertainties in geometry, material properties and construction details. For a prescribed limit state, the simulation procedure leads to a set of different realizations of the critical water height --reflecting the building-to-building variability in construction details and lack of information about material properties . These critical water height values are used then as data in order to calculate, using Bayesian parameter estimation (Box and Tiao, 1992), the posterior probability distribution for the parameters of prescribed analytic fragility functions. A large set of plausible analytic fragility curves can easily be simulated based on the posterior probability distribution derived. The set of simulated fragility curves can then be used in order to calculate various percentile fragility curves. **Errore. L'origine riferimento non è stata trovata.**Figure 11 below illustrates the 16th, 50th and 84th percentile fragility curves obtained for the Collapse limit state.

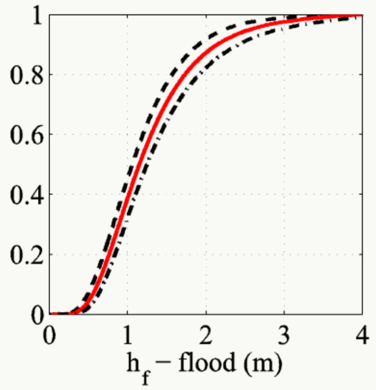


Figure 11 – Robust fragility curves for a class of buildings for the collapse limit state

Fragility (vulnerability) assessment for Addis Ababa
The portfolio of residential buildings in Addis Ababa has been divided in two main categories: formal and informal buildings. The first category is made of cement blocks (single or multi-storey structures) and and mud and wood buildings and the second category is made up of mud and wood buildings. The relative proportion of mud and wood buildings and cement blocks in the formal buildings is estimated based on the data provided by the Addis Ababa UMT map and the city Census results (included in the Appendix A). Figure 12 below illustrates the fragility curve for the two building categories/classes.

The fragility curve for the portfolio of mud and wood structures is evaluated defining the uncertain parameters as illustred in Appendix A, and are shown in **Figure 12**

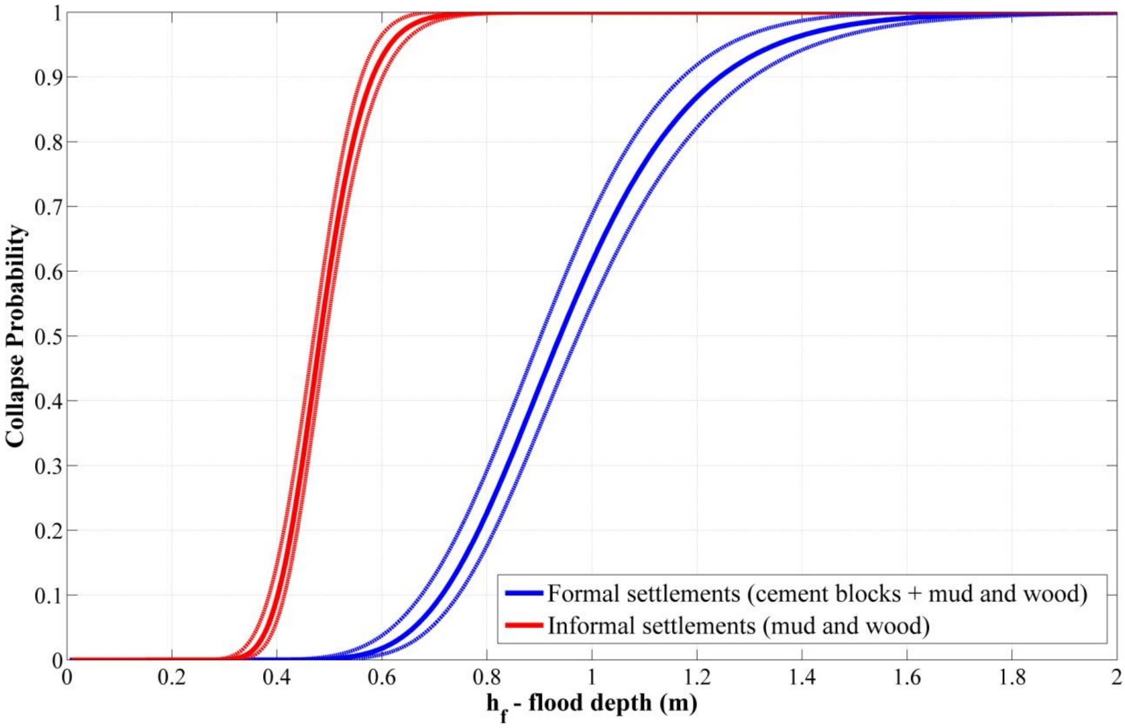


Figure 12 – Fragility curves for the formal and informal classes in Addis Ababa

Looking at the values corresponding to 50% probability of exceedance, it can be observed that the (median) capacity (in terms of the critical water height) of the informal settlements is evaluated around half of the capacity of the formal buildings.

How to read a fragility curve:
The red thick fragility curve in **Errore. L'origine riferimento non è stata trovata.** (informal settlements) can be read as: *the building is going to collapse with 50% probability due to a flood height of around 0.50m and it is going to collapse with 100% probability due to a flood height of around 0.80m.*

The blue thick fragility curve in **Errore. L'origine riferimento non è stata trovata.** (e.g., formal buildings) can be read as: *the building is going to collapse with 50% probability due to a flood height of around 0.93m and it is going to collapse with 100% probability due to a flood height of around 1.80m.*

The fragility curve for each category of buildings is reported together with two other

3.2.4 Hotspot identification

The maps of the flooding risk hotspots are particularly useful for a quick identification of the zones that are potentially subjected to high risk of flooding. These maps are a result of overlaying three GIS-based datasets: (a) map of potentially flood prone areas (identified by the topographic wetness index, TWI); (b) map of urban morphology types (UMT) for a specific class (e.g., residential, major roads, ...,etc.); (c) a population density dataset. The potentially flood prone areas are identified as the zones with a TWI index larger than a certain threshold. The TWI threshold is calibrated through a GIS-based probabilistic procedure, employing either information available about the historical flooding extent or the hydraulic profile calculated in the micro-scale. Apart from a quick identification of the high risk areas, the risk hotspot maps reveal differences in exposure characteristics for a range of different residential types; for example, between condominium/multi-storey buildings and the informal settlements. In the CLUVA project, the urban flooding risk hotspots for residential areas and the major urban roads are delineated for the cities of Addis Ababa (Ethiopia) and Dar Es Salaam (Tanzania).

Flooding risk hotspots identification for the residential buildings in Dar es Salaam
Figure 13 illustrates the delineated urban hotspots, obtained by overlaying the UMT and the TWI datasets, for maximum likelihood estimates of TWI threshold for informal settlements for Dar Es Salaam and Addis Ababa respectively (Figure 13a and Figure 13b). Herein, the information on population density obtained from the city Census 2005 for Dar and 2009 for Addis is integrated in order to estimate the number of affected people by flooding for different statistics of the TWI threshold.

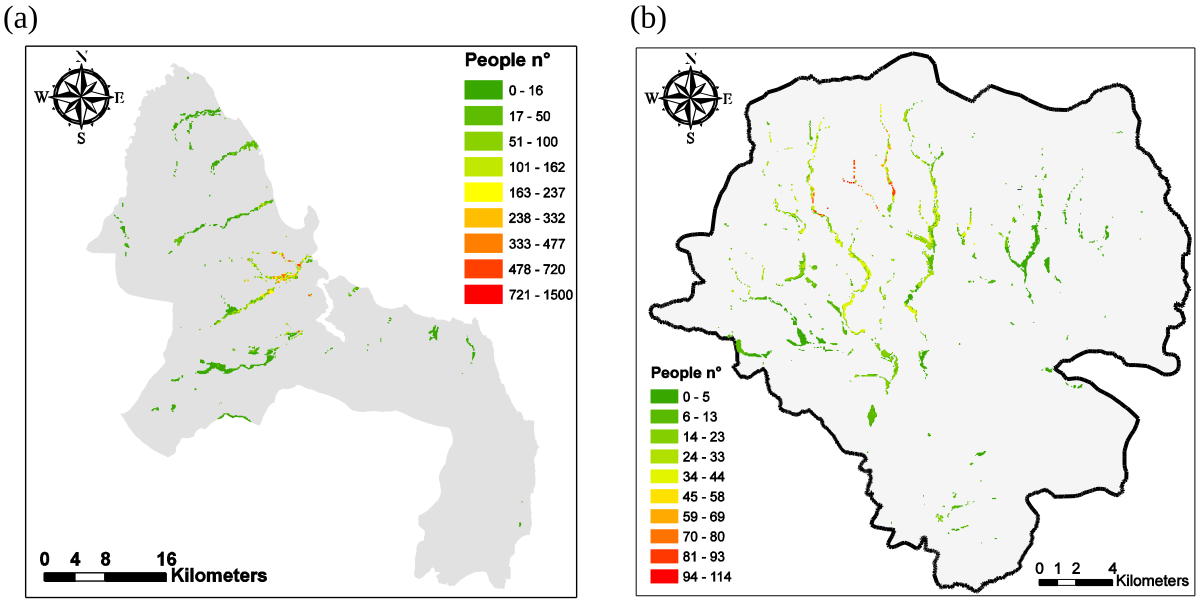


Figure 13 – Urban residential hot spots for flooding delineated for (a) informal settlements for Dar Es Salaam, and (b)Addis Ababa (De Risi and Jalayer, 2013)

Flooding risk hotspots identification for the major urban roads in Addis Ababa

Another application of the flood risk hotspots identification is reported for the UMT class of *major road corridors* in the city of Addis Ababa. Below in Figure 14 (b), the flooding risk hotspots for major urban roads (the red zones) are shown for the maximum likelihood estimate of the TWI threshold.

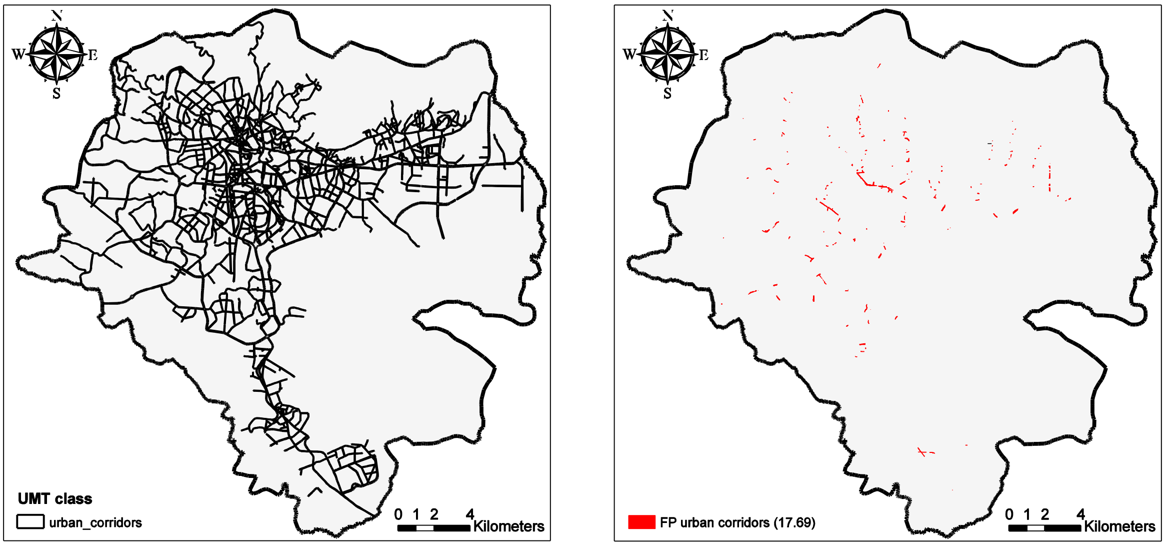

(a)
(b)

Figure 14 – (a) Urban corridor (major urban road) morphology type for Addis Ababa, (b) Urban corridors' hot spots for flooding delineated for maximum likelihood TWI threshold (Jalayer et al., 2013a)

This information can be quite useful for identifying the major roads that are most likely to be blocked in case of flooding. Eventually, intersecting the flooding hotspots for major roads with the map of points of principal interest for the city (e.g., fire station, hospitals, police stations, schools) is going to lead to a preliminary connectivity study for the road network of Addis Ababa in case of flooding. Arguably, more accurate connectivity studies need to take into account the spatial correlation in flood propagation in the city.

3.2.5 Flood risk mapping

The flood risk maps for residential buildings on the meso-scale are obtained in two different levels. In the first level, the risk, which is expressed as the annual probability of exceeding a prescribed limit state, is calculated by direct point-wise integration of hazard (hazard curve, as shown in Figure 9) and vulnerability (fragility curve, as shown in Figure 12). In the second level, the risk, which is expressed as the expected value of the number of people exposed to flooding risk, is calculated by direct integration of exposure, vulnerability and hazard for all the limit states considered. As far as it regards the vulnerability of the residential buildings, two different classes are defined: formal and informal. The UMT maps for residential buildings are used in order to spatially delineate the two above-mentioned classes.

What is the difference between (meso-scale) flood risk maps and the flood risk hotspots?
As mentioned before, the flood risk maps are obtained as a result of the direct (point-wise) integration of hazard, vulnerability (fragility), and exposure (population density dataset). The UMT map is used in order to spatially delineate the different classes of buildings. However, the flood risk hotspots are obtained as a result of a spatial overlay of the TWI map (it is not a hazard map), the UMT for residential buildings in this case and the exposure. The hotspots identification helps in prioritizing in the actions between the flood-prone and not flood-prone areas. On the other hand, the risk calculation allows for prioritization of actions within the flood-prone areas.

Flooding risk maps for residential buildings in Addis Ababa
Figure 15 below demonstrates the flood risk maps for residential buildings in Addis Ababa. It should be noted that the risk map in Figure 15 contains hazard and building vulnerability information and the risk is expressed as the annual probability of exceeding the collapse limit state for residential buildings (this metric varies between zero and one).

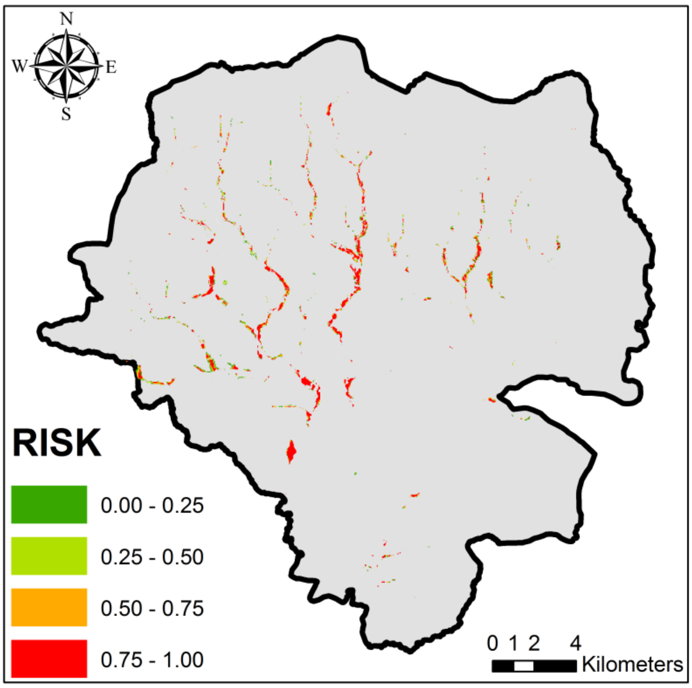


Figure 15 – Risk map for the city of Addis Ababa

Figure 16 below demonstrates the map of expected number of people (per unit area) exposed to risk (due to building collapse) for residential buildings in Addis Ababa. It should be noted that the risk map in Figure 16 contains hazard, building vulnerability, and population density information.

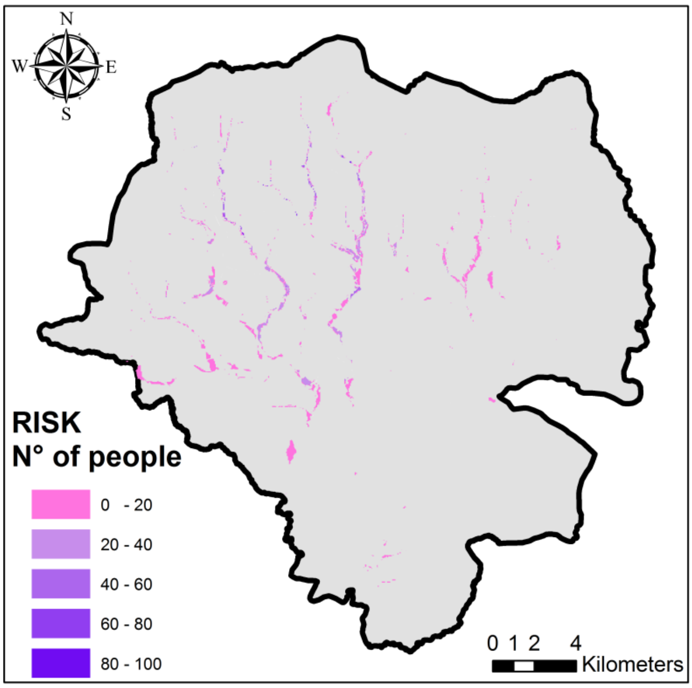


Figure 16 – Risk map in terms of number of people that may potentially risk their life due to flooding

3.3 Micro-scale risk assessment

3.3.1 Overview

Figure 17 demonstrates the flow chart of the micro-scale risk assessment procedure employed in this report. As it can be seen, historical rainfall data is transformed into rainfall probability curves. This information together with detailed topography of the area, geology maps and land-use maps are then used in order to evaluate the basin hydrograph and to develop the flooding hazard maps (i.e., inundation scenarios for various return periods). The vulnerability of a portfolio of buildings is then evaluated in terms of fragility functions for a specific limit state, based on orthophotos of the area, sample in-situ building survey and literature survey for mechanical material properties. Finally, the flooding risk map is obtained by integrating the flooding hazard map and the fragility functions.

What is the difference between meso-scale and micro-scale flood risk maps?
The same identical procedure (i.e., direct point-wise integration of hazard and fragility) is employed for obtaining the flood risk maps for meso- and micro-scale. The risk maps in meso- and micro-scale can be distinguished by the way hazard and vulnerability information is estimated. The hazard maps in meso-scale are obtained by up-scaling the results from micro-scale with significant loss of accuracy. The same for the vulnerability information (fragility curves for different classes of buildings), the mirco-scale field survey results for informal settlements are up-scaled (by undertaking some working assumptions) to the two mega-categories of formal and informal settlements in the city level.

This risk assessment methodology integrates climate modeling, hydrographic basin modeling and structural fragility modeling in order to generate the risk map for the zone of interest. The following sub-sections provide a brief over-view of the various steps outlined in the schematic diagram in Figure 17.

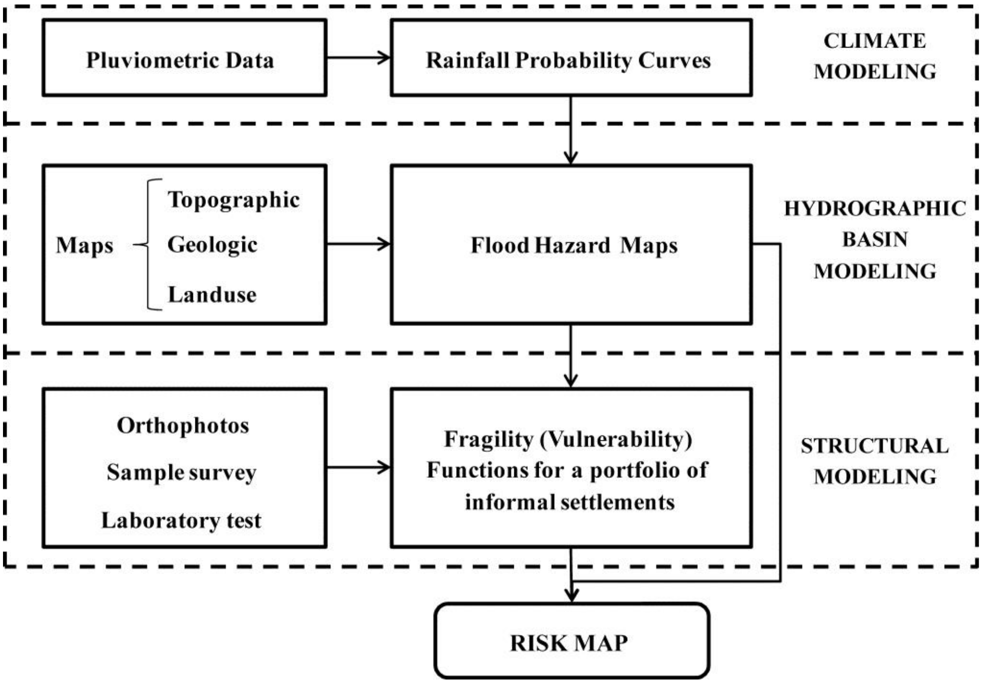


Figure 17 – Schematic Flow-chart representation of the methodology.

Historical rainfall data

The riverine flooding events are strictly connected to rainfall patterns. Therefore, the rainfall data time-series are essential pieces of information for determining the total flooding discharge. They can be obtained as pluviometer records from governmental organizations and/or internet sources (e.g., www.tutiempo.net and www.knmi.nl). It is desirable that the pluviometric data are available as precipitation extremes (maxima) recorded over a range of time intervals. The rainfall maxima recorded for different intervals are used in order to construct the rainfall curve, also known as, the Intensity-Duration-Frequency (IDF) curve (Giugni et al., 2012). The historical rainfall data, can be also used to evaluate the antecedent soil moisture condition. In hydrological modeling, antecedent moisture condition is usually associated with the pre-storm soil moisture deficit. This latter has a significant effect on the amount of rainfall drained by the river network and finally on the flooding potential of a rainstorm.

Climate-change projection rainfall data

There is increasing evidence in the favour of a correlation between the climate change and extreme weather-related phenomena (Khan and Kelman, 2011). In particular, the future climate patterns may manifest adverse effects on the frequency and/or intensity of extreme weather-related events such as floods. In compliance with the Intergovernmental Panel on Climate Change

(IPCC) scenarios (Alley et al., 2007), climate projections are evaluated using the General Circulation Model (GCM). A GCM is a mathematical model that simulates the general atmospheric and oceanic circulation over long periods of time using a specific formulation of the Navier-Stockes equation, discretized with spatial resolutions in the order of 100x100 km. Ideally, GCMs can be used to produce long-term simulations for catastrophe modeling. However, for a realistic simulation of precipitation patterns, representing the vertical structure of the atmosphere as well as the effect of the terrain on atmospheric circulation, a model must have a resolution less than 100 km. This is not practical since the calculation time increases exponentially. Therefore, using a GCM for direct simulation of precipitations is not feasible. Moreover, the GCMs are based on simplified microphysics and may not provide a solid representation of precipitation in the mountainous areas (Bellucci et al., 2012b).

On the other hand, the application of a Regional Climate Model (RCM) with horizontal spatial resolution of 10x10 km can be useful for the description of the climate variability in the local scale. However, a RCM depends on the definition of boundary conditions that can be obtained based on the results of a GCM. Finally, through statistical downscaling it is possible to obtain climatological data for finer spatial resolutions, in the order of 1x1 km. This provides the precipitation data necessary for comprehensive flood modeling. All the results used in the framework of CLUVA project are developed in the different project deliverables (Bellucci et al., 2012a, CSIR and CMCC, 2012a, Simonis, 2012, CSIR and CMCC, 2012b).

The maps reported in this deliverable are based on historical rainfall time-series and not on climate projection scenarios. The paper of Jalayer et al. (Jalayer et al., 2013b) provides an example where climate change projections have been used for micro-scale flood risk assessment in Suna neighborhood of Dar Es Salaam.

Field survey

Field surveys are useful means of laying out the spatial variation in building geometry and structural detailing within a class of buildings. Appendix A of deliverable 2.4 (De Risi et al., 2012) demonstrates the sample field survey form developed in this work for mapping out detailed geometrical configuration and construction details for the buildings. The building characteristics deemed particularly relevant for flooding vulnerability analysis are: wall thickness, height of the building, presence of barriers in front of the door, presence of raised foundation, quality of doors and windows (water-tight or not), dimension of and configuration of doors and windows, height of the barrier, and height of the raised foundation. The micro-scale risk assessment framework relies on a relatively small number of building surveys as opposed to exhaustive surveying of all the buildings in the zone of interest.

Material properties

Ideally, structural material properties should be obtained based on the results of specific laboratory tests. The laboratory tests mimic the construction materials and relevant techniques used in the field in order to evaluate material mechanical properties such as, the elastic modulus (E), the Poisson ratio (ν), the compression strength (f_m), the shear strength(τ), and the out of plane flexural strength (f_{fl}). The laboratory tests can also be used to gain an estimate of deterioration due to elongated contact with water. In this work, existing literature results are used in lieu of case-specific laboratory tests. In the Appendix B of Deliverable 2.4 (De Risi et al., 2012) there is an extensive description of the test to perform to know the material mechanical properties. In the same deliverable there is a comprehensive literature survey on the mechanical properties for the material frequently used in the construction of informal settlements in Africa.

3.3.2 *Micro-scale hazard assessment*

A schematic diagram of the procedure used for micro-scale hazard assessment is illustrated in Figure 18. As it can be observed, IDF curves, geologic and land-use information are used to calculate the hydrograph, which is characterized by the discharge denoted by Q and the total water volume (i.e., the area under the hydrograph), for different return periods. This information, together with the topographic map of the zone of interest are used in a two-dimensional diffusion model in order to generate the maps of maximum water height and velocity for each node of a lattice covering the zone of interest for a given return period (the flood hazard map). The flooding hazard curve for each point within the zone of interest can be constructed by plotting the inverse of the return period versus the flooding height corresponding to that return period, for all the considered return periods (De Risi et al., 2012).

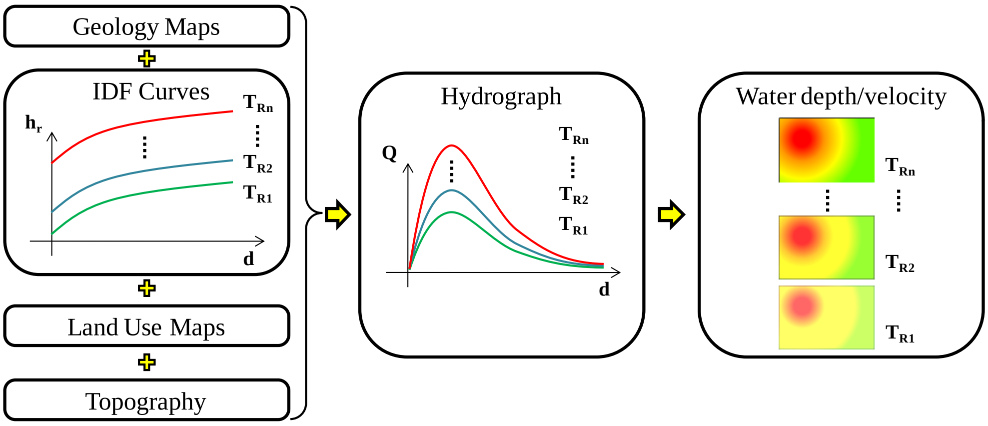


Figure 18 - The schematic diagram of the procedure for micro-scale flood hazard assessment

Micro-scale hazard profiles for Addis Ababa

Figure 19 illustrates the micro-scale inundation profiles (flood height values for a given return period) are reported for T=300 years for two areas in the city of Addis Ababa: a) Little Akaki area, in the southern part of the city and b) an area located between Arada, Yeka, Bole and Kirkos sub-cities, in the central part of Addis.

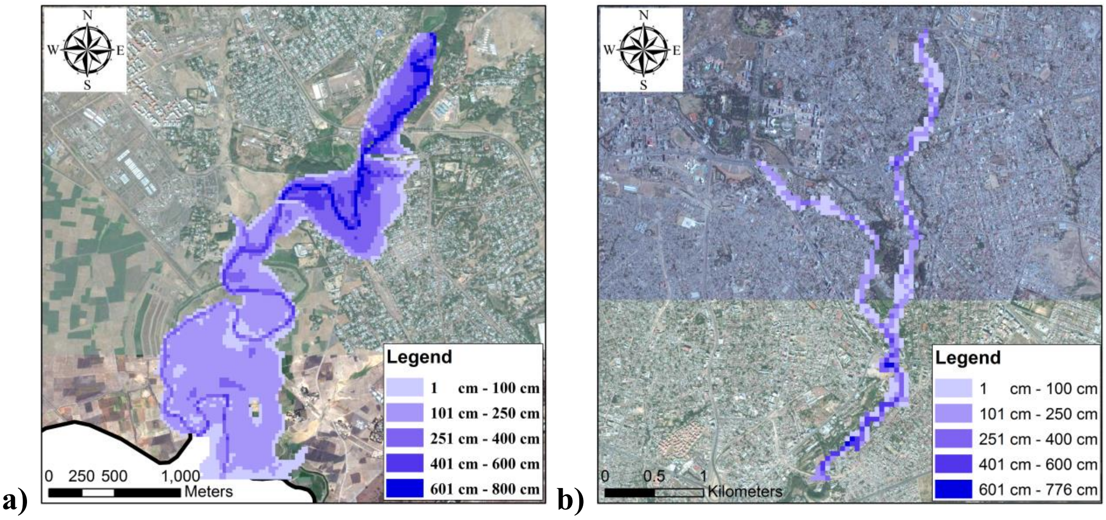


Figure 19 - Inundation profiles corresponding to T_R=300 years for a) Area1, and b) Area2

Hazard upscaling for Addis Ababa

The hydraulic profile calculated in the micro-scale is used in order to perform approximate hazard mapping on the city level for Addis Ababa. To this end, the definition of flood prone areas (areas characterized as having flood depth values larger than zero), as those with a topographic wetness index (TWI) larger than a certain threshold, is extended by defining flood depth-dependent TWI threshold for various depths and conditioned on a prescribed return period. For a given flood depth value, maximum-likelihood estimate for the TWI threshold is obtained by maximizing the probability of a correct identification of the contour with flood depth values larger than the specified value, conditioned on the return period and for a spatial window in micro scale (Little Akaki, a.k.a. Area 1 in Figure 19a). The resulting TWI threshold versus flood depth pairs are used inside a linear regression scheme in order to create a predictive model for flooding depth as a function of the TWI threshold and given the return period. The predictive regression model is verified analytically for another spatial window outside the zone where the model has been calibrated (Area 2 Figure 19b). Finally, this model is used for up-scaling the results into meso-scale. These leads to hazard zonation maps for various return periods. Such maps, in absence of more accurate results, can be used for a rapid screening and identification of areas that need immediate actions and more detailed evaluations (see De Risi et al. (De Risi et al., 2014) for details). Figure 20a,b show the overlay of the predicted hazard map (through upscaling) and the calculated hydraulic profile for Area 1 (Figure 20a, based on which the map is calibrated) and Area 2 (Figure 20b, used for verification of the upscaling procedure).

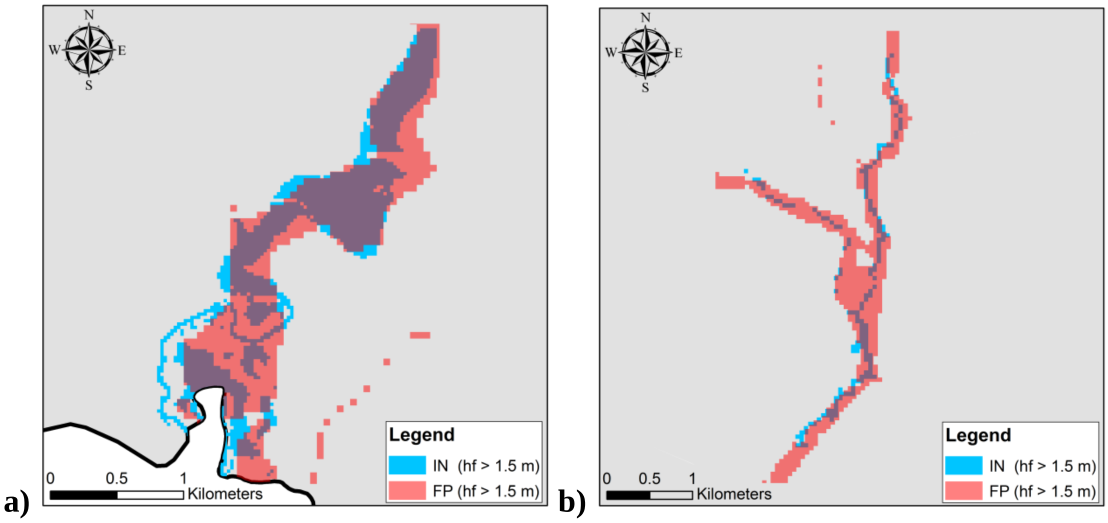


Figure 20 - Overlay of the predicted hazard maps through upscaling (in red) and the calculated inundation profile (in blue) for h>1.5m corresponding to T_R=300 years for a) Area1, and b) Area2

3.3.3 The fragility curves for a class

The procedure employed for the assessment of the vulnerability of buildings is suitable for a portfolio of buildings which demonstrate similar features with respect to the performance of interest (i.e., they belong to the same class of structures). Of course, the methodology can be extended to cases where more than one class of structures can be identified. As far as it regards the vulnerability assessment for the informal settlements located in the same neighborhood, these buildings can usually be classified as one single class. For instance, they usually have the same number of floors, the same wall material (e.g., adobe, rammed earth or cement stabilized blocks), the same roof material (e.g., corrugated iron sheet or wooden frame) and similar geometrical patterns. Therefore, the portfolio of the informal settlements located in the same neighborhood can be classified as one class of buildings. Figure 21 demonstrates the schematic diagram of the procedure used for the calculation of the fragility curves for a given class of buildings and for a prescribed structural limit state. The procedure is divided into three distinct modules: (i) data acquisition, (ii) simulation, and (iii) fragility assessment. The resulting fragility curve, also known as the robust fragility curve, represents the vulnerability of the class of the buildings for the prescribed limit state. The fragility curve for the class of buildings and the prescribed limit state is then integrated together with the flooding hazard curve in order to estimate the flooding risk expressed in terms of the mean annual rate of exceeding the limit state, as per the discussed methodology. The limit state probability values can then be implemented in order to calculate the expected annual loss or the expected number of affected people (see (De Risi et al., 2013b, De Risi et al., 2013a) for more information).

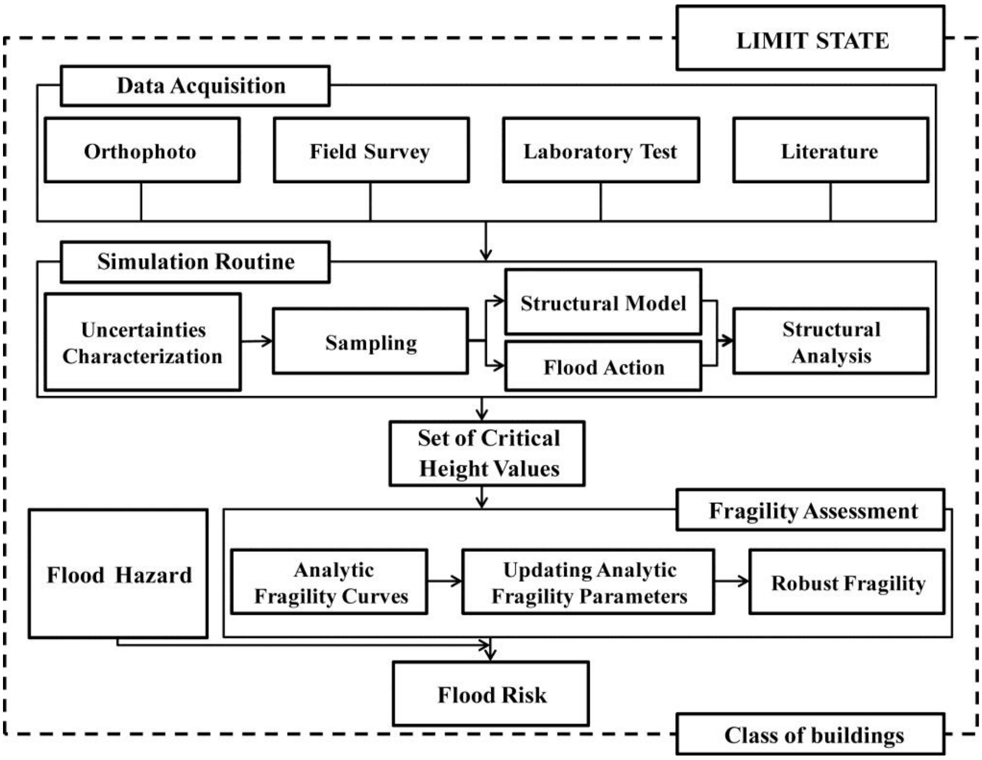


Figure 21 - The schematic diagram of the procedure used for the assessment of the vulnerability of a class of structures.

Micro-Scale boundary recognition
In this work, boundary-recognition based on recent orthophotos of the zone of study is employed in order to determine the plan dimensions of the buildings. As depicted in Figure 22, this helps in obtaining the buildings' dimensions in the zone of interest.

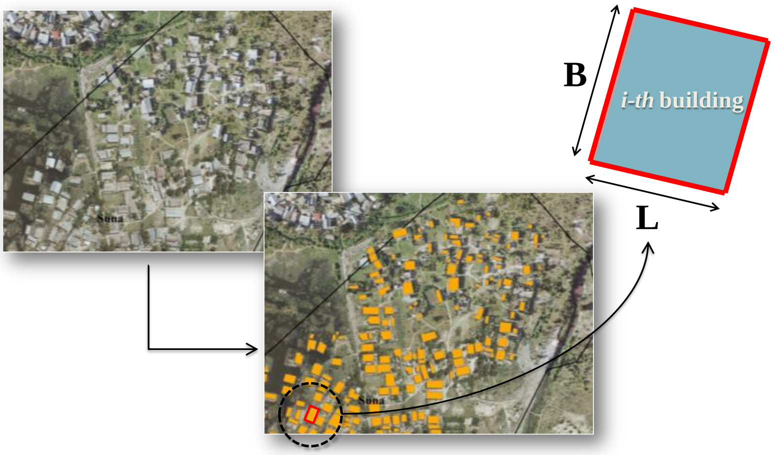


Figure 22 - Boundary recognition based on the orthophotos

As it will be demonstrated later, this boundary-recognition procedure is useful for obtaining information both for structural modeling and also for the estimation of the exposure (e.g., expected number of inhabitants, expected repair costs).

3.3.4 The risk maps in micro-scale

By direct integration of the hazard and fragility curves, the risk maps expressed in terms of the annual probability of exceeding the collapse limit state can be obtained. Again, the UMT maps can be employed in order to spatially delineate the two classes of formal buildings and informal settlements.

Micro-scale risk maps for Area 2, Addis Ababa

Figure 23 below illustrates the risk maps for Area 2 obtained trough integration of the hazard curves (based on hydraulic calculations) and the fragility curves for the two classes, formal and informal. It can be observed that the meso-scale hazard map manages to capture the areas most prone to flooding risk, although it seems to lead to a more conservative risk mapping.

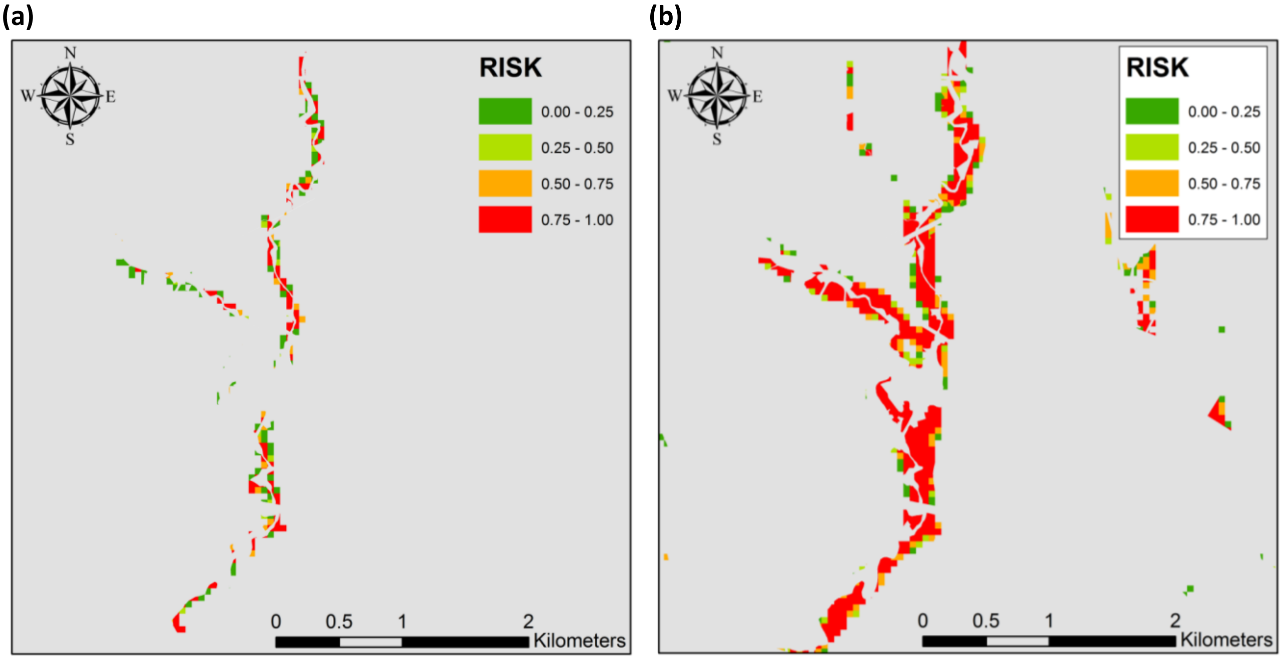


Figure 23 - (a) The annual probability of exceeding the collapse limit state (risk) calculated based on the calculated inundation profiles; (b) the zoom-in of the hazard map in the meso-scale to the same area

3.4 The relevance in urban planning

As mentioned in the introduction to this report, the methods presented in this chapter could be classified as out-come vulnerability methods, in comparison with the more context-oriented vulnerability methods. These methods also provide the formal and technical basis for incorporating the information coming from climate projection scenarios in risk assessment for climate-related hazards. Focusing the attention on flooding risk, an overview of the methods used in CLUVA

Project for the assessment of risk to the built environment (Tasks 1.3 and 2.1) has been presented in this chapter. These methods can provide valuable support to decision-making, by providing quantified risk information. From the point of view of the end-results that can be of support to decision-making, several maps can be produced in two different spatial scales:

- The hazard maps (micro- and meso-scale)
- The vulnerability maps (meso-scale)
- The risk maps (micro- and meso-scale)
- The maps of risk hotsposts (meso-scale)
- The maps of flood-prone areas (meso-scale)

The maps of flood-prone areas and the resulting maps of flooding risk hotspots (incorporating the exposure and the spatial delineation of buildings) provide very efficient and quick screening tools to the urban planner and decision-maker for identifying the areas that need immediate actions. The hazard, vulnerability and risk maps in the city level (meso-scale) can be useful for the urban planner in order to prioritize the actions to be taken for the critical areas. These actions can include for example adoption of more accurate small-scale risk assessment procedures and undertaking various prevention strategies. The prevention strategies range from planning for structures that help in mitigating the flood risk, to relocation policies (if advisable), territory restriction measures and actions that aim at increasing of public awareness.

4 A FRAMEWORK FOR MULTI-RISK ASSESSMENT AND ITS POTENTIAL IMPACT ON PLANNING AND DECISION-MAKING

The multi-risk concept refers to a complex variety of combinations of risk (i.e. various combinations of hazards and various combinations of vulnerabilities) and for this reason it requires a review of existing concepts of risk, hazard, exposure and vulnerability, within a multi-risk perspective. Under certain harmonization conditions there is a logic transition from the single- to the multi-risk assessment. The purpose of the multi-risk assessment is to make comparable the results of different types of risks taking into account possible interactions. Given the complexity of processes that the multi-risk problem poses, and in particular, with the kind exposed elements found in the African context and analysed in the CLUVA project, the multi-risk framework contemplates two levels of analysis: The first-level analysis, in which the evaluation of the potential physical damages is performed, and the second-level analysis, where a set of social context conditions is considered. One of the most challenging elements of the multi-risk assessment is the translation of the output of the quantification and analysis processes in useful information for decision-making under uncertainty. In fact, this is a critical step to consolidate the importance of the multi-risk analyses and also to define their ultimate importance and usefulness in the resolution of critical societal problems.

The results of the multi-risk analysis can be an essential tool for a decision making based on a comprehensive appreciation of all the risks threatening the target to be protected. To build the link between multi-risk assessment and decision-making it is necessary to define proper multi-risk evaluation strategies. Decisions may include ‘yes’ or ‘not’ decisions on a single action, may rank a series of alternative options, or may select the best option among a set of alternatives.

The first significant decision that the decision-maker has to face is to answer the question: Is the risk acceptable? At this point it is important to distinguish two important concepts: acceptable risk and tolerable risk. The risk is ‘acceptable’ when the occurrence probability is so small or the consequences are so slight that individuals or the society are willing to take or be subject to the risk that the event might occur. A risk that is not acceptable must be managed in order to reduce it –if possible– to an acceptable level, or at least to a ‘tolerable’ level. A tolerable risk is then a non-negligible risk that has not yet been reduced to an acceptable level (because unable to reduce the risk further, or the costs of doing so are excessive) and then is tolerated. A tolerable risk is still unacceptable, but its severity has been reduced to a point where it can be tolerated.

Deciding whether an assessed risk is acceptable or not and determining a tolerable level is a subjective matter, and decision-makers must take into account different elements as the scientific evidence, the uncertainty, the defined objectives, the available resources, etc. Even though there is not a magic rule for establishing acceptable and tolerable levels of risk, several principles are often used by decision-makers. Examples include the precautionary principle, the weight of evidence, the ALARA (as low as reasonably achieved), the ALOP (appropriate level of protection), or by using ‘reasonable relationships’ between the cost of the mitigation actions and the reduction in risk.

Beyond the direct comparative analysis, decision-makers can use the multi-risk results also to evaluate the effects of different risk management options (RMO). When different RMOs have been formulated, the decision-maker must get from a number of options to the best option by (1) assessing the options, (2) comparing the options, and (3) making a decision selecting the best option. In this process, the results of the multi-risk assessment may be of great help.

For example, let’s consider that a set of risk curves have been calculated for a given hazard are of interest. To assess different possible mitigation options (MO), a decision tree can be used to represent alternative MOs, as shown for example in Figure 24 for the floods. The decision node in Figure 24a considers different possible MOs oriented to reduce the flood risk. The first path (Figure 24b) shows the case without implementing any MO and then it represents assessing the existing risk. The other two paths are two possible mitigation options (MO1 and MO2) that might be proposed (Figure 24c and d, respectively).

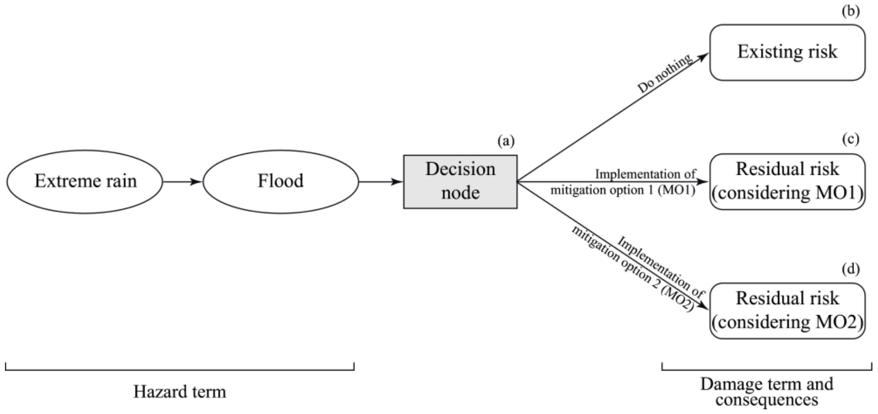


Figure 24 - Simplified example of a decision tree in which a decision node is used to assess the consequences of different scenarios defined by the implementation of alternative mitigation options.

After assessing a set of MOs, a set of data composed by the cost of implementing the MO, the residual risk, and the reduced (or mitigated) risk is available to help the decision-maker. For example, the decision-maker can use this information to perform cost/benefit analyses to decide where and how to operate more effectively considering the available resources.

The harmonized quantitative assessment of all the types of hazards threatening a specific target, of their interactions, and of the expected losses, is the result provided by an ideal multi-risk approach. These harmonized results are necessary in order to be readily used by the decision makers. The theory and examples discussed in this chapter are aimed at showing in general terms how the approach can be implemented and how the results can be used to help decision makers. Nevertheless, the kind of applications spans in a wide range of cases according with the specific needs of the problem.

For example, a long-term multi risk assessment, covering several tens of years, is useful for city and land use planning purposes. The assessment of the occurrence of each hazard with a given intensity, the probabilistic assessment of cascade events, and the quantitative assessment of the impact on the target area (in terms of economic or human losses) is a fundamental tool for deciding how a city could develop in time or to determine the destination of the land use. This is becoming a crucial element in particular when considering areas prone to the effects of time varying agents, such as those related to climate change. Conversely, short-term multi-risk assessments (days to months) are useful to analyse one of several possible scenarios to consider the relative consequences. Several disaster mitigation options can be analysed, compared and the residual risk can be calculated (see Garcia-Aristizabal et al. 2014 and (D2.14) Garcia-Aristizabal et al. 2013 for more in-depth discussion of the multi-risk assessment framework and its implication in urban-planning and decision-making).

5 CONCLUSIONS

The concept of vulnerability to climate change is central in the CLUVA project. One of the main attributes of this project is a polyhedric and multi-faceted outlook to vulnerability. In such context, two main interpretations of vulnerability stemming from two main classes of thought and background are adopted. These two interpretations, can be distinguished by the disciplines that nurture and host them. The interpretation known as the contextual vulnerability has its roots in social sciences and considers vulnerability as a starting point for climate-related adaptation strategies. The alternative interpretation called the outcome vulnerability has its root in scientific disciplines and is focused on the future impact of the climate-related hazards. This report discusses the alternative methods employed for vulnerability assessment in the CLUVA project. These methods, in one way or another, can be classified within the framework of one of the interpretations described above.

The *multi-dimensional vulnerability mapping* method is based on the contextual vulnerability framework and adopts various vulnerability indicators that are evaluated and verified based on stakeholders' participation. The CLUVA partner cities are advised to engage in vulnerability mapping using geomatics, as it is a straightforward way to work with multi-dimensional vulnerability to the effects of climate change, and the output is easy to comprehend for planners, policy- and decision-makers. Vulnerability maps help to distinguish between areas of varying vulnerability and are an aid in understanding what particular indicators are important and where. High-risk area maps (i.e. the overlay between vulnerability maps and hazard-likelihood maps) may be utilized to identify areas of immediate and particular concern. But also, the high-risk area maps may give indications on the ‘soon-to-become’ high-risk areas. Vulnerability mapping should preferably take place at sufficiently large scale (i.e. high resolution) so as to give detailed information useful for planning and directed actions. Stakeholder interaction is essential during several of the steps of the vulnerability mapping procedure. The stakeholder group ought to be represented by a wide variety of expertise and experiences (i.e. sector specialists, administrative levels, age, gender and background). The invitation of the local level stakeholders is of particular concern as they may contribute with first-hand experiences from the vulnerable areas. A well-functioning (geo) data infrastructure is central to the success of any vulnerability mapping task. Cities should work to improve the data capture activities and the data storage of important elements of vulnerability, such as land use and orthophotos, elevation, demography, solid waste management, drainage, water provisioning, road network etc. Cities are advised to maintain a (geo)data stock (including metadata) with great details that is up-to-date. Ideally the (geo)data stock should be compiled and stored in one place and readily accessible to researchers and municipal employees.

The *bi-scale method for flooding risk assessment for the built environment* is based on the outcome vulnerability framework and provides quantified estimates of risk and vulnerability for the residential buildings and with specific reference to flooding hazard. As a quick screening tool, the maps of urban flooding risk hotspots can be generated for the built environment. These maps are obtained as an overlay of the map of potentially flood-prone areas and geo-spatial datasets having information about exposure. These maps are an effective tool for identifying the areas that are potentially exposed to high risk. The city-level flood risk maps can be used by the urban planner for differentiating and prioritizing actions within the flood prone areas. In contrast to the maps of urban risk hotspots that provide relative information on exposure to risk, the risk maps provide information about the metric adopted for risk assessment (e.g., the annual probability of exceeding the collapse limit state or the expected number of people exposed to flooding risk). The risk maps are calculated by direct point-wise integration of hazard, vulnerability and exposure. The hazard maps are obtained by up-scaling the inundation profile calculated in the micro-scale to the city level through a GIS-based probabilistic procedure. Vulnerability mapping is done by distinguishing different classes within the built environment, whose vulnerability is represented by the corresponding fragility curve for a prescribed limit state. The fragility curves for a given limit state and a given class are calculated by adopting an efficient probability-based Bayesian procedure which relies on non-exhaustive sample field surveys. It should be emphasized that the risk maps obtained through the bi-scale procedure described herein, before being used by the urban planner, need to be subjected to an extensive verification process. This verification process involves very simple steps: performing laboratory tests for the material used in buildings (see Deliverable 2.4 for some recommended tests), performing several sample field surveys for various classes of buildings, create a database of the damages caused by previous flooding events, mark the maximum water levels reached during the flooding events, create a denser array of meteorological stations and decrease the duration of the rainfall recording intervals.

The *multi-risk assessment framework* provides a powerful tool for taking into account and harmonizing various critical risks. The results of the multi-risk analysis can be an essential tool for a decision making based on a comprehensive appreciation of all the risks threatening the target to be protected. To build the link between multi-risk assessment and decision-making it is necessary to define proper multi-risk evaluation strategies. Decisions may include ‘yes’ or ‘not’ decisions on a single action, may rank a series of alternative options, or may select the best option among a set of alternatives.

As a final word, the set of policy implications produced by the various vulnerability assessment methods are going to focus on different issues. The *multi-dimensional vulnerability mapping* method is going to provide indicators that directly reflect the kind of factors that are deemed most critical by the city and the community. The *bi-scale method for flooding risk assessment for the built environment* is going to lead to risk metrics that have at their center the physical integrity of buildings. Arguably, the loss of physical integrity in the building is going to lead to significant and devastating socio-economic consequences. The maps produced based on this approach are going to be crucial for delineating the zones not suitable for construction or zones that should be evacuated, the zones that are in dire need of being reinforced and the zones that may be suitable for future construction. The *multi-risk assessment framework* provides means of taking into account and combining various potential risks. This will provide the urban planner a quantified metric that incorporates the impact of several risks.

APPENDIX A

The tables oulined in this appendix list the parameters considered as uncertain in the caculation of the fragility curves for the limit state of collapse for the two classes of formal and informal settlements. These parameters take into account both the uncertainty material properties and also the building-to-building variability within a certain class. See De Risi et al. 2013b for adetailed description of how these information can be translated into fragility curves. The details of structural analysis and modeling for mud and wood and cement brick buildings can be found in CLUVA deliverable D2.5 (Carozza et al., 2013).

n° OF SURVEYED BUILDINGS	15
n° of buildings with visual signs of degradation DG	10
n° of buildings with ***Pl***	6
n° of buildings with ***Ba*** *given* ***Pl***	0
n° of buildings with ***Ba*** *given not* ***Pl***	0
n° of buildings with DS given ***Pl*** and ***Ba***	0
n° of buildings with DS given ***Pl*** and not ***Ba***	2
n° of buildings with DS given not ***Pl*** and ***Ba***	0
n° of buildings with DS given not ***Pl***, not ***Ba***	2
n° of buildings with WS given ***Pl***, ***Ba***, and ***DS***	0
n° of buildings with WS given ***Pl***, not ***Ba***, and ***DS***	2
n° of buildings with WS given not ***Pl***, ***Ba***, and ***DS***	0
n° of buildings with WS given not ***Pl***, not ***Ba***, and ***DS***	2
n° OF SURVEYED WALLS	60
n° of walls with ***D***	24
n° of walls with W given ***D***	20
n° of walls with W given not ***D***	0

Table A-1 The field survey results for mud and wood buildings (survey performed by the EiABC team)

Geometrical property	Distribution type	Mean Min	Standard Deviation Max
L (m) - wall length	Uniform	5.00	10.00
H (m) - wall height	Uniform	2.50	3.50
t (m) - wall thickness	Deterministic	0.04	0.04
L_w (m) - window length	Uniform	0.80	1.20
H_w (m) - window height	Uniform	0.80	1.00
H_{wfb} (m) - window rise	Uniform	0.80	1.20
L_d (m) - door length	Uniform	0.80	1.20
C_d (m) - corner length	Uniform	0.80	0.90
H_f (m) - foundation rise	Lognormal	0.20	50%
H_b (m) - barrier height	Uniform	0.10	1.00

*The walls are considered fixed at the bottom side.

Table A-2 The probability distributions considered for parameters taking into account the geometric building-to-building variability within the class of mud and wood buildings

Mechanical properties	Distribution type	Mean	Standard Deviation

		Min	Max
γ (kN/m3) – wood weight	Uniform	6.0	8.0
γ (kN/m3) – mud weight	Uniform	14.0	18.0
f_m (MPa) – wood compression strength	Uniform	10.0	20.0
τ_0 (MPa) – wood shear strength	Uniform	5.0	10.0
f_{fl} (MPa) – wood flexural strength	Uniform	2.0	3.0
E (MPa) – wood linear elastic modulus	Uniform	12000	15000

Table A-3 The probability distributions considered for parameters related to mechanical material properties for mud and wood material

n° OF SURVEYED BUILDINGS	10
n° of buildings with visual signs of degradation DG	0
n° of buildings with ***Pl***	10
n° of buildings with ***Ba***	0
n° of buildings with DS	10
n° of buildings with WS	10
n° OF SURVEYED WALLS	40
n° of walls with ***D***	12
n° of walls with W	28

Table A-4 The field survey results for cement brick buildings (survey based on working assumptions)

Geometrical property	Distribution type	Mean Min	Standard Deviation Max
L (m) - wall length	Normal	4.00	6.00
H (m) - wall height	Uniform	2.50	3.50
t (m) - wall thickness	Uniform	0.15	0.130
L_w (m) - window length	Uniform	0.80	1.20
H_w (m) - window height	Uniform	0.80	1.00
H_{wfb} (m) - window rise	Uniform	0.80	1.20
L_d (m) - door length	Uniform	0.80	1.20
C_d (m) - corner length	Uniform	0.80	0.90
H_f (m) - foundation rise	Lognormal	0.10	30%
H_b (m) - barrier height	Uniform	0.10	1.00

*The walls are considered fixed at the bottom side and hinged at the two lateral sides.

Table A-5 The probability distributions considered for parameters taking into account the geometric building-to-building variability within the class of cement brick buildings

Mechanical properties	Distribution type	Mean Min	Standard Deviation Max
f_m (MPa) - compression strength	Uniform	1.50	2.00
τ_0 (MPa) - shear strength	Uniform	0.095	0.12
f_{fl} (MPa) - flexural strength	Uniform	0.14	0.40
E (MPa) - linear elastic modulus	Uniform	1200	1600
G (MPa) - shear elastic modulus	Uniform	500	667
γ (kN/m^3) - self weight	Uniform	11	13

Table A-6 The probability distributions considered for parameters related to mechanical material properties for cement-brick material

The fragility curve for the mega-category of formal settlements is obtained as weigthed average of the fragility curves evaluated for mud and wood and cement bricks buildings as reported in the equation below.

$$F_{formal} = W_{Mud\,\&\,Wood} \cdot F_{Mud\,\&\,Wood} + W_{cement\ bricks} \cdot F_{cement\ bricks}$$

where $F_{Mud\,\&\,Wood}$ and $F_{cement\ bricks}$ are the fragility curves for mud & wood and cement brick buildings in the formal settlements, respectively. $W_{Mud\,\&\,Wood}$ and $W_{cement\ bricks}$ are weights that represent the proportion of the areal extent of the formal settlements made up of mud & wood and cement bricks buildings, respectively. These weights are evaluated as reported below:

$$W_{Mud\,\&\,Wood} = 0.41$$
$$W_{cement\ bricks} = 0.59$$

These weights are evaluated by intersecting the UMT map for Addis Ababa and the city Census results (as far as it regard a break-down with respect to building material per sub-city)

REFERENCES

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

Alley, R., Berntsen, T., Bindoff, N. L., Chen, Z., Chidthaisong, A., Friedlingstein, P., Gregory, J., Hegerl, G., .Heimann, M. & Hewitson, B. (2007). IPCC 2007: summary for policymakers. *Climate Change***,** 1-18.

Bellucci, A., Bucchignani, E., Gualdi, S., Mercogliano, P., Montesarchio, M. & Scoccimarro, E. 2012a. *D1.1 - Data for global climate simulations available for downscaling*. Available: http://www.cluva.eu/deliverables/CLUVA_D1.1.pdf.

Bellucci, A., Bucchignani, E., Gualdi, S., Mercogliano, P., Montesarchio, M. & Scoccimarro, E. 2012b. *Data for global climate simulations available for downscaling*. Available: http://www.cluva.eu/deliverables/CLUVA_D1.1.pdf.

Box, G. E. P. & Tiao, G. C. (1992). *Bayesian Inference in Statistical Analysis*, John Wiley & Sons, Inc.

Carozza, S., De Risi, R. & Jalayer, F. 2013. *D2.5 - Guideline to Decreasing Physical Vulnerability in the Three Considered Cities*. Available: http://www.cluva.eu/deliverables/CLUVA_D2.5.pdf.

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

Cred (2012). Disaster Data: A Balanced Perspective. Centre for Research on the Epidemiology of Disasters.

Csir & Cmcc. 2012a. *D1.5 - Regional climate change simulations available for the selected areas*. Available: http://www.cluva.eu/deliverables/CLUVA_D1.5.pdf.

Csir & Cmcc. 2012b. *D1.7 - Climate maps and statistical indices for selected cities* Available: http://www.cluva.eu/deliverables/CLUVA_D1.7.pdf.

De Risi, R. & Jalayer, F. 2013. *D2.1 - Identification of hot spots vulnerability of adobe houses, sewer systems and road networks*. Available: http://www.cluva.eu/deliverables/CLUVA_D2.1.pdf.

De Risi, R., Jalayer, F., De Paola, F., Iervolino, I., Giugni, M., Topa, M. E., Mbuya, E., Kyessi, A., Manfredi, G. & Gasparini, P. (2013a). Flood risk assessment for informal settlements. *Natural Hazards***,** 1-30.

De Risi, R., Jalayer, F., De Paola, F. & Manfredi, G. (2014). A semi-probabilistic GIS-based method for meso-scale flood hazard assessment. *ASCE-ICVRAM-ISUMA.* Liverpool.

De Risi, R., Jalayer, F., Iervolino, I., Kyessi, A., Mbuya, E., Yeshitela, K. & Yonas, N. 2012. *D2.4 - Guidelines for vulnerability assessment and reinforcement measures of adobe houses*. Available: http://www.cluva.eu/deliverables/CLUVA_D2.4.pdf.

De Risi, R., Jalayer, F., Iervolino, I., Manfredi, G. & Carozza, S. (2013b). VISK: a GIS-compatible platform for micro-scale assessmen of flooding risk in urban areas. *In:*

PAPADRAKAKIS, M., PAPADOPOULOS, V. & PLEVRIS, V. (eds.) *COMPDYN, 4th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering.* Kos Island, Greece.

Downing, T. E., Ringius, L., Hulme, M. & Waughray, D. (1997). Adapting to climate change in Africa. *Mitigation and adaptation strategies for global change,* 2**,** 19-44.

Garcia-Aristizabal A, P. Gasparini, and G. Uhinga (submitted) Multi-risk assessment as a tool for decision-making (Book Chapter), in: Urban Vulnerability and Climate Change in Africa (a Book to be published in the series “Future Cities”, Springer).

Garcia-Aristizabal A, W. Marzocchi, G. Ambara, and G. Uhinga (2013) Reports and map on multi-risk Bayesian scenarios on one selected city (Dar Es Salaam, Tanzania). Tech. Rep. D2.14, CLimate change and Urban Vulnerability in Africa (CLUVA project), URL http://www.cluva.eu/deliverables/CLUVA\s\do5(D)2.14.pdf, grant No. 265137

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

Giugni, M., Adamo, P., Capuano, P., De Paola, F., Di Ruocco, A., Giordano, S., Iavazzo, P., Sellerino, M., Terracciano, S. & Topa, M. E. 2012. *D1.2 - Hazard scenarios for test cities using available data*. Available: http://www.cluva.eu/deliverables/CLUVA_D1.2.pdf.

Jalayer, F., De Risi, R., De Paola, F., Giugni, M., Manfredi, G., Gasparini, P., Topa, M. E., Nebyou, Y., Yeshitela, K., Nebebe, A., Cavan, G., Lindley, S., Printz, A. & Renner, F. (2013a). Probabilistic GIS-based method for delineation of urban flooding risk hotspots. *Natural Hazards - under review*.

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

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

Khan, S. & Kelman, I. (2011). Progressive climate change and disasters: connections and metrics. *Natural Hazards,* 61**,** 1477-1481.

O'brien, K., Eriksen, S., Nygaard, L. P. & Schjolden, A. (2007). Why different interpretations of vulnerability matter in climate change discourses. *Climate Policy,* 7**,** 73-88.

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

Saaty, T. L. (1988). *What is the analytic hierarchy process?*, Springer.

Simonis, I. 2012. *D1.6 - Web Climate Sercive*. Available: http://www.cluva.eu/deliverables/CLUVA_D1.6.pdf.

Un-Habitat. 2009. *Slums: Levels and Trends, 1990-2005. Monitoring the Millennium Development Goals Slum Target.* Available: http://www.unhabitat.org/downloads/docs/9179_33168_Slum_of_the_World_levels_and_trends.pdf.

Un-Habitat. 2010. *State of the World's Cities 2010/2011 - Cities for All: Bridging the Urban Divide*. Available: http://www.unhabitat.org/pmss/listItemDetails.aspx?publicationID=2917.

Watts, M. J. & Bohle, H. G. (1993). The space of vulnerability: the causal structure of hunger and famine. *Progress in human geography,* 17**,** 43-67.