Master's Thesis

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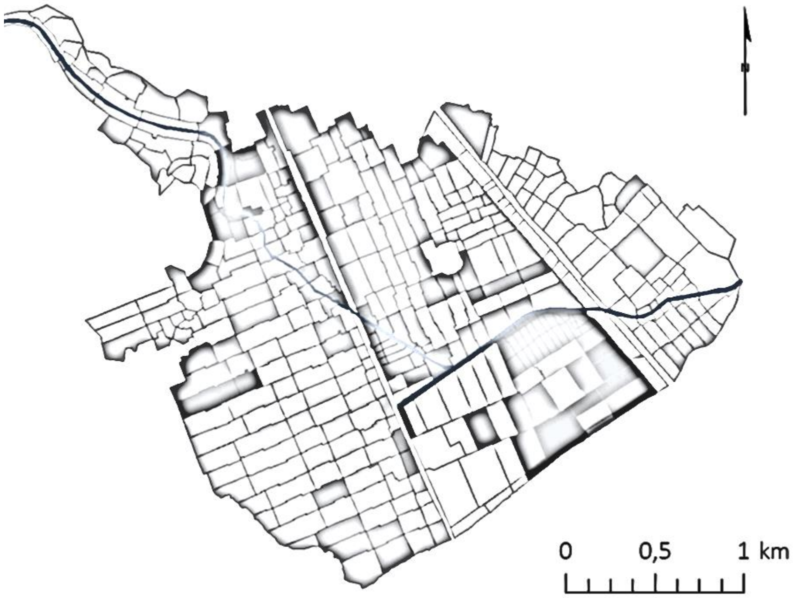
Urban Flood Resilience

A case study on how to integrate flood resilience in urban planning.

Louise Bertilsson
Karin Wiklund



Division of Water Resources Engineering
Department of Building and Environmental Technology
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Preface

This master thesis project has been carried out between March and September 2015 for the Laboratory of Computational Hydrology at the Federal University of Rio de Janeiro in cooperation with the Department of Water Resources Engineering at Lund University.

We would like to express our deepest gratitude to our supervisor Professor Marcelo Gomes Miguez for giving us the opportunity to be a part of this research and for offering tremendous support and help. We would like to express a great thanks to our co-supervisor Aline Pires Vérol for her support and for providing simulations and data needed for the research. The kindness and help offered by the students and employees at the Laboratory of Computational Hydrology also meant a lot to us.

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Louise Bertilsson & Karin Wiklund

Lund, September 2015

Abstract

Climate change and increasing urbanization gives societies great challenges in managing urban planning for a sustainable future. Urbanization aggravates floods by increasing the amount of impermeable surfaces and by modifying flow routes. Resilience is the capability to recover from a stress and high resilience is seen as the goal of a healthy development. By including the concept of resilience in flood risk analysis and decision making, flood control will be more complete and intrinsically more sustainable. This project investigates how flood resilience can be modeled in a way that allows spatialization. An index called Spatialized urban Flood RESilience Index, S-FRESI, was built and tested with promising results. It can be used to measure and visualize the changes in flood resilience obtained by flood control measures. The index show areas that are particularly vulnerable to flood hazards and where suggested flood measures enhances the resilience.

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Acronyms and Glossary

Cell/flow cell	The small sub-catchment module used for flood simulations in MODCEL.
Consequence	An impact such as economic, social or environmental damage/improvement that may result from a flood. May be expressed quantitatively (e.g. monetary value), by category (e.g. High, Medium, Low) or descriptively. (Samuels & Gouldby, 2009)
DRR	Disaster Risk Reduction
Exposure	Exposure is a measure of the total number of receptors in a given area and the proportion of these that will be exposed to the flood water. (Samuels & Gouldby, 2009)
Extreme event	An extreme event is an event that has a low probability of occurrence (i.e. statistically does not happen very often, although this does not mean that two rare events cannot happen in close succession). (Samuels & Gouldby, 2009)
Flood Hazard	Flooding that has the potential to result in harm; the description of flood hazard may include the physical characteristics of a flood at a given point; including depth, duration and velocity. (Samuels & Gouldby, 2009)

Flood risk	The combination of the probability of a flood event and of the potential adverse consequences for human health, the environment, cultural heritage and economic activity associated with a flood event. (Directive 2007/60/EC)
Flood risk management	Continuous and holistic societal analysis, assessment and mitigation of flood risk (Samuels & Gouldby, 2009)
FRI	Flood Risk Index
Hazard	A physical event, phenomenon or human activity with the potential to result in harm. A hazard does not necessarily lead to harm. (Samuels & Gouldby, 2009)
Inundation	Flooding of land with water
MODCEL	Urban flood simulation program
RS	Resilience scale
S-FRESI	Spatialized Flood RESilience Index. The index constructed in this thesis project.
Spatialize	To give spatial form to: think of as spatial or in space relations: localize in space (Merriam-Webster, 2015)
Vulnerability	Characteristic of a system that describes its potential to be harmed. This can be considered as a combination of susceptibility and value (Samuels & Gouldby, 2009).
UNISDR	United Nations International Strategy for Disaster Risk reduction

1. Introduction

The combination of climate change and increasing urbanization gives future societies great challenges in managing sustainable urban planning. Recent studies show that climate change is very likely to alter the hydrological cycle, causing a higher probability of extreme weather events such as droughts and floods (Bates, et al., 2008). Urbanization aggravates floods by increasing the amount of impermeable surfaces and by modifying flow routes. A flood by itself is a natural phenomenon that usually is connected with positive consequences. It is not until it occurs in the urban environment that it tends to have devastating consequences for the people inhabiting the area, both in terms of destruction of property and as a threat to human health.

To prevent and reduce flood damage, urban water management and flood risk management are key factors. They aim to provide society with knowledge and tools regarding water related issues. These managements are continuously evolving and identifying concerns not only related with inundation, but also considering the possible socioeconomic variables affected by inundation. Recent technical literature about urban water management often discuss the concept of resilience (see for example: Andoh & Iwugo 2002, Sayers, et al. 2013 and Brown et al. 2008). Resilience is the capability of a system to continually change and adapt, yet remain within critical thresholds, or simply, what the system's ability to cope with change is.

To help decision-makers invest in sound projects, it is of great importance to make relevant data easy to grasp. Since resilience is such a broad term, assigning values to it is rather complicated. However, for comparative purposes a measurable resilience capacity would have potential. What gets measured gets done. By ranking different flood control methods efficiency over long time, the choice of which project to implement would be facilitated.

In the changing society of today, it can be complicated to know how to invest in measures that will be efficient not only today, but also in a future urban environment. The aim of resilience capacities is to handle the uncertainty and try to find the flood control measures that are believed to maintain efficiency even in the long run.

By including the concept of resilience in flood risk analysis and decision making, flood control will be more complete and intrinsically more sustainable. A resilience scale, RS, was initially proposed in the doctoral dissertation of Veról (2013). It was meant to give supportive information concerning the choice of flood control measure. The main idea was to compare the long term outcome of projects and evaluate which ones can withstand stress over time. The RS provided an integrated response for the system as a whole, helping to classify projects future behavior in a simple way by a comparable single value. The model has shown some difficulties in spatialization which justifies the development of a new model.

1.1 Objective

The objective of this project is to investigate how resilience can be modeled in a way that allows spatialization.

This project aims to modify the RS or change the structure of it in order to enhance its spatialization. The aim of this work is to develop a tool to facilitate decision making concerning large infrastructural projects regarding urban drainage.

Spatialization is very useful when detailing projects since it helps to identify fragile areas in order to boost the projects responses. The spatialized resilience is meant to show areas that are particularly vulnerable to flood hazards and where suggested flood measures enhances the resilience. It is meant to be used as an information tool to support decision making concerning different design alternatives on flood control.

The model should be simple and easy to use, but still give a reliable result about the watershed behavior on the whole. It should concretize the long term effects of a proposed flood control measure. The tool should also aid in planning the development of residential areas less impacted by unexpected or hazardous flood related scenarios in flood prone cities.

The aim of this thesis project also is to contribute to the development of Veról's mathematical model RS.

1.1.1 Research Questions

1. What models already exist to calculate flood resilience?
2. How well does Veróls model of calculating resilience scale work after spatialization?
3. Can an alternative resilience model be developed?
4. How can the alternative model be tested?
5. How does the alternative model respond in tests?
6. Can the alternative model be used as a tool in decision making concerning urban drainage?

1.2 Limitations

This is a case study of a river basin in Rio de Janeiro, hence, the model components will be based on the situation in this specific region. The model will be tested only on the case study area.

It is difficult to decide when complete resilience is reached, hence, the model will not be an absolute measurement of resilience capacity – it will be a measurement used for comparative purposes. It is only possible to draw conclusions about whether the resilience in an area has increased or decreased.

The study area was chosen due to sufficient amounts of available data. However, this area is rather uniform in geography and architecture which might entail problems concerning testing and conclusions.

The study does not include information about historical flood responses or testing of real flood events.

1.3 Disposition

The report begins with a literature review in chapter two. The literature review comprises the background in disaster risk reduction and the base of understanding resilience in general, flood resilience and flood risk. Chapter three includes a description of how resilience is incorporated and applied in today’s society. It also gives an overview of former studies within the research area. Chapter four explains the case study that was developed, to give an understanding for the case study approach, the scenarios that were tested and also to provide an introduction to the case study area. Chapter five presents the credibility and source of the input data. Chapter six explains the analysis method and the methodology of the work. Also how the model is constructed and what the model is thought to express. The results and the analysis coupled with information from the literature review are discussed in chapter seven. Recommendation for future research is also listed as an important part. Conclusions are presented in chapter 8. Lastly, the appendix provides a deeper explanation of the Flood Risk Index and phase I – Modifications of the RS.

2. Literature Review

The literature review will provide an overview of basic concepts and knowledge in order to comprehend flood resilience in a broader perspective.

2.1 Resilience

The concept of resilience has become widely used and trendy in the sustainable development debate. During recent years the concept has more or less exploded in the sustainability discussion and in environmental research. The term has been around for centuries, but it wasn't until the 60's that the term started to be used in scientific publications (Becker, 2014).

The definition of resilience can vary greatly in composition depending on the context and choice of literature. Resilience is generally described as the ability to recover from a stress and high resilience is commonly seen as the goal of a healthy development.

Resilience is a complex concept and to identify if a system is resilient or not can be a rather difficult task. Walker (2002, apud Pendall et al., 2010) points out this complexity and says that: ''Any discussion of resilience in a particular ecosystem must be prefaced by the question, 'The resilience of what to what?'… The system needs to be defined in terms of (1) the variables that describe the state, and (2) the nature and measures of the external shocks.''

Foster et al. (2010) describe two common analysis approaches that stretch across various fields, from psychology to engineering, and that builds the base for the resilience concept. Firstly, equilibrium analysis, which would be the recovery to a normal state (in a single equilibrium system) or the change to a new adapted normality (in a multiple equilibrium system). Secondly, complex adaptive systems analysis, underline how multiple elements in a system interact to create dynamic feedbacks making a system more or less adaptable.

Additionally, resilience could be looked upon from two different angles: in a post-stress situation – how well did a system respond to and recover from a disaster, or as capacity measure in a pre-stress situation – how well prepared is a system to respond and recover from a disaster (Foster, 2011).

In order to be resilient, it is important to be prepared for future events, both with a short- and a long-term perspective. Forecasts and future evolvement of our societies can however never be taken for certain (Abhas , et al., 2013). Long-term plans need to be made, but it is important to consecutively evaluate them to keep them updated. By being prepared and having access to reliable forecasts it is easier to construct early warning systems and recovery plans to build a resilient society (Schelfaut, et al., 2011).

Many of the issues concerning resilience are about raising awareness about the subject, sharing information between professionals, creating clear responsibility hierarchies etcetera. These are important aspects but there is also a demand for a more concrete way of looking at resilience to enable the operationalization of the concept.

In operationalization of resilience it is central to find weaknesses and vulnerabilities in our existing systems. Studies have shown that it is important to identify and protect a society's essential services. The essential services can be communication, energy production, emergency services, health services, transportation, water supply, sanitation et cetera. Many of these services are interconnected and if one is malfunctioning it is likely that others are also affected. If they can stay operational during an unexpected or hazardous event, society is more likely regain full function within a reasonable time (McBain, et al., 2010) (Abhas , et al., 2013).

Working with resilience today is mainly done in a conceptual manner; there are various frameworks and guidelines that introduce the concept and how to build future resilient cities. The lack of practical tools for operationalization makes implementation quite a complicated procedure for decision-makers.

2.1.1 Commonly Used Definitions for Resilience

The United Nations International Strategy of Disaster Reduction, UNISDR, defines resilience as “The ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions” (UNISDR, 2009).

EU defines resilience, very similarly as “the ability of an individual, a household, a community, a country or a region to withstand, to adapt, and to quickly recover from stresses and shocks” (European Commission, 2012).

2.1.2 How to Measure Resilience

Today there is no agreement on how to accurately measure resilience due to the variation of interpretations of the concept. However, within the field of disaster risk reduction studies two general approaches to resilience measurements can be identified; the inductive approach and the deductive approach (Windler, 2014). In the inductive approach a set of relevant characteristics are chosen and then expressed and measured. The deductive approach is based on independent measurements (Béné, 2013).

Existing resilience measurements are mainly based on the inductive approach (Béné, 2013). They are generally based on the theoretical idea of what resilience is and they tend to be case-specific, emerging from a particular discipline. This makes it easier to apply the measurement in different geographical settings or cultures etc. but the measurement cannot easily be generalized (Windler, 2014).

The two approaches can complement each other as the deductive approach could be used to validate or test the inductive measurement since it is independent from household or community characteristics (Windler, 2014).

2.2 Flood Resilience

Because many of society's sectors are vulnerable to floods, it can help to look at flood hazards and flood resilience separately from society's total resilience. If a higher flood resilience can be achieved it will most likely lead to a higher resilience also for other areas.

2.3 Flood Risk

Risk in general and flood risk in particular have a range of meanings and uses. The understanding of risk often differs greatly between everyday language and technical language. The colloquial meaning of risk is, for example, often synonymous with the probability of a negative consequence or even chance. Technical terms has a broader meaning and usually also includes some way of valuing the consequences. However, technical definitions often disagree somewhat depending on which field it has been developed for and to what purpose (Samuels & Gouldby, 2009).

Components that are involved in the risk concept are often: a hazard and its probability, the severity of the hazard, type and degree of exposure, susceptibility to the hazard, and the value of the receptors (Samuels & Gouldby, 2009). Receptors are the people, property or other components of the system that could be damaged. These components should be further defined for each case since it is not self-explanatory what they mean, what they include and how they should best be measured.

As part of the European Union's Floods Directive, 2007/60/EC, a programme called FLOODsite was created as an aid to the implementation of the directive (FLOODsite, 2009). FLOODsite defines risk as "a function of probability, exposure and vulnerability", which is very similar to the definitions by many other organisations. For example the UN defines risk as "The combination of the probability of an event and its negative consequences" (UNISDR, 2009).

A conventional expression of risk is (Zimmermann, 2005):

$$Risk = Hazard * Vulnerability$$

Equation 2.1

Where hazard includes the frequency and magnitude of the event and vulnerability includes the exposure, susceptibility and value of the receptor (Figure 2.1).

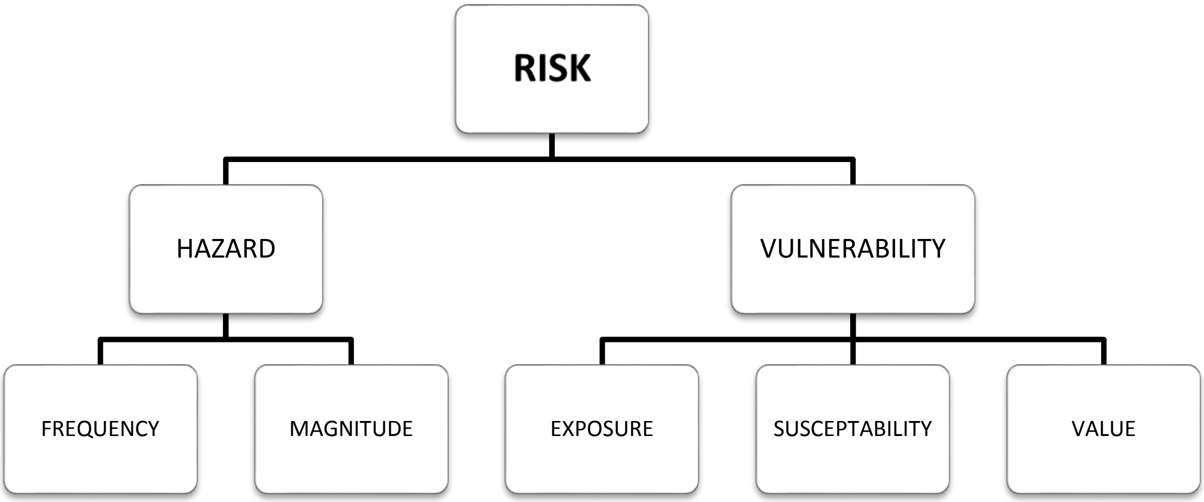

Figure 2.1 Common risk approach

The hazard applicable in this paper is the flood event. A flood occurs when water covers land that is usually dry (Samuels & Gouldby, 2009). A flood becomes a hazard when the flood has the potential of harming the receptors. In this paper the term flood is used concerning issues where floods are caused by hydrometrological events and cause problems or inconveniences in the urban environment.

The frequency is the estimation of how likely a flood is to happen, and the magnitude is the flood levels combined with the water velocity. Vulnerability is the potential of a receptor to be harmed (Samuels & Gouldby, 2009), but the exact composition can be somewhat obscure and is defined rather differently through the literature. According to, among others, the UN´s definition, vulnerability has three sub-elements (Figure 2.1): exposure is the amount of receptors that could be affected by a flood; susceptibility is the inclination of a receptor to experience harmful consequences of a flood; and value is anything that can be considered to be of worth in the society, e.g. lives, health, security or monetary wealth. (Samuels & Gouldby, 2009)

The flood risk only exists when some degree of weight can be put to each of the previously mentioned terms. In the extension of this, flood risk can only exist in a human system; it has no significant meaning in a completely natural system.

3. Application of Resilience

The concept of resilience is not only broad, it is also quite new in urban planning terminology and in terms of its operationalization. Governments often lack the knowledge, tools, strategies, organization, and in many cases even political will to handle flood resilience. They often fail to prepare their society for a possible flood, including how to handle the course of a flood event and how to recover from it (McBain, et al., 2010).

On a global level the work with Disaster Risk Reduction, DRR, (which includes resilience) has gained popularity over the last 20 years. There are numerous organizations working with the development of this area. In a report made by Winderl (2014) for the United Nations Development Program the evolution of measuring resilience is discussed. Six phases of maturity are presented; from early framework models with no defined indicators, to models that are institutionalized and collect data regularly. Winderl further states that "no general measurement for disaster resilience has been empirically verified yet" (Winderl, 2014).

Even if no measurements have been empirically verified there are ideas of how to express resilience. For example, Liao (2012) presents an alternative planning practice where she suggests a surrogate measure – the percent floodable area. She argues that resilience cannot be directly observed and therefore it must be inferred from so called surrogates. She proposed that one such measure could be to look at the percentage of available floodable area within the city which would not be harmed by inundation (Liao, 2012). Other approaches could be the UFRJ model Resilience Scale RS, further explained in Chapter *3.3 Resilience Scale by UFRJ*.

Chapter *3.1 Resilience Work by the United Nations* and Chapter *3.2 Resilience Work by the European Union* gives an overview of DRR and resilience work from some well recognized organizations.

3.1 Resilience Work by the United Nations

The UN General Assembly took their work with DRR to the next level in December 1999 when they adopted the “International Strategy for Disaster Reduction” and established UNISDR to secure the strategy’s implementation. The UNISDR’s main purpose is to connect stakeholders and convince them to reduce disaster impacts (UNISDR, 2012).

The UNISDR coordinates and campaigns for numerous initiatives concerning risk and disaster reduction with focus on resilience. For instance, “Making cities resilient” is a campaign that aims to encourage local governments in their work for a more resilient environment. The campaign emphasizes the importance of flood resilience, and two of their 10 main points are connected to flood preparedness.

Another initiative is the "Hyogo Framework for Action 2005-2015: Building the Resilience of Nations and Communities to Disasters", which was adopted during the World Conference on Disaster Reduction in Kobe, Hyogo, Japan in January 2005. The Hyogo Framework has five priorities for action: make DRR a priority, know the risks and take action, build understanding and awareness, reduce risk, and be prepared and ready to act. The concern of flood resilience is also included within the framework (UNISDR, 2007).

As a subsequent instrument to the Hyogo Framework the “Sendai Framework for Disaster Risk Reduction 2015-2030” was adopted by the UN member states in March 2015 in Sendai city, Miyagi Prefecture, Japan. During the coming 15 years the Sendai Framework is thought to achieve a “substantial reduction of disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries” (UN General Assembly, 2015).

As of March 2015 UNISDR are working on a new ISO-standard on the same theme together with the World Council on City Data (UNISDR, 2015).

The Flood Resilience chair group, is a group of established researchers within flood resilience connected to UNESCO – Institute for Water

Education. The group is strongly connected to European and Dutch funding, but recently they have been putting more focus on an international perspective with focus mainly on Asia (UNESCO, 2015).

3.2 Resilience Work by the European Union

Collaborative Research on Flood Resilience in Urban Areas, CORFU, is a project funded by the European Union's Seventh Framework Programme for research. The aim is to join European and Asian partners in the work for an urban environment with high resilience to floods (CORFU, 2010).

Another European initiative is the Global Flood Partnership, GFP, under the lead of European Commission's Joint Research Centre. The GFP aims to bring together scientific communities, satellite and weather service providers, national flood and emergency management authorities, humanitarian organisations and donors. GPF for example developed the first operational hydrological network in Europe, the European Flood Awareness System (JRC, 2014).

3.3 Resilience Scale by UFRJ

In the doctoral dissertation "River restoration integrated with urban water management for sustainable cities" (Veról, 2013), a resilience scale, RS, is developed as one way of comparing different flood control designs within a catchment. The idea was to create a user friendly tool that could give an integrated resilience value for a whole river basin.

Veról investigated the effect of different urban drainage measures, both conventional and sustainable alternatives, planned for the Dona Eugênia River basin. Veról's project consisted of a thorough case study of the catchment area where data were collected from the Brazilian Institute of Geography and Statistics, IBGE, and by dividing the catchment into smaller flow cells and making flood simulations in MODCEL (Miguez, et al., 2011) a mathematical modelling tool for urban flooding.

The RS is based on a Flood Risk Index, FRI, (Zonensein, et al., 2008) which was modified to fit the dwelling density, income per capita and other factors of the study area. FRI values were calculated for two time perspectives; the present, with the degree of impermeable surfaces at the time of the study, and the future, where the degree of impermeable surfaces was altered to express a saturated urbanization. The two time perspectives were simulated with different combinations of flood reductive measures. The measures involved river restoration, parks, detention ponds and a reservoir. The FRI values can be used to evaluate the measures and weigh them against each other. As a last step in the study, the RS (Equation 3.1) was introduced as a way to account for the long term effect. However, since resilience was not the main aim of the study, the equation was not fully evaluated for spatialized results. This tool was meant to give an integrated value as additional information for decision makers when choosing among design alternatives for flood control.

$$RS = \alpha * \beta$$

Equation 3.1

$$\alpha = 1 - \frac{\left(FRI^{F+Proj} - FRI^{P+Proj}\right)}{FRI^{P+Proj}}$$

Equation 3.2

$$\beta = \frac{\left(FRI^{F-Proj} - FRI^{F+Proj}\right)}{FRI^{F-Proj}}$$

Equation 3.3

$F = Future$

$P = Present$

$+Proj = scenario\ with\ project$

$-Proj = scenario\ without\ project$

The RS was built by Equation 3.2 and Equation 3.3. By subtracting the FRI of a project from the estimated future FRI of the same project, the increase of FRI over time will be obtained. By dividing the increase of FRI with a non-changing FRI, Equation 3.2 provides the relative increase and thus the loss in resilience.

Equation 3.3 on the other hand, relates the FRI reduction with the future estimated FRI. By subtracting the future FRI with a project from the future FRI without a project, the risk reduction is obtained. By dividing the risk reduction with the future estimated FRI, Equation 3.3 provides a measurement of how the FRI reduction persists over time.

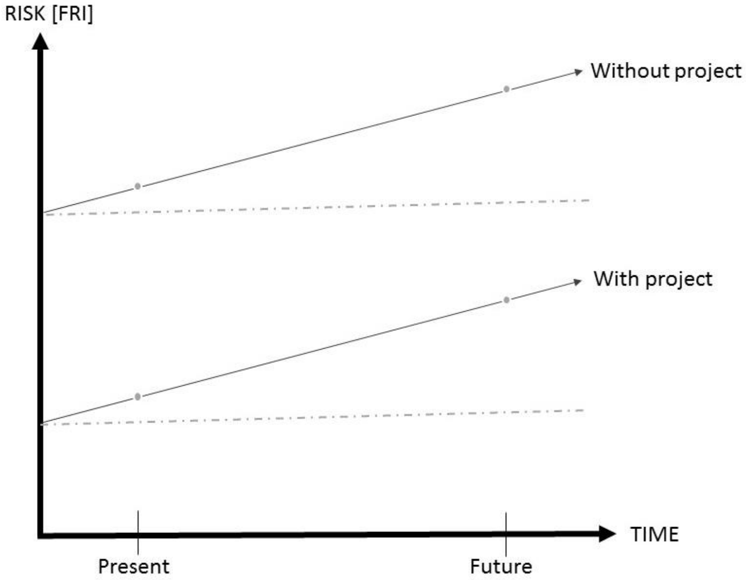

Figure 3.1 Graphical representation of the resilience idea in RS.

The goal with the RS is to distinguish which measures give a good risk reduction, both at implementation and over time, even if the circumstances changes. If the risk associated with a certain project scenario remains unchanged over time (*see horizontal line in* Figure 3.1), and remains lower than without the project, this project probably increases the resilience. The RS is helpful because it is not certain that the measures that give the largest reduction currently will remain the most effective in the long run. A comparative tool like the RS can help in deciding which measure will give the best combination of short- and long term effects.

The RS was calculated as an integrated value for the whole basin and emphasis was put on making the tool simple. The analysis (Chapter *6.2*

Phase I – Modifications of the RS) showed that when the RS is spatialized some of the flow cells that are not flooded get low RS values which means low resilience. This contradicts logical reasoning, and an alteration of the model is justified if one aims to use it for spatialized results.

4. Case Study

This research aims to make it easier to involve resilience in urban planning by creating a mathematical model to calculate a quantitative value for comparison of different flood control measures. The approach to resilience was characterised by a technical discussion linked to engineering and sustainable urban development.

The case study is based on Dona Eugênia river catchment, Rio de Janeiro, Brazil, because a solid work of surveying, mapping, modelling and simulations had already been performed which made it a logical choice for continued studies. The case study focuses on the urban portion of the catchment.

4.1 Study Area

The metropolitan region of Rio de Janeiro has, during the last decades, seen a great increase in urbanization (Figure 4.1) (Nacif Xavier & Magalhães, 2003). Many of the new settlements are illegal and built in areas that are not necessarily suitable for habitation.

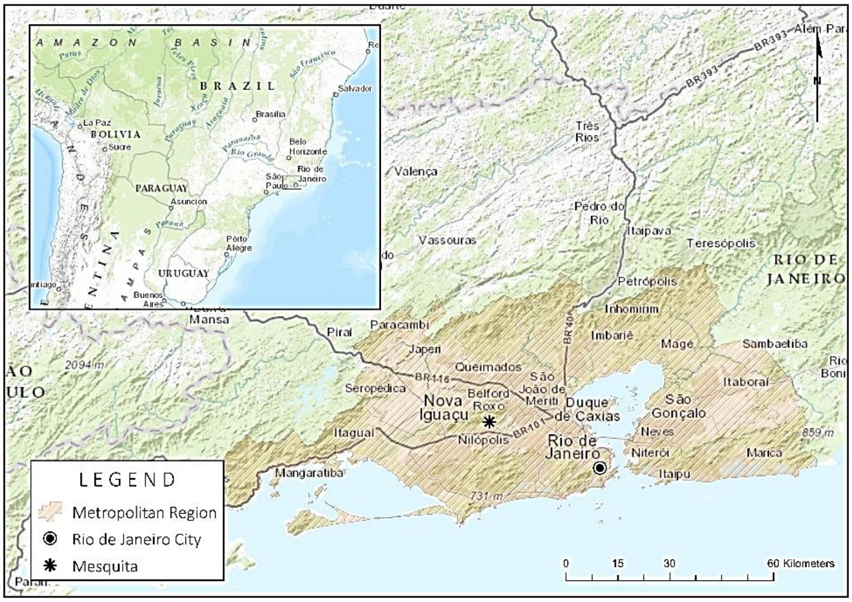

Figure 4.1 The metropolitan region of Rio de Janeiro.

Parts of Rio de Janeiro experiences uncontrolled urbanization. An uncontrolled urbanization leads to an environment very sensitive to natural hazards and disasters. Hence, Rio de Janeiro is in great need of improving its resilience.

4.1.1 Dona Eugênia River Basin

The Dona Eugênia river basin is located in the metropolitan region of Rio de Janeiro. It has been a project area for UFRJ since 1996, which has resulted in valuable observations and simulation data.

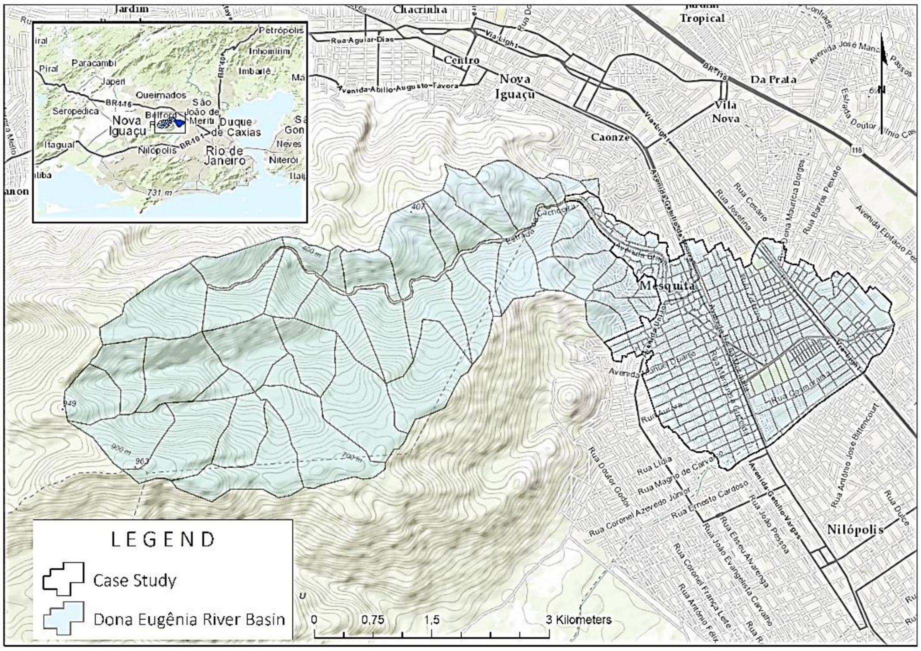

Figure 4.2 Dona Eugenia river catchment divided into flow cells (light grey boundaries). The urban part of the catchment makes up the case study and is marked by the black boundaries on the east side of the catchment.

The river basin has an area of 18 km^2 and stretches over the municipalities of Mesquita and Nova Iguaçu (Figure 4.2). The municipalities are located in the region Baixada Fluminense, which translates into The Fluminense Lowlands (Veról, 2012). The Dona Eugênia River is about 10 km long, and has its headlands in the Gericinó environmental preserve and discharges into the River Sarapuí.

Figure 4.3 Informal settlements along Dona Eugenia River (Rezende, 2013).

Figure 4.4 Illegal connections of sewage into Dona Eugenia River (Rezende, 2013).

The catchment's urbanized parts are mainly located within Mesquita (Figure 4.2). Half of Mesquita municipality is covered by the environmental preserve and the other half is urbanized. The urbanized parts are located in flat lowlands containing only small variations in altitude. The population in Mesquita is estimated to 170 751 inhabitants for 2015, which corresponds to 4 371 inhabitants/km^2 (IBGE, 2014). This estimation does not consider the preserve which in practice makes the population density greater. Only 10.6 % of the population has permanent employment, the salaries are low and the area can be considered poor (IBGE, 2014).

The infrastructure in Mesquita consists mainly of one- or two-storey buildings with some three-storey buildings. The building directive has however recently changed and the maximum allowed number of floors is now six. Therefore an increase of building height can be expected in the future. The city has a number of illegal settlements, many along the river (Figure 4.3 and 4.4). The poor infrastructure throughout the city combined with the illegal settlements and the general poverty has a negative effect on the flood situation.

4.1.2 Flood Situation in the Catchment

The climate in this region is hot and humid, with a rainy summer season. The average annual precipitation is 1 700 mm. Floods are common and during severe flooding events, 80 % of the population in the area is affected (Veról, 2012).

The river suffers from many problems originating from the unregulated environment; buildings are constructed in a way that causes channelization in long stretches of the river, there is sedimentation at various points, there are many illegal connections of sewage discharging directly into the river and a lot of general accumulation of waste. The lack of sufficient sewage and waste management makes the situation of inundation worse due to the increased risk of contamination and spreading of water borne diseases.

The impact of inundation affects the areas with illegal and uncontrolled settlements more than regulated constructions. The uncontrolled settlements often suffer higher risk of damage due to inadequate construction and unfavorable placement. Additionally, debris from damaged buildings can be moved long stretches by flowing water which potentially exposes a larger amount of people to danger.

4.2 Case Study Approach to Resilience

Resilience is sometimes simplified to mean resistance. The concepts are related because resistance is the ability to withstand a hazard. However, resilience must be considered in a wider perspective, somehow also including the process of getting back to normal or evolve into an even healthier state.

This project treats resilience as a capacity to maintain and regain functionality after a hazardous event. More specifically, it aims to quantify which preventive infrastructure measures are best equipped to prepare a certain urban area to recover smoothly after a flood. The quantification is done in a spatialized manner in order to distinguish if there are some extra vulnerable areas and if there are certain measures that these areas gain more from than from others.

This project aims to account for a combination of the risk in the area and the inhabitants' ability to materially rebuild their lives after an event. In extension it should be possible to include other components that are considered specifically important for a chosen area, such as essential services or other items in need of extra protection.

It does not include political cooperation and information strategies or disaster task force strategies even though these are also needed to achieve a complete picture of the level of resilience.

This project combines flood levels, population exposed to flood hazard, amount of inhabitants directly affected by a flood, monetary losses, monetary capacity and inundation times in a spatialized way in order to get a quantitative image on how sensitive certain parts of the case area are in comparison to others. The flow cells were analysed in order to get a good idea of their status. For example: a low income household living on the ground floor close to the river where it easily floods is not considered very resilient while a high income household on the second floor in a dryer part of town is considered resilient.

5. Input Data

The case study joins data from various sources. This chapter will explain the input data and also justify choices and approximations made connected to the data. The input data originates from models and simulations made by master and doctoral students at UFRJ. Demographic facts and statistics is taken from the Brazilian Institute of Geography and Statistics, and spatial measurements are made in the geographic information system program ArcGIS.

5.1 Flood Simulation Data

The study area catchment is a well-studied area with a long research history. Flood levels and permanency time simulations have been made by Veról in her doctoral work "*River restoration integrated with urban water management for sustainable cities*". All water related simulations are made in the urban flood modeling tool MODCEL using rain events with a statistical 25 year return period. 25 is the standard return period used in Brazil for flood calculations (Ministério das cidades, 2011).

Permanancy factor is a concept developed by Zonensein (2007) that is used in the index's "duration effect". The permanancy factor handles duration time at three reference threshold water levels. It aims to describe the impact on pedestrians (10 cm), traffic (25 cm) and buildings (50 cm). By normalizing the permanacy times of the treshhold water levels the impact is given a value between zero and one. It makes it possible to get an indication of the severity of the waterlevel in combination with the duration time.

5.1.1 MODCEL

MODCEL is an open source modelling program for urban spaces in flood prone cities developed at UFRJ (Miguez, et al., 2011). It consists of several modules that each represent the flow pattern and how different aspects of the drainage net links together. It has been applied to several case studies with successful results (Miguez, et al., 2007), (Miguez, et al., 2009), for example in the river basin of Joana (Miguez, et al., 2011) and Dona Eugênia (Miguez, et al., 2014) in Rio de Janeiro.

The model deals with periods when water flow does not follow the pattern that was initially intended in the city plan. Once water ends up outside of the drainage net its course becomes influenced by buildings and other structures in the urban environment. MODCEL links the surface flow, channel flow and underground pipe flow in these situations. MODCEL is founded on the concept of flow cells created in *Mekong Delta Mathematical Program Construction* (Zanobetti, et al., 1970 refered in Miguez, et al., 2011) . The catchment is divided into a web consisting of five different types of cells depending on the topography or land use; channel or river, storm drains, urban surface, natural surface and reservoir. The cells interact via 13 types of links; "Surface Flow Link" which models the free surface flow without inertia terms between superficial cells, "Inlet Gallery Link" which act as a channel link with local head loss due to flow contraction or according to Bernoulli's principle if submerged, etcetera (Miguez, et al., 2011). Links do not only communicate with side cells but also vertically with the drainage gallery net which creates a pseudo 3D-model even though the mathematical relations are 1D (Miguez, et al., 2011).

5.2 Brazilian Institute of Geography and Statistics

Instituto Brasileiro de Geografia e Estatística, IBGE, is directly translated to English as the Brazilian Institute of Geography and Statistics. IBGE provides a number of geographical and statistical data from the whole country. Demographic data for Rio de Janeiro that is used in this study is from 2010. The reliability of the data is considered high when it handles measured quantitative data such as population and building density. The data from IBGE in this study considers population, income, number of houses and apartments.

5.3 Monetary Losses

The evaluation of monetary losses in this study is based on two previous master theses by Nagem (2008) and Salgado (1995). The two studies have been combined to get a value of the expected monetary losses from a flood event. Nagem creates a monetary loss estimation model (Equation 5.1) in order to quantify damages from floods in monetary terms. She makes various classifications and assigns an expected living space for each income class.

The standardized living space of Brazilian homes from Nagem's methodology is applied in the work of Salgado. It calculates the economic loss of content (Equation 5.2) depending on the height of the flood. The loss is calculated as a percentage of the home's value and also takes into account that high income class homes have a higher quality and therefore more expensive content.

The home's construction related losses (Equation 5.3) are estimated with tables provided by Sindicato da Indústria da Construção Civil no Estado do Rio de Janeiro, SINDUSCON – RIO, which is the Union of Construction Industry in the State of Rio de Janeiro (SINDUSCON, 2015). It is important to keep in mind that the evaluation and testing of Nagem and Salgados concepts was made on a master thesis level. The concepts has not been used in other publications.

$$I_{RA} = \frac{BDC + CDC}{I}$$

Equation 5.1

$$CDC\ (Content\ Damage\ Cost) = 0{,}5 \cdot BUCC \cdot CPI \cdot PCD \cdot A$$

Equation 5.2

$$BDC(Bulding\ Damage\ Cost) = 0{,}5 \cdot BUCB \cdot PBD \cdot A$$

Equation 5.3

$I_{RA} = Material\ Recovery\ Ability$
$I = Income$
$BUCB = Basic\ Unit\ Cost\ of\ Building$
$PBD = Percentage\ of\ Building\ Damage: in\ relation\ to\ water\ level$
$BUCC = Basic\ Unit\ Cost\ of\ Content$
$PCD = Percentage\ of\ Content\ Damage; in\ relation\ to\ water\ level$
$CPI = National\ Consumer\ Price\ Index$
$A = Area$

5.4 GIS Adjustments

To get a reliable transfer of data from the administrative units of IBGE to the catchment flow cells it is important to make sure that the fitting of the units to the cells is correct. The catchment model in ArcGIS was lacking information about the coordinate system and made the projection of the catchment impossible. The IBGE maps use the geographical coordinate system “SIRGAS 2000” which is commonly used for similar applications, and was therefore chosen to define the projection of the catchment in ArcGIS as “SIRGAS 2000 UTM zone 23S”. This did not, however, result in a perfect fit and the map was adjusted to fit the satellite image better by using easily recognisable features like the stadium, cemeteries, rivers etcetera. For example the rounded catchment cell (Figure 5.1) should follow the outlines of the stadium and the slightly meandering green line (Figure 5.2) should follow the matching, red, IBGE line where the river is.

Figure 5.1 The catchment displacement in relation to the satellite image of the stadium (ESRI 2015)

The adjustments were done in ArcMap by affine transformation using 83 displacement links (Figure 5.3) evenly distributed over the whole area with a root-mean-square error of 16, 99 m. The resulting cell areas changed somewhat, but the alterations are negligible in comparison to the total cell areas, and the overlap with the IBGE divisions was considerably improved.

Figure 5.2 The catchment displacement in relation to the satellite image of the river in the southwest part of the case study area (ESRI 2015).

Figure 5.3 Example of the size and spread of the displacement links. The links are displayed as arrows or black lines, however, not all of the links are visible (ESRI 2015).

6. Method

The first step in this study, Phase I, was to investigate research question one and two – *What models already exist to calculate flood resilience?* and *How well does Veróls model of calculating resilience scale work during spatialization?*

The RS model was reviewed, enhanced and adapted to handle spatialization of the results. A spatialization test of the RS was made with the help of the geographical information system program ArcGIS. Several model variations of the RS were examined with varying and unsatisfying results (Appendix A).

After analysing the results, it was determined that there was a need for a second step, Phase II: further investigation of research question three, four, five and six– *Can an alternative resilience model be developed?, How can the alternative model be tested?, How does the alternative model respond in tests?* and *Can the alternative model be used as a tool in decision making concerning urban drainage?*

The following section describes the analysis method and the methodology of phase I and II.

6.1 Test Scenarios

The models were tested in two time frames, present and future. Each time frame was tested in a scenario **with** implementation of flood control measures and one scenario **without**. The 4 scenarios are:

- Scenario I – Present, no modifications
- Scenario II – Present with flood control
- Scenario III – Future, no modifications
- Scenario IV – Future with flood control

The project scenario is taken from Veról (2012) and consists of the implementation of a fluvial corridor and river restoration plus sustainable urban drainage solutions such as flood parks.

Future time is not a specific amount of years forward but instead implies a time when the city has reached saturated urbanisation and 90 % of surfaces are assumed impermeable. This mean that the runoff increases and also the flood hazard. No consideration has in this stage been taken to increased precipitation due to climate change, because this was not the focus of the original work.

It is assumed that resilience is going to decrease in the future. And that the implementation of a project will increase the resilience.

6.2 Phase I – Modifications of the RS

In the RS (Equation 3.1), an integrated value for the whole urbanised part of the catchment is the end product. If the goal, however, is to identify sensitive areas, establish which areas need extra attention or how certain projects differ geographically, it is no longer possible to look at the integrated RS. A stronger model that can withstand scrutiny of every cell is necessary.

The first idea of how to accomplish a stronger model was to evolve the existing model mathematically to see if a rearrangement or addition of new factors could help give a fairer picture. Several changes were tested (Appendix B) but the changes did not give satisfactory results and the idea about evolving the original RS was abandoned. This was more or less expected, especially due to the parts of the FRI related to the economics.

6.3 Phase II – Construction of S-FRESI

The RS as a concept did not give the desired result in spatial terms, therefore a new approach was tested. Since some of the features of the FRI are still relevant to flood resilience, these were used to develop a new index.

Since resilience capacity depends on a variety of indicators it was convenient to present them by an index. This way each indicator can be measured individually and weighed according to its importance.

The construction of the index was based on the definitions of resilience and risk stated previously a so called inductive approach (Chapter *2. Literature review*), The Index (Equation 6.1) was named **S**patialized urban **F**lood **RES**ilience **I**ndex, S-FRESI. It aims to combine components that are important to resilience in the context of urban floods. The S-FRESI is thought to integrate the social and economic aspects with the flood hazard.

Chapter *6.3.1 Structure of the Index* describes the structure and interpretation of the index. The indicators that were chosen to measure the sub-indices and how they are expressed are explained in detail in Chapter *6.3.2 Indicators and Sub-indices*.

The sub-indices are calculated and then subtracted from one in order to have high numbers representing high resilience in S-FRESI. All the calculations are based on flood simulations made by Veról and the area is divided according to the flow cells from MODCEL, closely related to street blocks.

6.3.1 Structure of the Index

An index is used to characterise a set of data as one value by the use of a formula. It can consist of different “dimensions” that together are considered to be representable for what one wants to express. The dimensions are measured in an “indicator” that is normalized through its “dimension index”.

It is not an easy task to quantify resilience, partly because putting numbers on the ability to recover from an urban flood is complicated. It depends on a wide range of factors, many of which are difficult to define and/or measure. Still, based on the literature study, five dimensions were chosen to represent the essence of resilience: low hazard with short time of influence, small exposure, low susceptibility and ability to recover property loss.

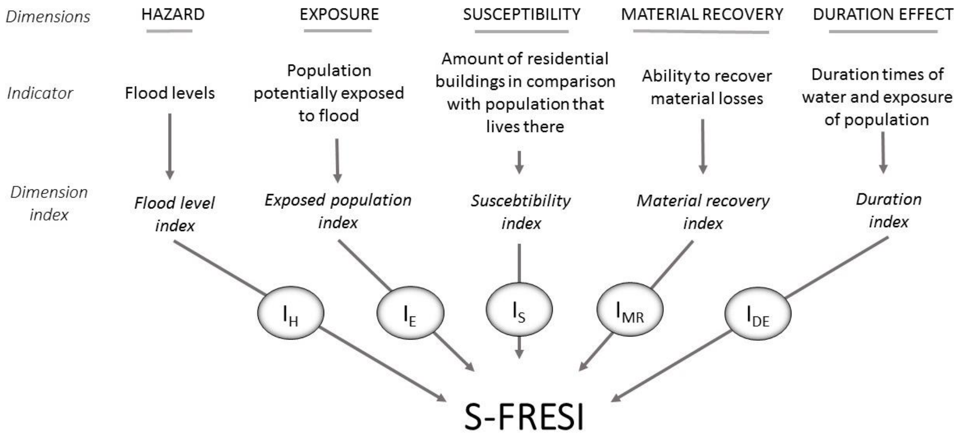

Figure 6.1. Graphical presentation of S-FRESI.

$$S\text{-}FRESI = [1 - ({I_H}^{n_1} \cdot {I_E}^{n_2} \cdot {I_S}^{n_3})] \cdot m_1 + [1 - I_{MR}] \cdot m_2 + [1 - I_{DE}] \cdot m_3$$

Equation 6.1

S-FRESI (Equation 6.1) aggregates different aspects that influence resilience. The S-FRESI aspects can be divided into three parts, where each can be weighted after importance. However, the focus in this study has been on evaluating the indicators, testing the impact of the weights was not prioritized at this stage. The three parts were assigned equal weights, $m_1=m_2=m_3=0.33$. The three sub-indices, I_H, I_E, I_S, have exponential weights: $n_1=0.5$, $n_2=0.25$, $n_3=0.25$. The interpretations of the three parts of S-FRESI are:

$$Part\ one = [1 - ({I_H}^{n_1} \cdot {I_E}^{n_2} \cdot {I_S}^{n_3})]$$

Equation 6.2

In the context of resilience this part of the model (Equation 6.2) aims to represent the degree to which the population is protected from physical harmful effects. It combines the sub-indices hazard, exposure and susceptibility dimensions in order to evaluate the impact of the flood in the study area. If resistance is sustained over time it implies a greater resilience.

$$Part\ two = [1 - I_{RV}]$$

Equation 6.3

Part two (Equation 6.3) of the model aims to show the economic ability to recover from flood related losses connected to residential buildings and contents of the home.

$$Part\ three = [1 - I_{PF}]$$

Equation 6.4

Part three (Equation 6.4) aims to show the impact of drainage capacity and its capability to recover functionality after an event. An area's ability to function during and after a heavy rainfall will depend on the drainage system capacity. Hence Equation 6.4 gives an indication of how great the impact on buildings and population will be, in regards to infrastructure, property and the spreading of water borne disease.

6.3.2 Indicators and Sub-indices

All indicators are normalized into sub-indices with values between zero and one.

Hazard, I_H

During a flood event the hazard is linked to the flooding prevalence, and thus the indicator representing hazard was chosen to be water levels above ground level.

The flood levels were normalized by dividing them with a reference flood depth. Flow cells with water levels above the reference flood depth was given the maximum I_H value. For all other cases Equation 6.5 was applied. The reference flood depth should be considered a threshold flood level where significant, if not total, losses become the result if surpassed. Here the reference value was chosen to be one meter above ground level.

$$I_H = \frac{h}{h_{ref}}$$

Equation 6.5

$h = Water\ level\ in\ sub\ catchment$
$h_{ref} = \ Reference\ water\ level$

Exposure, I_E

All the people that live in a catchment can potentially be affected by a flood and is therefore exposed to flood hazard. The sub-index "Exposure" aims to express the relative exposure of the population with household density as the indicator. Higher household densities will put more people in contact with flood water. Households are used because it is easily compared to property loss, which is used in I_{RV}. For the future scenario an increased population was taken into consideration.

The household density was normalized by dividing it with a reference value. The reference is calculated as the 75th percentile. This choice avoids distorting the scale – isolated high density values could compress a great number of values in the lower part of the scale. All household densities over the reference value was given the maximum I_E value. For all other cases Equation 6.6 will be applied.

$$I_E = \frac{HHD}{HHD_{ref}}$$

Equation 6.6

$HHD = Household\ Density$
$HHD_{ref} = Household\ density\ reference\ value, 75th\ percentile$

Susceptibility, I_S

Susceptibility can be seen as the likelihood of getting impacted by a flood consequence. The assumption is that impact occurs in the form of property damage when households have direct contact with flood water.

Households on ground level are assumed to experience more material loss than households on higher floors. The apartment buildings in the area are small, which led to the assumption that all multi-story buildings have one household on each floor. Hence, every building in a flooded area generates one inundated household.

In the context of flood resilience, areas with single household houses are considered more susceptible than areas with apartment buildings since houses almost always have living spaces on the ground floor.

The sub-index "Susceptibility" (Equation 6.7) is calculated by the ratio of flooded households to the total amount of households within the particular flow cell.

$$I_S = \frac{HH_{Inundated}}{HH_{Total}}$$

Equation 6.7

$HH_{Inundated} = Inundated\ households$
$HH_{Total} = Total\ households$

Ability to Material Recovery, I_{MR}

The sub-index "Material recovery" (Equation 6.8) aims to give an indication of the ability to replace flood damaged property. It is calculated by looking at economic loss in relation to income.

$$I_{MR} = \frac{L}{0{,}3 \cdot 12 \cdot I}$$

Equation 6.8

$L = Monetary\ losses\ (Chapter\ 4.3\ Monetary\ losses)$
$I = Annual\ income$

The methodology for calculating monetary losses is based on the master's theses by Salgado (1995) and Nagem (2008), where economic loss is estimated from calculations based on flood levels and income class *(*Chapter *4.3 Monetary losses).*

The total expected monetary losses are divided by 30 % of a households annual income. The 30 % is a typical financing limit associated with the real estate market in Brazil and is assumed to be the amount a family can spend on recovering from a flood.

Duration Effect , I_{DE}

The longer an area stays inundated the greater the consequences will be. The indicator chosen to express this is flood duration time.

An updated version of the permanancy factor (Zonensein, et al., 2008) is used in combination with exposure and susceptibility to create the sub-index (Equation 6.9). Basically, I_E tells us how many households are likely to get affected, while I_S tells us how many apartments or houses that are likely to suffer material damage.

Water levels under 25 cm are not likely to damage buildings. However, these water levels are enough to hinder pedestrians, disrupt traffic and increase the risk of spreading waterbourne deceases. Therefore the permanancy factor has been separated and coupled to two different indicators.

$$I_{DE} = (0{,}2 \cdot T_{10} + 0{,}3 \cdot T_{25}) \cdot I_E + (0{,}5 \cdot T_{50}) \cdot I_S$$

Equation 6.9

$$0{,}2 \cdot T_{10} + 0{,}3 \cdot T_{25} + 0{,}5 \cdot T_{50} =$$

$$Permanancy\ factor\ by\ Zonensein\ with\ updated\ weights.$$

$$T_{10}, T_{25}, T_{50}$$
$$=\ Normalized\ permanancy\ times\ of\ water\ levels\ 10, 25\ and\ 50\ cm$$

7. Results and Analysis

The first analysis of the model is based on scenario I, present time without the implementation of a project and is divided into three parts. The first part focuses on getting an overview of the situation in the study area by observing variations of income, flood levels and household density. The idea is to make it easier to see which areas theoretically should be represented by low or high resilience.

In the second part the sub-indices are analysed thoroughly by comparing cells that have at least one variable value in common. The most confident conclusions are made where two out of three variable values are equal.

In the final part, the sub-indices are compared with the S-FRESI to see how well each indicator is reflected. The four different S-FRESI scenarios are then compared: the present situation with and without implementation of the sustainable urban drainage project, and a future scenario of a saturated urbanization with and without the implementation of the project.

7.1 Analysis of River Basin

To evaluate the accuracy of the S-FRESI, analysis of the catchment was done by looking at the flood levels in combination with income and household density. By combining the three data types it is possible to get an indication of which range the S-FRESI values should be in and thus make an evaluation of the plausibility of the mathematical model. An area with high water levels, poverty and high household density was considered to be associated with low S-FRESI values and vice versa.

The maps below represent household density (Figure 7.1), flood levels (Figure 7.2) and income (Figure 7.3). They show the information that the indicators are based on. It is possible to get an idea of how the S-FRESI result will look just by looking at these maps.

The areas marked in figures 7.1, 7.2 and 7.3 gives a rough idea about how it is expected that the S-FRESI will look. Red markings show low flood levels, blue medium flood levels and black high flood levels. The circles mark areas with higher income and triangles mark areas with lower income. It is expected that the red marked cells will have higher S-FRESI values than the black marked cells and that the circles will have lower S-FRESI values than their colour matched triangles. Household density will have a minor impact since it was not assigned a substantial weight in the S-FRESI composition. For analysis with S-FRESI values see Chapter *7.3 The Index: S-FRESI*.

Some cells are not considered for S-FRESI calculations since they were not in the original work by Veról. These cells are marked by a dotted pattern in the maps and consists of burial grounds, a stadium and a power transmission line.

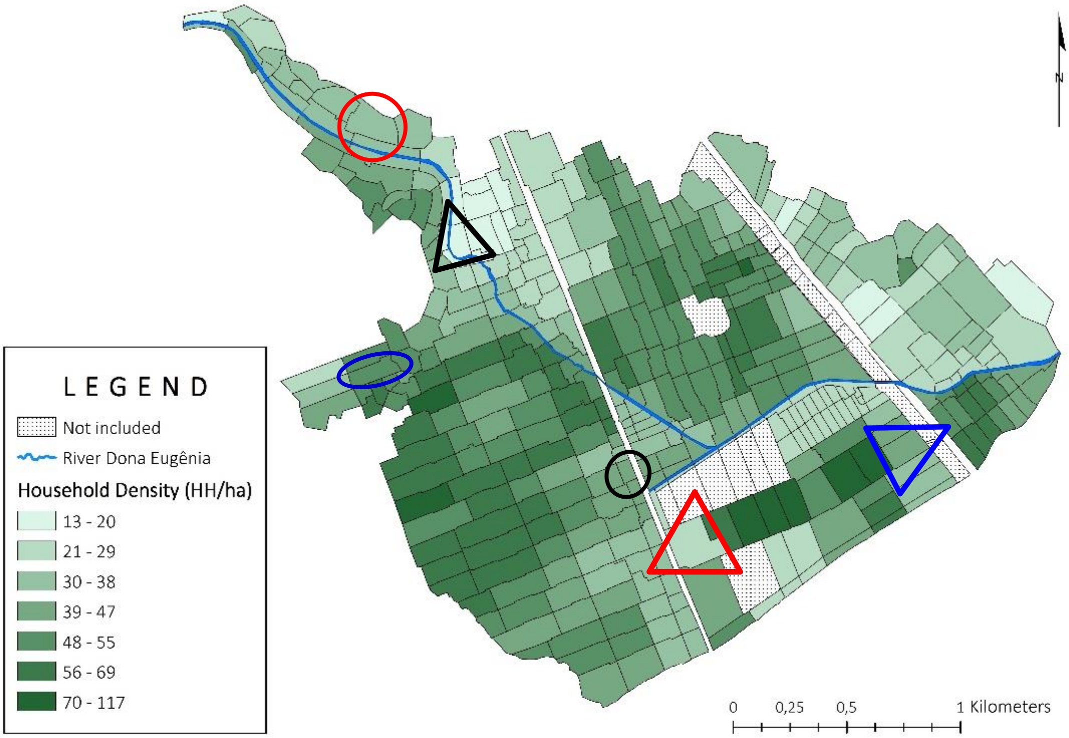

Figure 7.1 Household density in the case study area expressed as households per hectare. Red markings show areas with low flood levels, blue medium flood levels and black high flood levels. The circles mark areas with higher income and triangles mark areas with lower income.

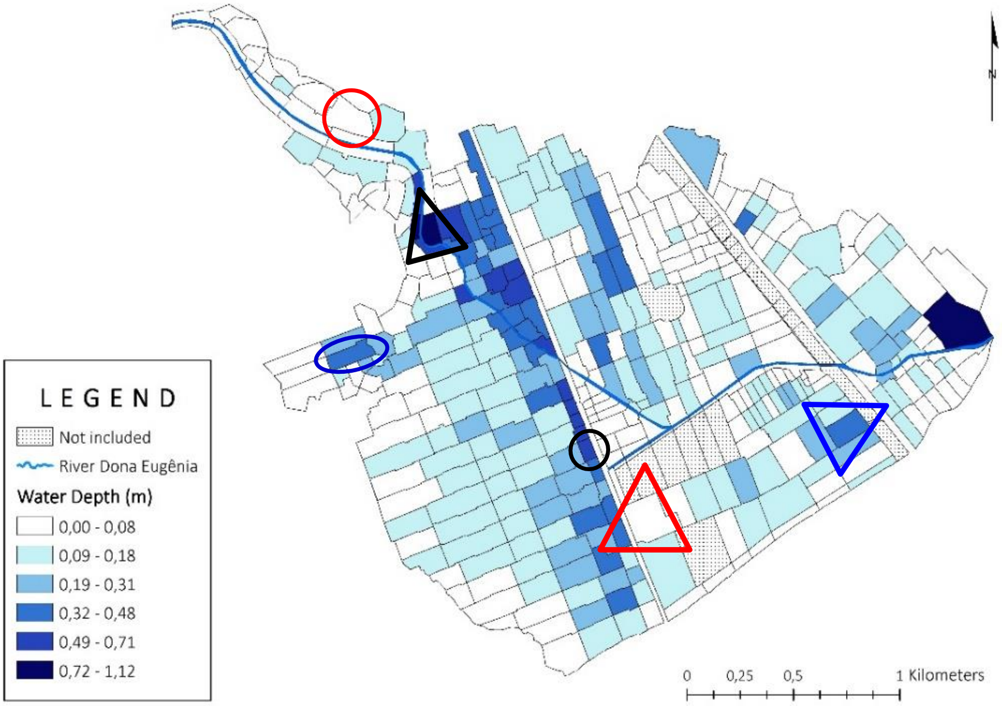

Figure 7.2 Simulated flood water depths for a rain event with a 25-year return period, Scenario I. Red markings show low flood levels, blue medium flood levels and black high flood levels. The circles mark areas with higher income and triangles mark areas with lower income.

The worst flooding stretches in the north to south direction, slightly tilted, along the railway that goes through the western portion of the map. There is also considerable flooding in one large cell in the eastern point of the map on the north side of the river bank. This cell is a natural wetland that has partly been occupied by unregulated settlements. This cell will in the resulting index maps show a notable value difference, compered to the surrounding cells, due to the high flood levels.

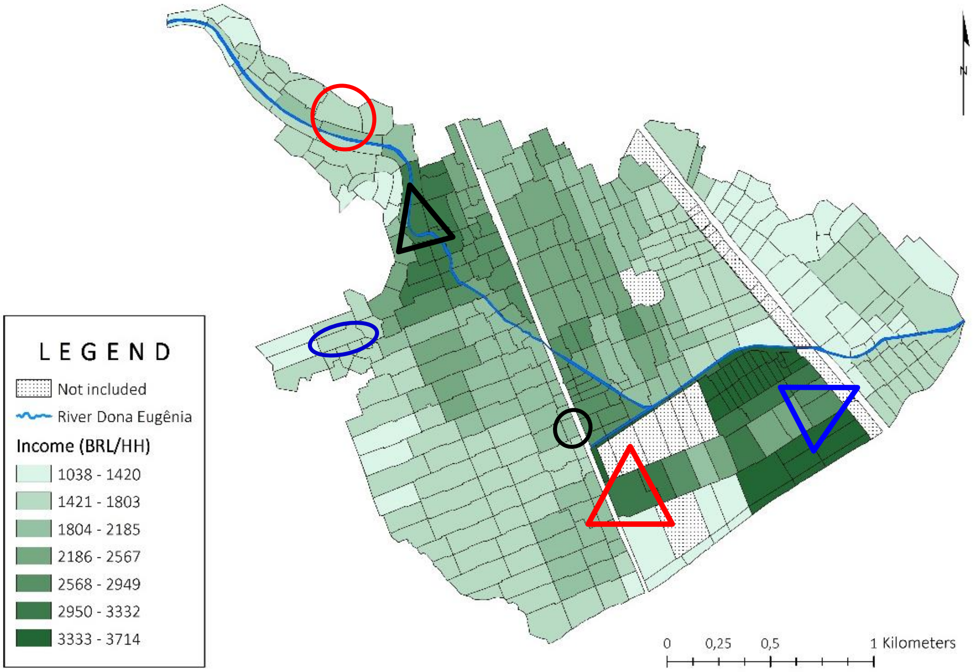

Figure 7.3 Monthly household income for the case study area, in Brazilian real (BRL). Red markings show areas with low flood levels, blue medium flood levels and black high flood levels. The circles mark areas with higher income and triangles mark areas with lower income.

7.2 The Sub-indices

7.2.1 Hazard

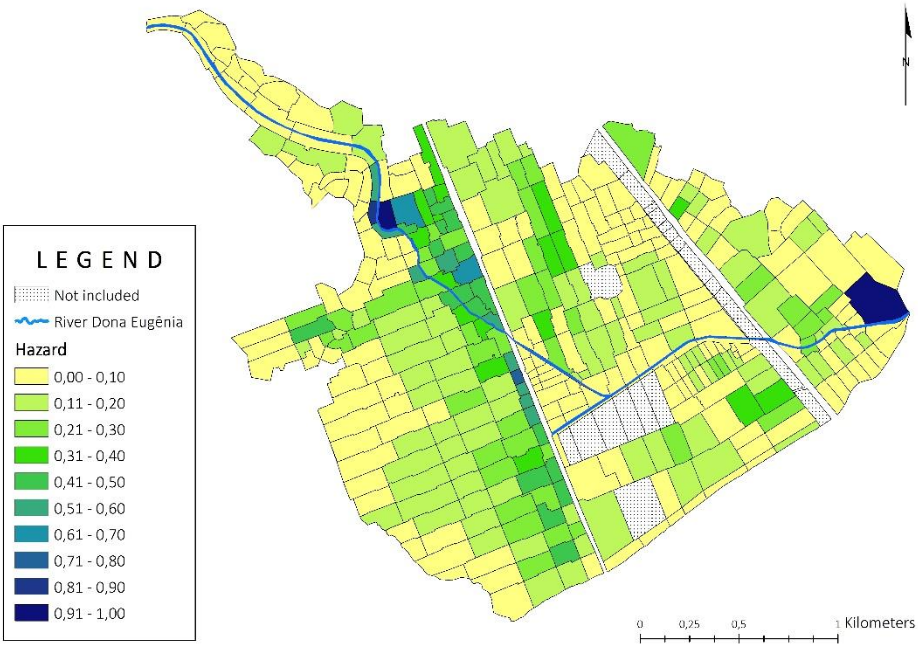

Figure 7.4 Sub-index hazard. Large hazard is represented by high numbers (blue colours).

The sub-index hazard (Figure 7.4) represents the water depth divided by the reference value, a maximum acceptable depth. All water depths above the reference value get the highest indicator value – one. In this study the reference was chosen to be one meter above the ground and yielded almost identical I_H- and flood depth-maps.

7.2.2 Exposure

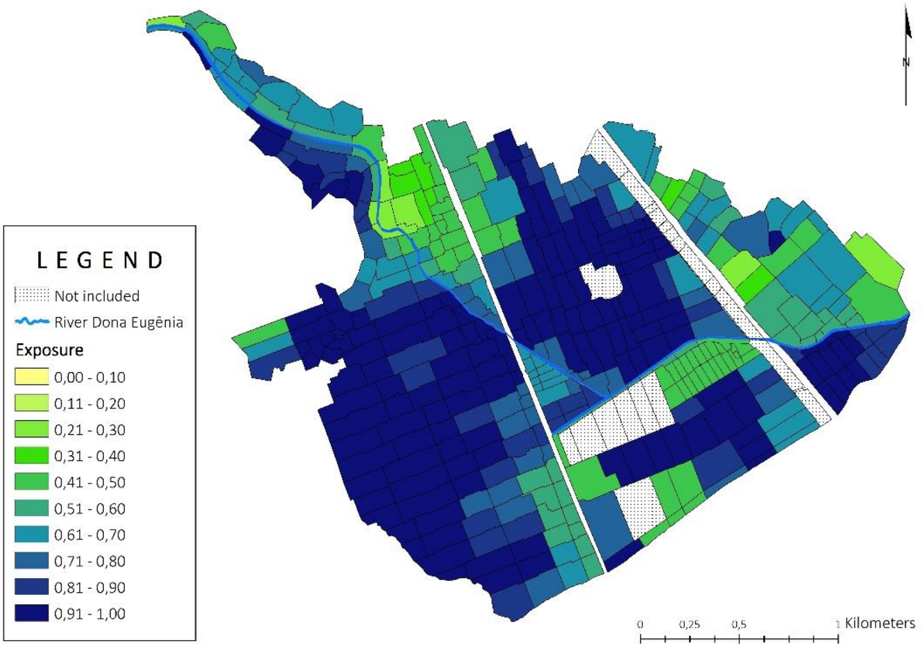

Figure 7.5 Sub-index exposure. High exposure is represented by high numbers (blue colours).

The sub-index exposure (Figure 7.5) shows the normalised household densities. All values above the 75th percentile become one; in this case these are values between 52 and 117 HH/Ha. The lowest density of the area is 13 HH/Ha which when normalised becomes 0.25 in exposure, so there are no yellow or light green fields in this figure.

7.2.3 Susceptibility

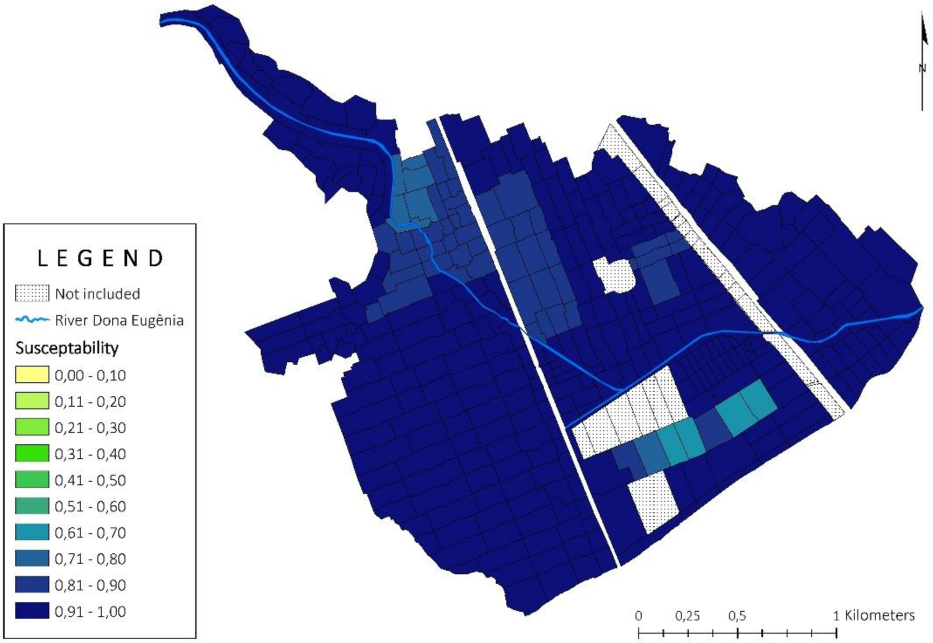

Figure 7.6 Sub-index susceptibility. High susceptibility is represented by high numbers (blue colours).

The sub-index susceptibility (Figure 7.6) has even and high values due to the homogeneous building patterns in Mesquita, with mainly densely built, one floor houses. The lower values for susceptibility correspond with the more apartment-dense areas. This is due to the assumption that households on higher floors are less vulnerable to floods since their belongings stay above water.

7.2.4 Material Recovery Ability

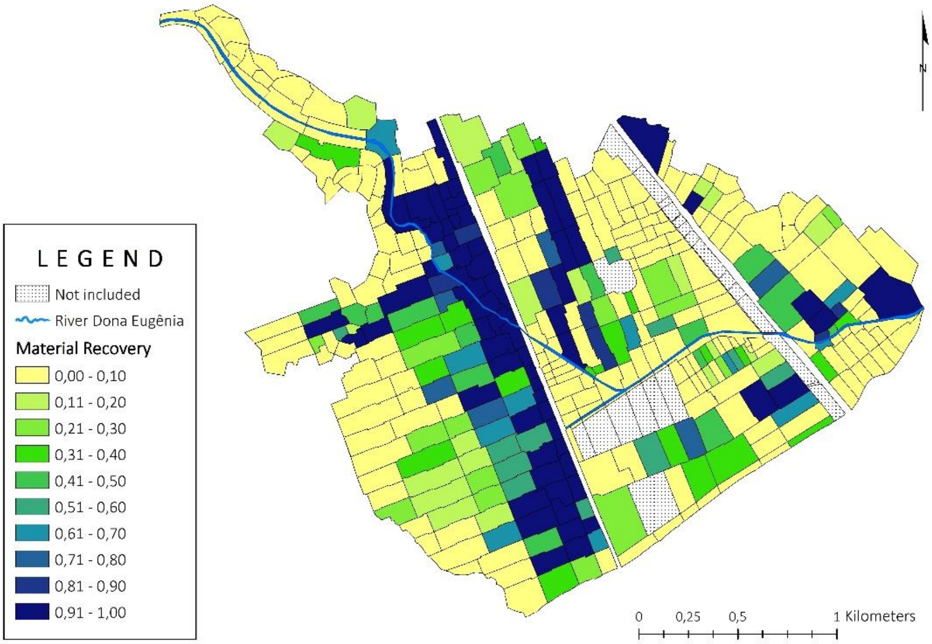

Figure 7.7 Sub-index material recovery ability. Low ability for material recovery is represented by high values (blue colours).

The sub-index material recovery ability (Figure 7.7) has a rather good spread through the range but with somewhat more weight on the maximum and minimum values: 54% of the cells get an I_{RV} value of zero, 17% get an I_{RV} of one and the remaining 29% get intermediate values.

High I_{RV} values are to a large extent connected with cells inhabited by income class B. The mean I_{RV} value for “class B cells” is 0.40 and the mean I_{RV} value for “class C cells” is 0.13. This is because class B cells are affected by large water depths to a greater extent: The mean water depth for class B cells is 0.084 m and the mean water depth for class C cells is 0.068 m.

7.2.5 Duration Effect

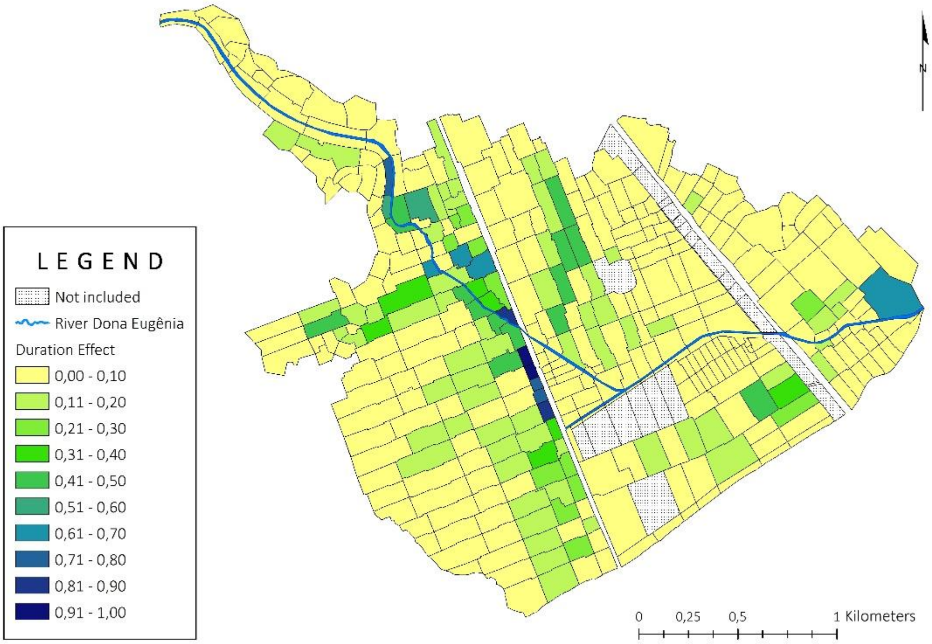

Figure 7.8 Sub-index duration effect. High duration effect is represented by high numbers (blue colours).

The sub-index duration effect (Figure 7.8) is mainly dependent on the permanency factor (Figure 7.9). Since 54% has a permanency factor value of zero, 54% of the I_{DE} will also be zero.

The cells around the meandering portion of the river in the northern part of the case area get intermediate I_{DE} values even though the permanency factor is very high. This is due to low exposure, I_E. The area contains the city hall, a sports club and commercial buildings which dilute the population density and yield the low I_E.

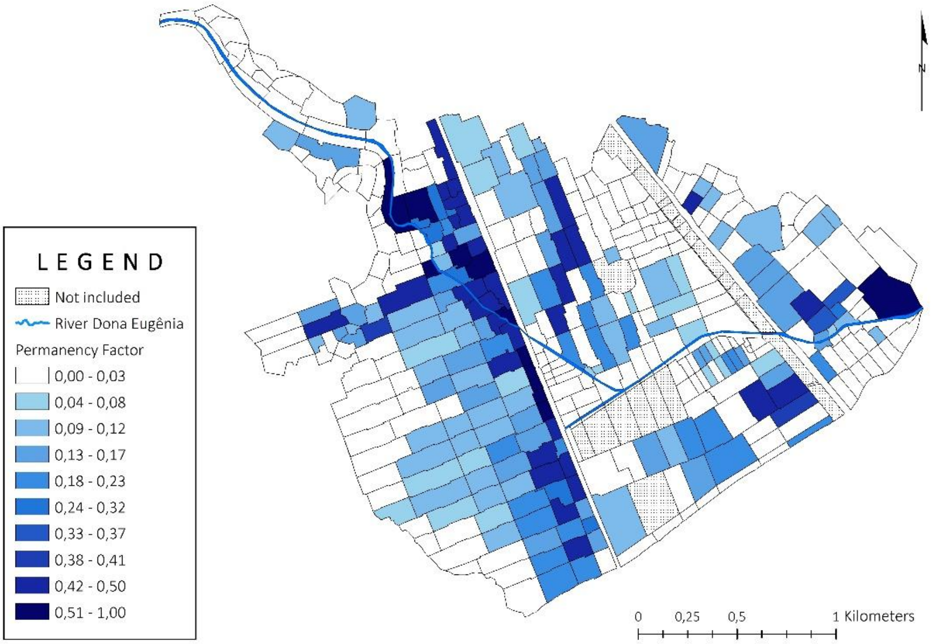

Figure 7.9 Permanency factor by Zonensein (0.2 T10+0.3 T25+0.5 T50).

7.2.6 The three parts of S-FRESI

The S-FRESI (Equation 6.1) is divided into three parts (Equations 6.2, 6.3 and 6.4) each of which can be assigned with a weight. These three parts are represented, without weights, in the following three maps (Figures 7.11, 7.12, and 7.13).

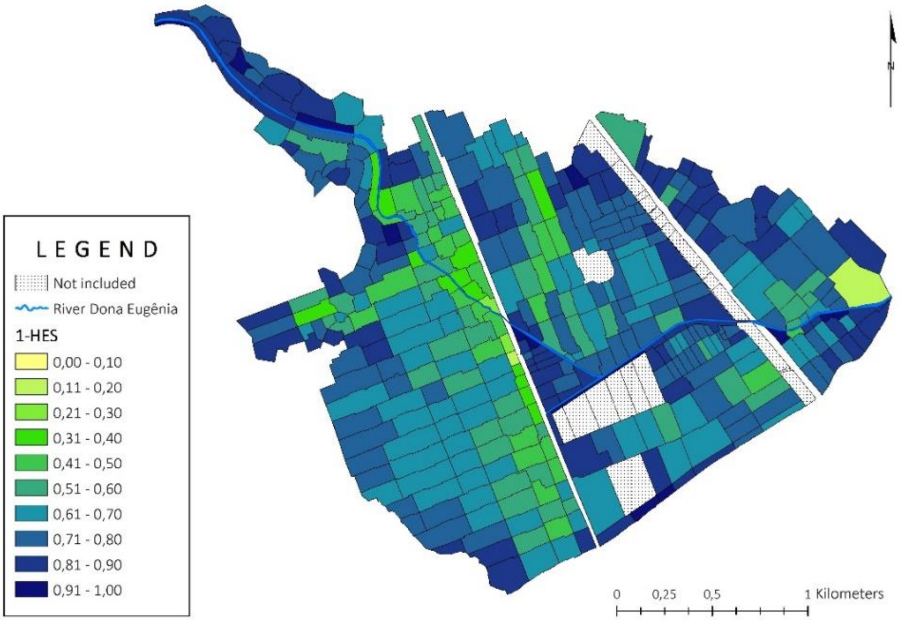

Figure 7.10 Combination of Hazard, exposure and susceptibility as it is in S-FRESI.

Figure 7.11 Duration effect as in S-FRESI: 1- I_{DE}.

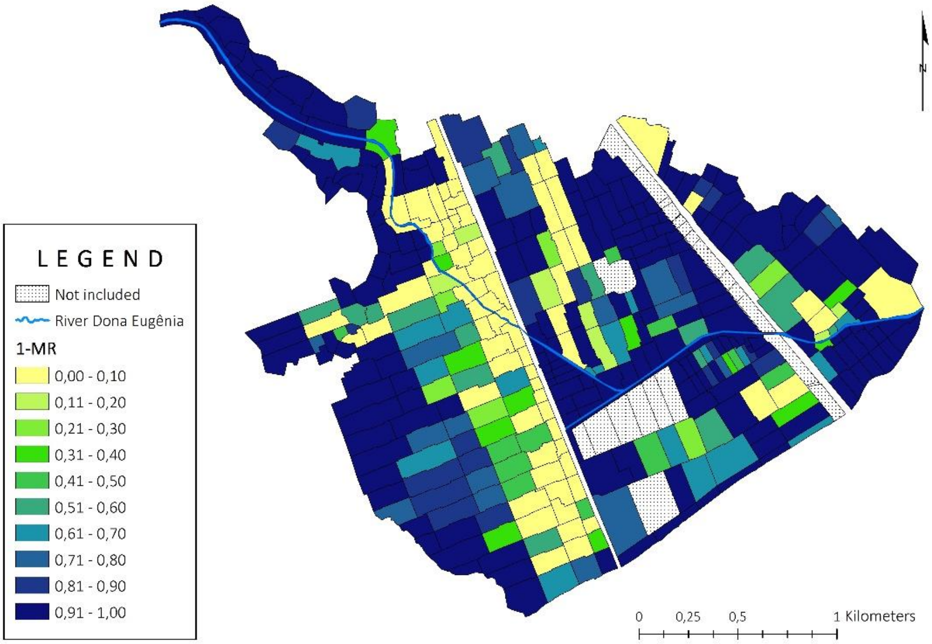

Figure 7.12 Material recovery ability as in S-FRESI: 1-I_{MR}.

7.3 The Index: S-FRESI

The maps below (Figures 7.13, 7.14, 7.15 and 7.16) show the results of the combined index, S-FRESI, for each scenario. They show a good spread of values and they correspond to what was expected. A great increase in resilience can be seen when comparing a scenario without modification compared to a scenario with implementation of a project (explained in Chapter *6.1 Test Scenarios*). The green colour represents high resilience and orange-coloured values represent low resilience.

There is one flow cell in the northwest part of the catchment, and a few flow cells in the east, both parts along the river, which are planned project areas. These cells get turned into flood parks in the project and are marked blue in scenario II and IV.

Figure 7.13. S-FRESI for scenario I, present time without flood control modifications. Red markings show areas with low flood levels, blue medium flood levels and black high flood levels. The circles mark areas with higher income and triangles mark areas with lower income.

The marked cells responded as expected: red marked cells yield high S-FRESI values, blue yield middle rang values and black yield low values. The circles yield lower values than the triangles which was also expected. It was concluded from the extended analysis that the general trend in the S-FRESI calculation spreadsheet is consistent with the sample values (Table 7.1).

Table 7.1 Numerical values of the cells marked in figures 7.1, 7.2, 7.3 and 7.13.

		Cell number	*Flood [m]*	*Income [BRL/HH]*	*HH density [HH/ha]*	*S-FRESI*
Red	○	3326	0,04	1570	34	0,93
	Δ	2179	0,02	3309	25	0,95
Blue	○	3375	0,41	1654	54	0,32
	Δ	2103	0,33	2796	41	0,37
Black	○	3259	0,57	1885	40	0,17
	Δ	3352	1,09	3280	15	0,27

Figure 7.14 S-FRESI for scenario II, present time with flood control project.

Figure 7.15 S-FRESI for scenario III, future time without flood control modifications.

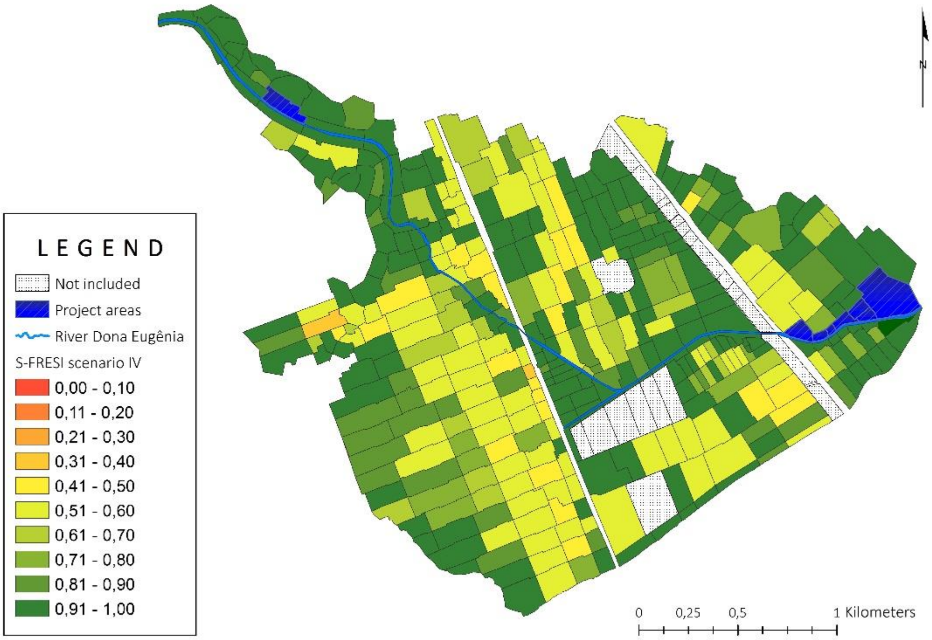

Figure 7.16 S-FRESI for scenario IV, future time with flood control project.

The different scenarios have been compared and analyzed. Mean, maximum and minimum change between scenarios was calculated to see general trends. Also the amount of flow cells showing a change larger than 10 % and 50 % were calculated to get an idea of the variation of the S-FRESI values. The numerical result analysis can be seen in Table 7.1.

Column one (Table 7.2) shows a decrease in S-FRESI from present to future. The mean value declined by 19 %.

Column two compares scenario I and II, showing an increase of resilience with the implementation of the project.

Column three compares scenario III and IV, showing an even higher increase of resilience with the implementation of the project.

Table 7.2 Changes in S-FRESI between different scenarios. The change in each flow cell was calculated.

	Change in S-FRESI in the future compared to the present, without project	Change in S-FRESI by implementation of project, present	Change in S-FRESI by implementation of project, future
Mean change	-19%	12%	20%
Maximum change	-79%	83%	93%
Minimum change	2%	-3%	-8%
More than 10% change	-55%	34%	55%
More than 50% change	-5%	5%	13%

8. Discussion

It is not reasonable to believe that floods or any natural disasters can be avoided or fully predicted; we need to learn how to live with floods and how to alleviate the consequences of them. The reason to develop S-FRESI is to be able to pinpoint the flood resilience related aspects that are possible to express in mathematical terms. By working with relations and normalizations it is possible to compare impacts of, for example, demographic characteristics and flood levels.

There will always be weaknesses in simplified models that try to put numbers on complex concepts. However, what gets measured gets done, and therefore a simplified model can still be very important and push development in the right direction.

8.1 Research Questions

1 – What models already exist to calculate flood resilience?

Resilience is an ambiguous concept which makes it complex to express in quantitative terms. This is reflected in the lack of mathematical models that in a tangible way calculate and quantify resilience; no flood resilience indices or concrete planning tools were found during this study. The implementation of projects to increase resilience seems to be dependent on frameworks or municipal target documents.

Unfortunately, using a framework to work with resilience can be complicated due to the difficulty in distributing responsibility. Who should be responsible and what interests should be prioritized can be seen as a great challenge when it comes to implementation. Vaguely formulated goals can easily become neglected.

2 – How well does Veról's model of calculating resilience scale work during spatialization?

After the first tests, spatialization of the RS proved to be inadequate and the formulation of the FRI makes it problematic to use directly as a base for the RS. The economic component of the FRI indicates the absolute economic value of losses and not the relative value. It connects high monetary standard with high risk. Basically, the FRI considers it worse if a high class home is flooded since the economic loss is greater. When discussing resilience this is not a correct assessment. It is usually considered that the recovery ability is greater where economic standards are high and lesser where standards are low (ADB, 2013; Abhas , et al., 2013). One of the first recommended steps in order to increase the general resilience of a city is to increase the lowest standard areas (ADB, 2013).

The RS also shows very low resilience in parts of the catchment that are not flooded. It is not reasonable that less flood prone areas should be represented by low RS values, and this was a strong reason for the decision to revise the model.

3 – Can a resilience model be developed?

This study found that resilience can, at least to some extent, be described by mathematical models. It is possible to measure some of the constituents of resilience and combine them into a model. The model says more than the constituents taken separately or can, at least, increase the accessibility and be faster to work with. However, it is always important to be aware of the model restrictions.

Even though a model can give insight about flood resilience it would be extremely difficult to create a single model that can express the whole array of what resilience can entail. There are factors associated with flood resilience that were found to be difficult to represent through mathematical formulas. Examples of factors that are difficult to include in a model are: long term psychological effects, how people react during a flood and what access people have to different kinds of aid.

The elusive aspects of resilience should be quite similar for most people in the same region. For example: early warning systems, evacuation plans, and recovery aid are likely to be equally accessible for everyone within the spatial extent of the modelled area. These factors should therefore not affect the result substantially. However, in a segregated society, like Brazil, it can be difficult to evaluate whether people have access to the same information, aid or response programs. The gap between social classes is very large and could imply that not all citizens are treated or respond in the same way.

4 – How can the alternative model be tested?

In this study the model was calibrated to fit what the literature states about resilience. It was researched what characteristics usually are connected with high or low resilience and the equations were formulated and modified to give the expected result. This method was chosen because the model should create easily accessible and manageable information, not be used to draw new conclusions about the resilience concept as such.

The model should be tested further in order to increase its credibility. The model can be tested at more sites in order to prove its generalizability; it should preferably also be tested with a real project implementation with real rain events in order to see if the calculated results match reality.

The results are presented graphically in maps since this is an easy way for the recipient to take in information. However, there is a risk of missing information if the difference is too small to be visible in the graphical divisions. There were a few cases during the examination of the results which seemed somewhat strange until the values behind the graphics where scrutinized.

5 – How does the alternative model respond in tests?

The S-FRESI responds within the frame of what was expected. However, some of the indicators measure very complex matters and it was found to be very difficult to evaluate whether they actually express what they are constructed to measure.

The material recovery was connected with many complicated issues. For example, as it is formulated now it expresses how well one can repair and replace what was damaged in a flood, but perhaps this should not be the highest priority when considering flood resilience. It is plausible that it would be better to express how well one can return to a certain living standard instead.

Another complicated issue was the duration effect. The duration effect is connected with exposure and susceptibility since low flood levels are expected to, to a greater extent, affect people and transportation (exposure) while high flood levels are expected to damage property (susceptibility). This is reasonable when just looking at the indicator but perhaps gives the exposure and susceptibility indices too much influence when looking at the complete S-FRESI. There would be a point in keeping all the indicators independent in order to gain better control of what affects what.

6 – Can the alternative model be used as a tool in decision making concerning urban drainage?

The results in this research suggest that S-FRESI can become a useful tool for urban flood planning. However, in order to incorporate models like S-FRESI into the decision process, it is extremely important that politicians show interest and commitment to creating a resilient society.

The graphical output of S-FRESI makes it accessible to laymen, but an understanding of flood resilience is necessary in order to make the best use of it. To make wise decisions about flood protective measures, additional information will also play a vital role. One example is cost, which will always be an important factor. It would be beneficial to make a separate study on how S-FRESI, or models like S-FRESI, are best incorporated into the decision making process.

The S-FRESI would likely be of most benefit if incorporated into a broader program to increase the city’s general resilience. The local government in Mesquita has shown interest in previous flood resilience work at UFRJ and both Mesquita and the neighbouring city São João de Meriti participated in the “Making cities resilient” campaign by UNISDR (UNISDR, 2012). This suggests a local awareness of the problems and a will to improve the city through resilience.

8.2 Further Reflections on the Research

Flood resilience is an important and complex subject that includes many aspects that the scope of this research did not allow for. These aspects include, for example, how the resilience work is affected by Brazilian law, how much governments and NGOs are encouraged to work with these questions, how different interests are prioritized, and how responsibilities concerning floods and urban planning are distributed.

During this research there have been many reflections about what resilience is and how it can be measured. The approach for the index was to learn what the literature says about resilience and then translate this into values. This is a valid way to make measurement tools, but there is a danger that this approach leads to circular arguments. It is important to remember that tools developed in this way only measure the chosen variables and cannot be used to prove that the choice of variables was made correctly.

From the beginning it was thought that S-FRESI should be a user-friendly tool. As it is now, it is particularly the visualization of the result that is easy to interpret and understand. In order to apply the index in a new catchment it is necessary to have knowledge within the subject and a great amount of reliable data is required.

In this study the index was used to evaluate an already populated area concerning resilience. However, it is also an idea that a similar approach as S-FRESI could be used in the planning stage of future settlements.

8.3 Recommendations for Future Research

It would be interesting to make a sensitivity test to see how much each indicator affects the S-FRESI and if the chosen weights should be adjusted. Depending on who the end user is, the indicators can have more or less importance.

The weakest part of the S-FRESI is the indicator expressing the material recovery ability. As a first step it is recommended to adjust this mathematical expression by doing more tests and surveying in the area.

One idea is to investigate how much different income classes can spend of their yearly income in a crisis situation. In S-FRESI it is assumed that 30% of the yearly income could be spent on material recovery, but it is very probable that this varies from one income class to another. For example it could be assumed that poor people have little or no opportunity at all to save a buffer for emergency situations, while rich people have a completely different situation. It is suggested to investigate this, for example by surveying, to be able to see what the limits are and what more reasonable assumptions could be.

Another aspect that is important to consider is the location of essential services. Perhaps it is too complex to mathematically integrate all essential services in the index. Still, they are important to consider and it is recommended to at least identify them and be aware of their locations in order to not disregard them.

Elderly people and children might have a harder time handling a severe flood event. It should be investigated if it could be valuable to integrate this indicator in the S-FRESI.

It is also recommended to look into how S-FRESI can be implemented as a tool in decision making concerning urban drainage.

9. Conclusion

In order to create concrete goals for flood resilience work and to evaluate its progress, it is necessary to measure flood resilience. S-FRESI has shown promising test results and can be used to combine important concepts of resilience into a single value. S-FRESI makes it easier to understand, use and work with the necessary information. For example it enables the comparison of different flood control measures against each other.

The spatialization of the index enhances the possibilities to detail project plans better in order to boost their outcome. It enables the identification of sensitive areas which are in the greatest need of improvements. Information about the spatial distribution of resilience is particularly valuable since well targeted resilience projects can enhance also the surrounding areas considerably. By spatializing the S-FRESI result it can be displayed in maps. This makes it possible to quickly get an overview of the area in question and easily pinpoint where actions have to be made. By presenting the information in maps it would also be possible to easily include more spatial information such as location of essential services or other objects extra worth of protection.

The S-FRESI in its current state needs further testing. The economic factor is somewhat weak and would need additional assessment. If more time is invested in research of the S-FRESI it is likely that the index can become a valuable tool in urban planning. It can be used to measure and visualize the changes in flood resilience obtained by flood control measures.

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Osvaldo Moura Rezende, 2013

Appendix

A. Flood Risk Index

A flood risk index, FRI, was developed in a master's thesis project by Zonensein (2008), at the UFRJ Laboratory of Computational Hydraulics, as a way of quantifying risks associated with flooding. The FRI is calculated through the probability of a flood event occurring and its estimated consequences (Zonensein, et al., 2008). Zonensein used seven indicators that were chosen and evaluated based on the situation in Rio de Janeiro. The indicators represent direct and indirect damages to goods and constructions, and costs of interrupted public services and infrastructure. The aspects are normalized and assigned weights according to their relative importance. The indicators are: flood depth, flood duration, hydrodynamic forces represented by a velocity factor, dwelling density, income per capita, traffic hierarchy and sanitation. These were judged to be the most representative factors of the main damages associated with flooding in the study area and manageable with the available data. The formulation of the FRI (Equation A.1) was designed to be flexible enough to also be used in other situations and locations but would in such cases have to be modified in choice of indicators and weights in order to reflect that particular situation.

$$FRI = \left(\sum_{i=1}^{n} I_i^{FP} * p_i^{FP}\right)^{q_{\boldsymbol{FP}}} * \left(\sum_{j=1}^{m} I_j^{C} * p_j^{C}\right)^{q_C}$$

Where $0 \leq p \leq 1 \ and \sum_{i=1}^{n} p = 1 \ and \ 0 \leq q \leq 1 \ and \ q_{FP} + q_C \leq 1$

Equation A.1

Indicators are labeled by I and range between 1 and 100. Weights associated with the indicators are labeled by p. FP and C are sub-indices that represent flood properties and flood consequences, and weights associated with these are labeled q. The FRI can take on values between 0 and 100 where 1 is associated with minimum risk and 100 with maximum risk.

B. Phase I – Modifications of the RS

The first modification of the RS was made to Equation B.1 by changing the nominator to FRI^{F+Proj}.

$$\alpha = 1 - \frac{\left(FRI^{F+Proj} - FRI^{P+Proj}\right)}{FRI^{F+Proj}}$$

Equation B.1

The formulation of Plot 1 was changed to avoid negative values. A change in the formulation was tested, altering the product of α and β to a summation (Equation B.2). This intended to valorize the mid values of RS, instead of emphasizing the extreme values of the scale.

$$RS2 = \frac{\alpha + \beta}{2}$$

Equation B.2

This makes the individual RS fall within the definition, but the result is still not realistic. For example, several cells receive RS=0 even if they are not located within flood hazardous zones. To correct this, a coefficient C_1 (Equation B.3) is introduced and combined with RS2 to create RS3 (Equation B.4). This gives RS2 a lot of weight if the flood depth of the cell is low and lesser weight the higher the flood level.

$$C_1 = \frac{h_c - h_1}{h_c}$$

Equation B.3

Where h_c is the reference depth, here taken as the maximum flood depth of the study area, and h_1 is the flood depth of the particular cell. Both depths are simulated for the chosen flood event.

$$RS3 = RS2 * \ C_1$$

Equation B.4

RS3 gives unexpectedly small changes compared to RS2. RS4 (Equation B.5) was introduced where one minus α and β is tested. α was changed into γ (Equation B.6) and β into δ (Equation B.7). To accommodate this change, C_1 was altered into C_2 (Equation B.8). The intention was to directly map the increasing risks, in order to calculate resilience in the end of the process, by taking the complement to one of the result. The intention was to directly calculate the increasing risk and then take the compliment to one to receive the resilience.

$$SR4 = \frac{\gamma + \delta}{2} * C_2$$

Equation B.5

$$\gamma = \frac{\left(FRI^{F+Proj} - FRI^{P+Proj}\right)}{FRI^{F+Proj}}$$

Equation B.6

$$\delta = 1 - \frac{\left(FRI^{F-Proj} - FRI^{F+Proj}\right)}{FRI^{F-Proj}}$$

Equation B.7

$$C_2 = \frac{h_1}{h_c}$$

Equation B.8

Where h_1 and h_c are as described below Equation B.3.