Resilient flood management for Xochimilco, Mexico City

Master's Thesis Internship – Master Water Science and Management

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Abstract

Thanks to geologic, geographic and anthropogenic reasons, Mexico City is very vulnerable to flooding. Xochimilco, in the southern part of the city, has a rich historical and cultural heritage that is under direct threat of excess water. In the future, climate change can lead to more intense floods. Some elements are critical in Mexico's history and unique, like the *chinampas,* a zone that attracts a lot of tourists. In the past, floods have had devastating effects on the poor district of Mexico – it is largely neglected and has low *flood resilience.* In this thesis, certain concepts are translated into criteria by which we can measure flood resilience of an urban area. Due to poor governance and limited water management, the waterworks are getting worse and water availability is dependent on external sources, and even then limited – leading to societal unrest. If a 'do nothing', or *business as usual*-strategy will be employed, the city will face a gigantic (social) catastrophe that is unprecedented in Latin-America, or western society for the sake of argument. Luckily, huge advances can me made resilience-wise. There is a wide range of measures and adaptations that can be considered on short, medium and long term. This requires a new, inclusive form of government with bottom-up influence from the population. The technical know-how and financial assets are available, but needs to be done fast – the proverbial clock is ticking.

Keywords

Resilience, flood resilience, flood modelling, Mexico City, Xochimilco

List of abbreviations

100RC	100 Resilient Cities
BCE	Before (the) Common Era
CONAGUA	Comisión Nacional del Agua
CDMX	Ciudad de Mexico
CRF	City Resilience Framework
CRO	City Resilience Officer
DEM	Digital Elevation Model
MLS	Multi-Layered Safety
OSM	OpenStreetMap
SACMEX	Sistema de Aguas de la Ciudad de México
UNESCO	the United Nations Educational, Scientific and Cultural Organization

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1. Introduction

1.1. Background

Deltares is a partner of the 100 Resilient Cities (100RC) project. This platform, developed with the supervision of the Rockefeller Foundation, aims to improve the resilience of 100 cities around the world, regarding their physical, social and economic challenges (Nelson, 2015). Mexico City is part of this network. The city has to face several challenges with respect to water. One of the major challenges is to cope with flooding. Specifically, a part of the project is focused on the Xochimilco borough, in the Southern zone of the Federal District of Mexico City. Xochimilco, situated at the foot of the southern foothills, is hit frequently by floods that are capable of causing serious damages to the important land of Xochimilco. Over 80% of the area of Xochimilco corresponds to a Conservation Zone, due to its high ecological value and to its vital agricultural activities (Aguilar & Lopez, 2009).

There are several (historic) reasons that have caused Mexico City to be susceptible to flooding. The prime one is its geological setting. Mexico City lies in the floor of the Mexico Valley basin, and it receives runoff from the nearby mountains, a site that is improperly managed (Comision Nacional del Agua, 2012).

The basin was once covered with lakes that acted as natural drainage for precipitation runoff. The majority of the lakes were either intentionally drained or have disappeared due to the overexploitation of the aquifers in the region (ibid). The overexploitation of the aquifers also causes subsidence that damages the existing drainage infrastructure, which is at risk of losing its slope, required for gravitational discharge (ibid).

Climate change is leading to an increase in rainfall intensity and to more frequent extreme events (Lankao, 2010). This will likely increase the pressure severity on the capacity of the drainage system, which is already overloaded, to frequent flooding events in the city (Lankao, 2010).

In the second part of the 20th century, the population of the Valley of Mexico increased greatly: from around 2.8 million inhabitants in 1950 to 18 million in 2000. This had great implications for the functioning of the city. The increased population and fast urbanisation led, and is still leading to deforestation and to the reduction of water infiltration zones (Lankao, 2010; Comision Nacional del Agua, 2012). Currently, Mexico City and its suburban areas (total urban area) host 20.4 million inhabitants, and a sizable share lives in 'informal settlements' (a euphemism if you will for non-legal housing). The changing land use change requires a practical approach in which the increasing population can still live with water in a safe and sound manner.

At a national level, 30% of the impacts of flooding are concentrated in the Mexico Valley sub region (Comision Nacional del Agua, 2012). The actual water system presents several issues. There is an overall lack of maintenance, as reported from Conagua (ibid) which affects the functioning of pumping stations and of the drainage system (ibid). There are no warning systems for hydro-meteorological phenomena (ibid). At a regional level, yearly investments in flood management are currently not sufficient (ibid).

1.2. Problem description

1.2.1. Scientific problem

The district Xochimilco is one of the areas in Mexico City that faces a multitude of problems, though with its own peculiarities. As for the illegal settlement of population in Xochimilco, at the moment 15.000 inhabitants live in informal settlements. Due to the extensive abstraction of water from the aquifer and to the small recharge, the area is subsiding (UNESCO, 2006). Some of the effects are the lowering of water levels in the canals and changes of the flux direction (ibid). Also, urban infrastructure is affected.

Groundwater abstraction is partly a direct result of water insecurity among the poorest groups in Xochimilco. Among the urban poor, fresh water supply is characterized by insecurity and exclusion. The needs of the population are met by different non-conventional and officially non-recognized operators: in irregular settlements the supply is the most precarious, inconsistent and expensive.

Due to the low water levels, Xochimilco receives treated wastewater from three treatment plants, in order to maintain the water level (ibid). These plants operate in basic conditions and lack maintenance. Some channels have been modified to drain wastewater from the population, so that the capacity for rainwater is reduced. The infrastructure for rainwater drainage is scarce (ibid). The biggest scientific challenge lies in identifying how all these separate conditions and processes influence the extent and probability of floods in Xochimilco.

1.2.2. Societal problem

Xochimilco is a unique historic district within Mexico City. Its cultural value and assets should not be lost as result of poor governance. At the beginning of its history, the inhabitants of Xochimilco developed a unique agricultural system, with artificial narrow and long islands made of layers of silt and soil that were created on the shallow lakes (UNESCO, 2006). These systems of canals and agricultural land are called *chinampas*. In the twentieth century, Xochimilco became more connected with (the rest of) Mexico City. A system of pumps and pipes was created in order to bring water from the Xochimilco springs to Mexico City, in order to account for the increase of water demand for the growing population (ibid). This led to the progressive decrease in the size of the lakes and to the disappearance of the springs.

In 1987 Xochimilco was included in the World Heritage List by UNESCO (ibid); not only for its peculiar physical characteristics, but also for the cultural, social and economic system behind them (ibid). For the inhabitants of the area, Xochimilco is a symbol of their cultural identity, where rituals and festivities take place (ibid).

As a cultural heritage, the main parts to protect are the Chinampera Zone and the historical centre of Xochimilco, because of the presence of historical monuments and because it is home to the Chinampa farmers (UNESCO, 2006). Several archaeological zones are part of the area, and they represent settlements of the population of the Nahuatlacas, with archaeological remains that date back to 1400-1500 B.C.E. Furthermore, the Chinampera zone has an economic value for the region, since it is a popular touristic area. The area hosts the Ecological Park of Xochimilco (*Parque Ecológico de Xochimilco*) that was designed to show and recreate the characteristic lake ecosystem of the Mexico Valley, its agricultural techniques and to preserve original flora and fauna (ibid).

Apart from being capable of destroying houses and cultural value, floods also cause monetary damages. Thousands of inhabitants are poor, and live in houses that are not equipped to withstand floods. There is not enough money for flood damage repairs. It is of prime societal importance that the region has decent ways to deal with large precipitation events, and prevent water from accumulating in the streets, sometimes meters high in altitude.

1.2.3. Specific problem for Deltares

Deltares will work together with the Chief Resilience Officer (CRO) of Mexico City for the planning of a Resilient Water System for Xochimilco. The collaboration consists of three phases. The first one is the understanding of the water system and it comprises the modelling of groundwater flow and surface water movement. The second phase consists of the development of a resilience strategy; afterwards the last part of the project will be focusing on the implementation phase of said strategy.

The first task is to understand what flood resilience is for Xochimilco and which measures would contribute to make it resilient with respect to flooding. Moreover, the company is interested in developing a tool that will help predicting flooding impacts and to see how this and other tools can be considered effective for enhancing stakeholders' participation and how they influence the decision making processes.

1.3. Aim and research question

The aim of the first part of the master's thesis is to analyse what is meant by resilience, urban resilience and flood resilience and what criteria can be identified. The framework to which this constitutes will be further elaborated on in subchapter 1.4. The focus will predominantly lie on flooding, but resilience is broader than just that: it is subject to different interpretations within different contexts. It is important to specify the **criteria** that make a system resilient, and how these criteria are **quantified** or otherwise **measured**, or **conceptualised**.

In the second part of the thesis the situation in Xochimilco and Mexico City will be assessed using the criteria defined in the first part. First, the current state of the water system is to be assessed, meaning how the system is able to cope with flooding at this moment in time. Then, flood processes are explored to see what specific areas are most vulnerable, and how they react to precipitation events of different magnitude. After the past and current resilience is evaluated, we can identify what measures would be appropriate, where, and why. Together, this leads to the following research question;

To what extent is Xochimilco flood resilient at this moment in time, and how can modelling and water management increase resilience in the future?

1.4. Scientific framework and methods

In order to answer the main question in a clear and concessive manner, a simple framework has been established. The framework consists roughly of two parts. In the first part (represented by the grey boxes in figure 1.1.), background on resilience, urban resilience and flood resilience is obtained from background literature, in order to translate conceptual methods into certain criteria that account to flood resilience. With these criteria, Mexico City and Xochimilco will be 'tested' in the second part of the thesis.

The second part consists of two *building blocks* or broad categories if you will, that will assist in assessing the criteria put up in part 1. The two coloured blocks are *Water System* and *Modelling Flood Behaviour*. Together, they will make it possible to give a preliminary assessment of Mexico City's and Xochimilco's current flood resilience.

The block *Water System* is a description of Mexico City's and Xochimilco's water system. A short historic overview and general development will be given. This will lead to an understanding how past processes and human-system interactions have had an effect on the current situation on the socio-ecological system.

In *Modelling Flood Behaviour*, a visualisation is made of the depth, extent and spatial occurrence of floods. Deltares' D-HYDRO Suite is utilised. At first, external forcing in the form of small precipitation events will be explored. Afterwards precipitation events with a low probability rate will be modelled to acquire a view of a 'black swan' -event, or worst case scenario. The output of the models is flood maps; an overview of which parts of Xochimilco experience higher risk, and what assets and critical infrastructure is at risk. Some elements that are particular worth noting are presented in a *Critical infrastructure* flood map, containing amongst others hospitals and other infrastructure that are of key importance in upholding day-to-day society. The overall goal of the flood maps is to give *resilience* a spatial dimension: the resilience of Xochimilco is certainly not uniform but rather differs throughout the area.

The two blocks together will result in an assessment of Current Resilience. Afterwards, through the building block Measures, Adaptations, and Improvements an exploration will be made what of what

Xochimilco's future resilience might become. Here the goal is to build further on the spatial resilience, and identify what water measures are appropriate and where. Examples are delaying or retaining water, re-using or storing it. These are just general terms and are achievable in different ways, dependent on multiple variables. Some methods are perhaps applicable to the whole district of Xochimilco. The goal of this section is to grant basic insight in available methods to enhance the water system, and how and why this differs on spatial scale. This step will also try to suggest *what* the advisable steps and policy changes are towards a more flood resilient Xochimilco and Mexico-City as a whole. Currently, there is no authority with an integrated responsibility for water management, and responsibilities are scattered throughout the water system. How can we progress forwards to smarter governance?

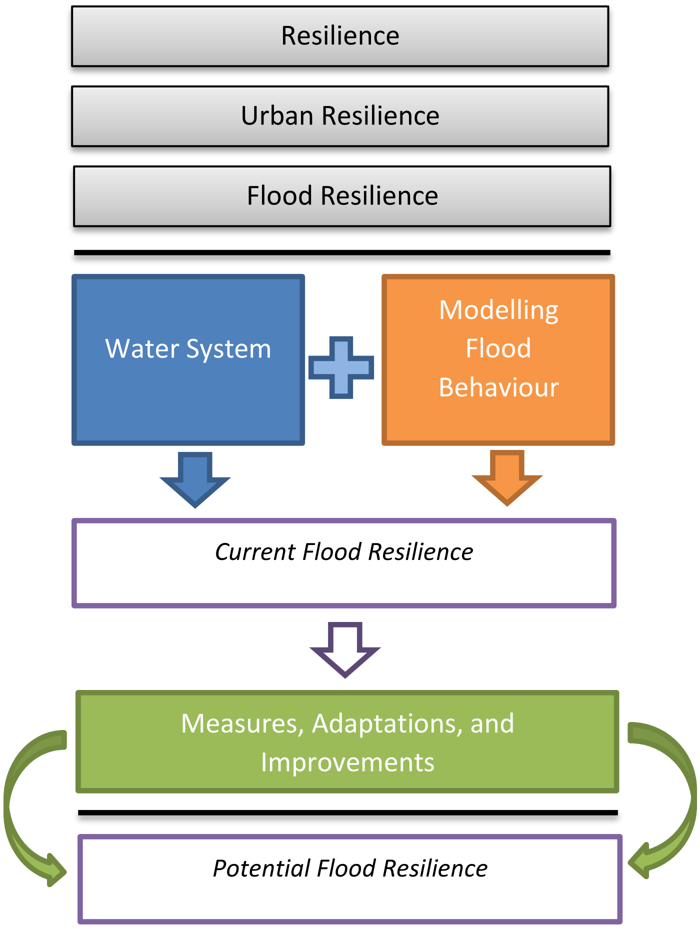

Figure 1.1. Scientific framework

1.5. Hypothesis

The main question as displayed in paragraph 1.5. is *to what extent is Xochimilco flood resilient at this moment in time, and how can modelling and water management increase resilience in the future?*

The question is multi-facetted; and therefore must be answered as such. Prior to establishing what *resilience* is and how to qualify and quantify it, the current state of Xochimilco's resilience is difficult to assess. A rather educated assumption can be made based on (scientific) literature however. Currently, Xochimilco's resilience is deemed **unsatisfactory**. Predominantly, this is the result of a growing population, unsustainable use of the aquifer and illegal housing. To illustrate with non-scientific literature: in 2014 VICE News reported from Mexico City's impoverished boroughs, where "*miserable flooding is a fact of life*". While the report largely focused on Izatalapa (the borough north of Xochimilco), the characteristics are the same: regular floods in the rainy season, crippling infrastructure and largely neglected by the federal government due to the impoverished nature of the demography.

From the current situation, the *only way is up*, one might argue. As for the second part of the main question, the notion exists that within the next decade(s) there are **lot of possibilities** for Xochimilco to increase its flood resilience. However, resilience can never be absolute – but water management wise, a lot of low hanging fruit; or *quick wins* that can be implemented within a reasonable time frame. Examples are new education programmes, catching rain water for later use and better (centralised) organisation of how illegal housing treat their 'dirty' water.

The expectation is that modelling floods certainly is able to increase resilience. For once, if we know which specific zones have a higher risk of flooding, we can act accordingly. Furthermore, additional protection measures of critical zones can be realised, and future development of housing, amenities, and other infrastructure can be planned and executed better.

2. Resilience theory

2.1. Resilience

On May 30th 2016, inhabitants of the south-western German state Baden-Wuerttemberg were caught by surprise by a number of flash floods and hail storms that ravaged their way across Germany, destroying houses and sweeping away cars. At least four people were killed, and many more left severely injured as the storms caused rivers to burst out of their banks. At least 7000 fire-fighters, policemen and rescue workers were dispatched to oversee over 2200 incidents. The flooding was the result of a severe storm that hit Germany and other parts of Europe over the course of one weekend (Daily Mail).

At the same time, on the other side of the Atlantic Ocean, six people lost their lives following torrential rain in large parts of Texas. In Washington County (TX), record amounts of precipitation caused identical scenes as Germany: houses were damaged, cars disappeared into water and thousands were evacuated. The heavy precipitation was not able to infiltrate into the lime- and sandstone, causing the creeks to rise above their borders. This was not the first dramatic event in Southeast-Texas, since it was struck earlier that same year: two 500-year flood events occurred in the span of just two months' time (CNN).

While the scope, intensity and chance of floods may differ from location to location, the negative external effects are shared. Loss of life, liveability and damages to assets and infrastructure are common denominators. Ultimately, whole communities may be disrupted for multiple years. Conversely, other cities and urban settings have developed effective strategies to deal with both preventing, as well as coping with floods. A comparison between different settings may give rise to a myriad of interesting questions. Why is one city more resilient than the other? What factors account for resilience? One might even ask: what *is* resilience?

"No head of state wants to be remembered for another Katrina".

The concept of *resilience* opens the doors for (semantic) discussion. The scientific community is still discussing on the meaning. It is used in many ways: a modern *buzzword,* a principle, a tool, and a goal towards sustainability. While there probably will never be a definite interpretation of resilience, one aspect that most definitions agree upon is that resilience has a positive connotation: the world 'needs more of it'. Classified under the overarching title *Sustainable cities and communities,* resilience is explicitly mentioned in the United Nations (2015) Agenda for Sustainable Development: Goal 11 encompasses making cities and human settlements inclusive, safe, resilient and sustainable.

There has been a significant amount of scientific output regarding resilience and its relationship with other (abstract) concepts like vulnerability, sustainability, robustness, adaptability and recovery. In the following section, an exploration is made what the most common and prevalent interpretations are in scientific literature, and how we can translate these concepts one step further into *flood* resilience.

2.1.1. Origins of resilience

The concept *resilience* originated in the ecology domain, but has since then spread out to other relevant fields of research. In scientific literature, the first known occurrence of resilience dates back to the 1970's. Scientists used *resilience* as the extent to which ecosystems or organisms are able to recover from a disruption and are able to return to the original (stable) state. When this is the case, we speak of *recovery* of the system. Within ecology, this application of resilience is predominantly found when referring to rivers, lakes and forests (Fiering, 1982). Mens et al. (2011) adds that when a system does not recover to the original state, but rather into another stable state (without change of the underlying structure), we also can deem it *recovery*. In general, the relative force of the disruption that is needed to permanently destabilise the original system displays the extent of ecological resilience (ibid).

From the 1990's onwards, the concept of resilience has moved to other research fields. Within the socio-ecological domain, resilience was predominantly used to describe changes within socio-ecological systems (Folke, 2006). Socio-ecological systems behave different when compared to ecological systems, since the *human* factor is introduced into the equation. The 'changes' within this context are changes within a system that are the (direct) result of a changing environment. In other words, system characteristics cannot be observed or judged outside of a social context (ibid). Furthermore, the resilience framework requires a frame of reference in which the relationship must be regarded between (i) the survival of wanted system structures, (ii) the renewal of unwanted structures, (iii) disruptions and (iv) innovation opportunities that are the result of disruptions (ibid).

Holling (2000) explains another important concept within resilience: thresholds. The assumption is made that a socio-ecological system adjusts itself to its environment (and changes therein); the system is considered stable as long as it does not reach the threshold. When a system is 'pushed over the edge' of a threshold by an external force, the system becomes unstable or changes into another system. The **threats** for a system primarily originate in disruptions in stability, which is why the system will try to counter the disruptions.

Folke (2006) proposed a three-way definition of resilience in socio-ecological systems; (i) the maximum disruption a system is able to cope with, (ii) the extent to which the system can adapt and/or reorganise *itself*, and (iii) the extent to which the system can increase the capacity specified under point (ii).

Alas, "*it is difficult to prophesy, especially about the future*," as the Danish proverb says. Nature and the environment is unpredictable, therefore we can never predict disruptions with an absolute level of certainty. Disruptions will always occur, be it predicted or as total surprise, and can devastate a system. Increasing resilience can help reducing the impact of disruptions.

2.2. Urban resilience

"*No head of state wants to be remembered for another Katrina*", Erwann Michel-Kerjan states in a 2015 editorial in *Nature* magazine. Hurricane Katrina probably serves as one of the most horrifying examples of failure in public administration and urban resilience. When the levee system failed, water from the Mississippi river flooded a large part of New Orleans. Hurricane Katrina struck New Orleans in 2005 and remains the most destructive natural hazard in recent US history. It caused more than 1800 deaths, $125 billion dollar in economic losses and lasting social and political impacts. The local government was unprepared and had no appropriate reaction. By 2006, the population of New Orleans had halved and the city was still in shambles (Nature, 2015).

More than a decade after Katrina it is safe to say that New Orleans was not destroyed *without consequences*, and societies have learned valuable lessons. Disaster forecasting, crisis management, communication to the general public and effective governance is higher on the agenda. Previous factors (and more) in an urban setting are assembled under the umbrella term *urban resilience*. In this subchapter, a general overview will be given on different views of urban resilience. What makes a city resilient? What it is *urban resilience* comprised of and how we can quantify it?

Cities are becoming increasingly more important and complex webs of institutions, infrastructure and social platforms. The share of Earth's population that lives in cities has increased significantly in the 20th century and this trend continues further in the 21st century (Arup, 2015). Large cities are attractive as cultural, financial centres with myriads of opportunities and innovation possibilities. Alas, when densely crowded cities are not resilient they are vulnerable to *shocks* and *stresses,* which can cause social breakdown, physical and economic collapse. The challenges at hand have evolved over time, however. Resource shortages, natural hazards, war and conflicts are no longer the primary resilience benchmarks; new pressures have prevented themselves in the form of climate change, disease pandemics, economic fluctuations and terrorism (ibid).

Urban Resilience, as set out by 100 Resilient Cities, is *the capacity of individuals, communities, institutions, businesses, and systems within a city to survive, adapt and grow no matter what kinds of chronic stresses and acute shocks they experience* (100 Resilient Cities, 2015).

Resilience is applicable to cities because they are complex systems that are always adapting to changing conditions and circumstances. Conceptually, it becomes relevant when physical and social systems are threatened: a city's ability to maintain essential functions can be threatened by acute *shocks* and chronic *stresses*. In turn, these shocks and increasing stresses may result in economic and physical damages, or even societal collapse (Arup, 2015). Examples of acute shocks are earthquakes, floods, terrorism and extreme cold or heat; examples of chronic stresses are water scarcity, lack of social cohesion, poor air quality and poverty. Resilient systems need certain qualities that enable them to withstand, respond and adapt in suitable ways; Arup (2015) sees the following qualities (figure 2.1.).

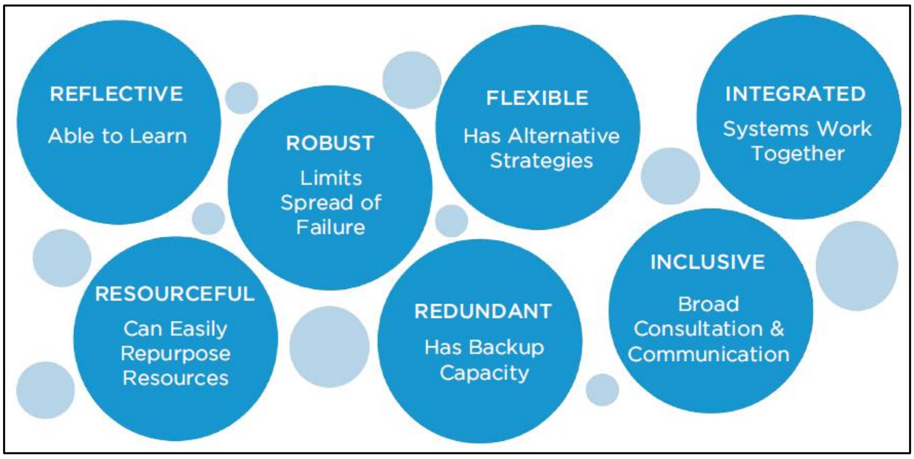

Figure 2.1. Qualities of a resilient city

The seven qualities are characterised as follows (Arup, 2015);

Reflective; reflective systems accept the increasing uncertainty and change in the world, and have mechanisms to evolve. They will modify standards and norms based on evidence rather than seeking a 'permanent' solution. Institutions systematically analyse past experiences to better their future decision-making.

Resourceful; people and institutions are capable to rapidly achieve goals and meet needs during shocks or when under stress. This can include setting priorities, and mobilising and coordinating human, financial and physical resources. Resourcefulness is of key importance in restoring functionality of critical systems.

Robust; robust systems include well-constructed and managed physical assets, that can withstand the impacts of hazards without significant damage or loss of function. Robust design anticipates possible failures. Over-reliance on a single asset, cascading failure, and thresholds that might lead to catastrophic events when exceeded must be avoided.

Inclusive; inclusiveness emphasises the need for broad consultation and engagement of communicates, including vulnerable groups. Addressing shocks and stresses per sector, location or community in isolation is detrimental to inclusiveness. A sense of 'shared ownership' is needed to build urban resilience.

Integrated; integration and alignment between systems promotes consistency and makes sure that all investments support a common goal or outcome. Exchange of information between systems enables a collective functioning and enables rapid response through shorter feedback loops in the city.

Flexible; this implies that systems can adapt and change as a response to different circumstances. It can be achieved by introducing new knowledge and technologies. Furthermore, it also means using traditional knowledge and practices in new ways. Decentralised are usually favoured.

Redundant; redundancy is spare capacity within created on purpose systems so that they can accommodate disruption, extreme pressures or surges in demand. Diversity is needed: the presence of multiple different methods to achieve a need or fulfil a certain goal. Redundancies must be intentional, cost-effective and prioritised at city-scale.

100RC has, together with engineering multinational Arup, developed the City Resilience Framework (CRF), a comprehensive list of drivers that contribute towards resilience. The CRF provides an accessible, evidence-based articulation of city resilience. Currently, it is being developed further towards the City Resilience Index. With the help of the CRF cities are able to identify areas of weakness and find corresponding actions to improve. The CRF is comprised of twelve drivers within four dimensions. The twelve drivers are derived from the proposed qualities in figure 2.1. The four listed categories are health and wellbeing, economy and society, infrastructure and environment, leadership and strategy. The twelve corresponding drivers are stated in figure 2.2.

Dimension	Driver
Health & Wellbeing	1. Meets Basic Needs: Provision of essential resources required to meet a person's basic physiological needs.
	2. Supports Livelihoods and Employment: Livelihood opportunities & support that enable people to secure their basic needs. Opportunities might include jobs, skills training, or responsible grants & loans.
	3. Ensures Public Health Services: Integrated health facilities & services, & responsive emergency services. Includes physical & mental health, health monitoring & awareness of healthy living & sanitation.
Economy & Society	4. Promotes Cohesive and Engaged Communities: Community engagement, social networks & integration. These reinforce collective ability to improve the community & require processes that encourage civic engagement in planning & decision-making.
	5. Ensures Social Stability, Security and Justice: Law enforcement, crime prevention, justice, & emergency management.
	6. Fosters Economic Prosperity: While Driver 2 is about individual livelihoods, Driver 6 is about the economy on a wider scale. Important economic factors include contingency planning, sound management of city finances, the ability to attract business investment, a diverse economic profile & wider linkages.
Infrastructure & Environment	7. Enhances and Provides Protective Natural & Man-Made Assets: Environmental stewardship, appropriate infrastructure, effective land use planning & enforcing regulations. Conservation of environmental assets preserves the natural protection afforded to cities by ecosystems.
	8. Ensures Continuity of Critical Services: Diversity of provision, redundancy, active management & maintenance of ecosystems & infrastructure, & contingency planning
	9. Provides Reliable Communication and Mobility: Diverse & affordable multi-modal transport networks & systems, ICT & contingency planning. Transport includes the network (roads, rail, signs, signals etc.), public transport options & logistics (ports, airports, freight lines etc.)
Leadership & Strategy	10. Promotes Leadership and Effective Management: Relating to government, business & civil society. This is recognisable in trusted individuals, multi-stakeholder consultation, & evidence-based decision-making.
	11. Empowers a Broad Range of Stakeholders: Education for all, access to up-to-date information, & knowledge to enable people & organizations to take appropriate action. Along with education & awareness communication is needed to ensure that knowledge is transferred between stakeholders & between cities.
	12. Fosters Long-Term and Integrated Planning: Holistic vision, informed by data. Strategies/plans should be integrated across sectors & land-use plans should consider & include different departments, users & uses. Building codes should create safety & remove negative impacts.

Figure 2.2. Drivers and dimensions of a resilient city (Arup, 2015)

Within cities, resilience has helped to bridge the gap between disaster risk reduction and climate change adaptation. Traditional disaster risk management related to specific hazards, resilience rather accepts the possibility that a broad diversity of events may occur (both shocks and stresses); which may or may not be predictable. Resilience focuses on enhancing the performance of a system in the face of multiple hazards, rather than preventing or mitigating the loss of assets due to specific events (Arup, 2015).

2.3. Flood resilience

Having acquired a general understanding of resilience and urban resilience, we can now move forward to *resilient flood management*, or flood resilience. At the root of flood management is establishing what flood risk means, and how the risk can be minimised.

Taken literal, flood risk management is a three term component. Flood is defined as *the overflowing of water onto land that is normally dry.* Within this context we usually refer to flood plains and delta zones. In nature, flood plains and delta areas are good basic conditions for human settlement and economic activity. Often times, these areas are under threat from natural hazards such as floods: *flood risk*. The second term, (flood) *risk* is defined as the probability of a flood multiplied by the damage (Jorissen, 1997). Flood risk increases with economic development. The final term, *management,* refers to actions that can be taken to either increase or decrease flood risk.

The *umbrella* term of these sets of actions within flood management is called flood risk strategies. Certain flood risk strategies, like heightening dikes to protect land may even add to the risk: the growing certainty or feeling of safety behind a dike triggers financial investments, hereby adding value to the infrastructure at risk (Vis et al, 2003). Furthermore, by continuously increasing the dike heights, the potential flood depth (and impact) increases (ibid). Within flood risk management, the approach can be twofold: either the actions are targeted at (A) reducing the chance of a flood, or (B) minimising the (negative) effects of flooding.

Reducing the chance of flood can be done in different fashions. Parker (2000) recognises three structural elements: (i) preventing discharge, (ii) preventing floods and (iii) reducing the effects. Herein, a separation between structural and non-structural solutions is made; structural solutions are targeted in preventing floods, non-structural solutions are targeted at reducing negative impacts. Parker's first two elements are structural, the third is non-structural. The first element, preventing discharge, is aimed at the reduction of peak discharges. In Parkers work the context is a river, and preventing that excess water reaches the lower course of a river. It can also be applied to runoff and discharge from a higher altitude, *in casu* runoff from the mountains to the lower zones of Mexico City. One application is the storage or delaying of excess water in the upper course of the river (or mountains) and releasing it when the water height in lower areas is lower again, after a while. The second element, preventing floods, implies that the peak discharge does not cause a flood. An example to this extent is increasing the amount and height of dikes. The last element is reducing negative effects of a flood. Methods that can be attributed are experimenting with early warning systems, adapting national insurance systems to incorporate floods, and different land use management: flood risk zones should be used differently (Burby, 2001). A society can make a consideration not to facilitate critical, vulnerable or valuable infrastructure in a higher risk zone. Hiding (2009) adds the category *preparation*. Preparation implies reducing the impacts of a flood, which is comparable to the last category of Parker. Herein, a flood is more or less considered a given, or *fact of life,* and cities are prepared as such: e.g. by constructing new infrastructure in a waterproof fashion, and introducing a new (urban) system that innovates alarming, evacuating and structures the repair afterwards.

With regards to flood risk management, the approach does not have to binary: methods reducing flood chance methods that minimise negative effects methods can be employed simultaneously. This approach is generally referred to as *multi-layered safety* (MLS). Multi-layered safety is an approach that tackles different safety aspects. The first later is prevention, for example the strengthening of dikes. The second layer accounts for spatial solutions, for example elevating houses and flood proving them. The third layer is aimed at crisis management: faster evacuation methods and early warning systems. In figure 2.3., MLS (albeit in a typical Dutch context) is displayed graphically (Atelier Groenblau, 2009).

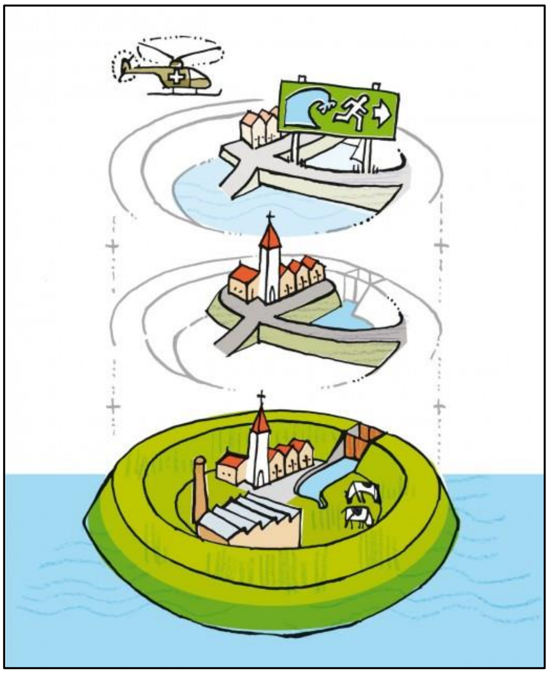

Figure 2.3. Multi-layered safety conceptualised (Atelier Groenblau, 2015)

2.3.1. Flood resilience criteria

Within urban context, we can make a step from flood risk management to flood resilience. De Bruijn et al. (submitted) divide resilience into four *abilities:* (i) the ability to avoid impact, (ii) the ability to limit impact, (iii) the ability to recover from impact, and (iv) the ability to adapt.

The ability to avoid impact (i) is centred on prevention. This implies that either the water does not reach the risk zone, or replacing the vulnerable objects outside the reach of the water. The latter is quite utopian. In a country with unlimited financial means and unlimited free space, this would be the favoured method. Unfortunately, this method is limited by reality. The first approach is more realistic, and can be achieved in two fashions. The first is by the construction of flood barriers, like an infrastructure of dikes. The second is achieved by reducing the intensity of the peak discharge- either by (i) storing the water where there is capacity to do so, or (ii) transporting the water at a faster rate where storage is not possible.

The ability to limit impact (ii) focuses on limiting damages after a flood. The damages are limited by taking precautions beforehand. Important herein is that the basic assumption is made that a flood will take place, and the water will subsequently reach vulnerable objects and critical infrastructure. The societal task is constructing or adapting said objects and infrastructure in a matter that it can withstand water better. Within Xochimilco, this will largely amount to private residences and companies. Existing real estate must be adapted and new real estate must be constructed in a waterproof fashion. Furthermore, the establishment of evacuating systems and early warning systems can limit impact in the form of reducing human casualties.

The ability to recover from impact (iii) focuses on how the system can recover from a flood into a stable state as fast as possible. Within this category, societal elements are incorporated. Public health can be a good example; a healthier population is able to recover more quickly. Assets can also contribute. Richer countries with larger reserves may endure larger set-backs. Available knowledge and proper governance and leadership on how to initiate and establish recovery processes can also have significant influence. A well-organised insurance system is of key value; where *insurance* is defined herein as a financial compensation of suffered damages as a direct result of flooding. When this is organised on national scale, the suffered damages can be spread out over the population (Hegger et al, 2016).

The ability to adapt (iv) is the last category and slightly more abstract. This ability refers back to the first three abilities: how can they be improved to increase the total flood resilience of a system? This ability can be split up in a (i) reactive and a (ii) proactive component. The reactive component encompasses that lessons are learned from (a) previous flood(s) and that the awareness is actively increased. The proactive component encompasses the thorough analysis of current and future risk. Also, the notion must exist that future risk can follow different development paths and is not fixed, and therefore changes in future scenarios must be met by an ‘open’ and flexible societal attitude (ibid).

3. Current and future resilience

3.1. Mexico City's water system

The first pillar of resilience is a general analysis of Mexico City's water system. The current and future *resilience* of Xochimilco is path dependent on past processes and occurrences. The main finding herein is that the water system is limited, unreliable, and largely dependent on outside sources. In order to comply with the future, it needs large scale improvement. This is largely the result of Mexico City's location, its tectonic and geologic setting and historical processes that included abstraction and poor water management.

3.1.1. Geologic setting

Mexico City is located in the Basin of Mexico, in the southern half of Mexico. The average annual temperature is 15 °C. Most of the average annual precipitation falls between May and September: between 600 mm in the northern and 1200 mm in the southern areas). The basin is comprised of 12 sub-basins. The basin is a high mountain valley, is approximately 9000 km^2 in size, and has a minimum altitude of around 2200 meters above sea level. It is surrounded by mountains and volcanoes that have elevations of well over 5000 meter (National Research Council, 1995). The basin was artificially opened at the end of the 18^{th} century to control flooding. In Figure 3.1., the Basin of Mexico is displayed relative to Mexico itself. The Basin is part of the Trans-Mexican Volcanic Belt (or Sierra Nevada). In geologic sense, the Belt is a Pliocene-Quaternary (2.58 MA) calk-alkaline (subdivision within magmatic petrology) province that runs through Mexico from west to east. The Belt includes most of historic and present volcanic activity in Mexico. In it are andesitic-dacitic stratovolcanoes, cinder cone fields, and major rhyolitic centres (Huizar-Álvarez et al, 1997).

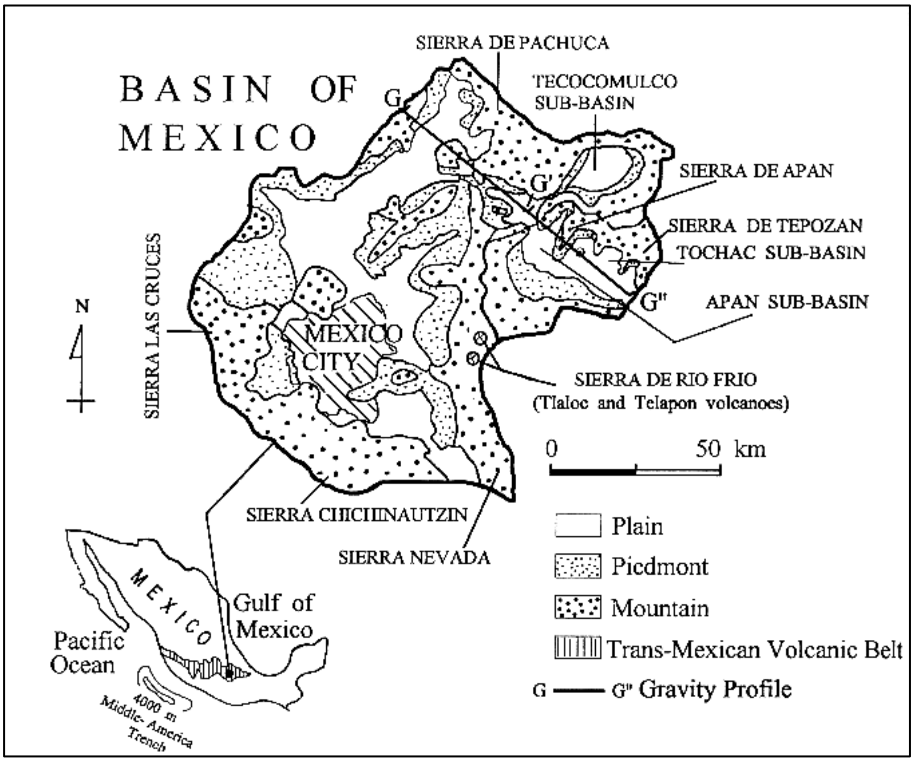

Figure 3.1. Overview of the Basin of Mexico (Huizar-Álvarez et al, 1997)

Mexico is located near the border of the Cocos Plate and the North American Plate (Figure 3.2; adapted from Kim (2011)). Towards the south-east of Mexico, the smaller Caribbean Plate is situated. Mexico is located on one of Earth's subduction zones, where the ocean floor of the Cocos Plate is forced beneath the continental edges of the North American Plate. As a result of this gradual geologic process, a chain of volcanoes (or 'volcanic arc') has been formed above the subducting plate (Molnar et al, 1969 as cited in Huizar-Álvarez et al, 1997). Where two tectonic plates collide, large earthquakes can be triggered. Since Mexico is located on a subduction zone, it is prone to earthquakes.

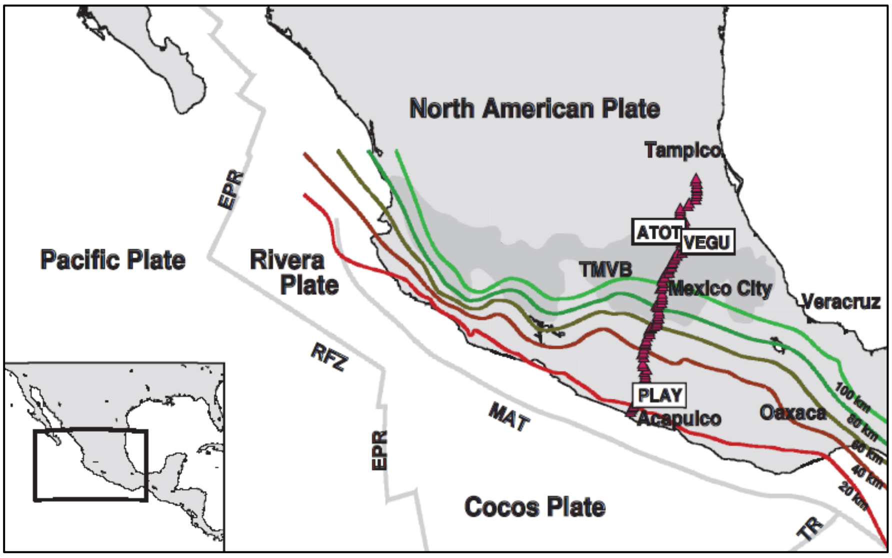

Figure 3.2. Tectonic situation near present-day Mexico: the Cocos Plate moves in north-western direction towards, then underneath the continental North-American Plate (image adapted from Kim, 2011)

The geology of the Basin of Mexico has historically allowed enough water resources to reach the inhabitants of Mexico City. Groundwater recharge mainly comes from infiltrated precipitation and snow melt in the neighbouring mountains. The ground water flow produces springs in the foothills and upwellings in the valley (ibid). Figure 3.3. displays the ground water flow system in the Mexican Basin. Precipitation and snow melt create a deep water table (letter **A**). Parts of the downward gradients become shallow water tables (**Bi**) in the piedmont zones (foothills). The majority however flows under the valley floor, upward through the clay. It enters through fractures in the aquifer as either diffuse discharge (**Bii**) or thermal springs (**Biv**). Discharge is done by means of evapotranspiration (**C**) (Durazo and Farvolden, 1989, as cited in National Research Council, 1995).

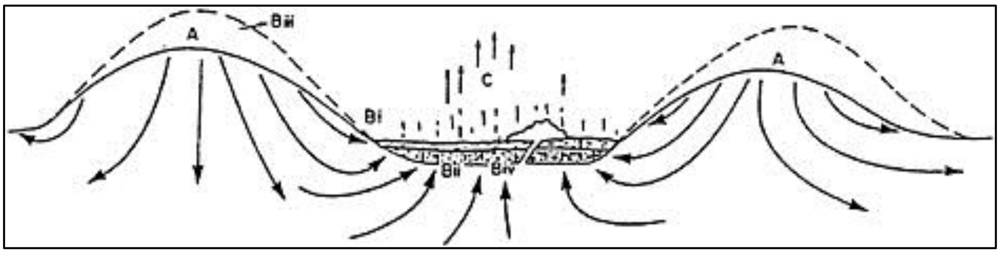

Figure 3.3. Historic ground water flow in the Basin of Mexico

3.1.2. Geographic implications and historic alterations

The Valley is enclosed: there is no natural outlet for water to flow towards. There is, however, a 'gap' in the Northern part of the Valley without high peaks. Since there is no natural drainage, the water that originates in the mountains (mainly as precipitation) and flows towards the city needs to be processed via manmade constructions (National Research Council, 1995).

Geologically, the Valley of Mexico is a closed basin that can be divided into three hydrologic zones: (i) the low plain, the bed of where the lakes used to be, (ii) the piedmont (or foothill) area and (iii) the surrounding mountains. Altitude wise, the old lakebeds are the lowest and consist mainly of clay with high water content. It is almost fully covered by urban settings. The foothills' composition is a mixture of clay and silts and sands. From the mountain ranges, rain and snow enters the Valley's water system. The groundwater flow causes upwellings in the valley floor, and springs in the piedmont zone. This flow connects to five aquifers that supply a majority of Mexico City's drinking water supply (ibid).

Prior to human involvement, water either entered the subsoil or evaporated. First signs of water engineering dates back to ancient civilisations like the Aztecs, who constructed dikes to separate fresh water from saline and prevent floods.

Figure 3.4. The lake system within the Valley of Mexico prior to the Spanish Conquest, around 1492AD (Wilson, 1992)

The part of the Valley we now recognise as Mexico City used to be a lake area (figure 3.4.). Saline lakes could be found in the north, freshwater lakes in the south (National Research Council, 1995). The five lakes (Zumpango, Xaltoca, Xochimilco, Chalco and Texcoco) covered 1500 km^2 of the basin floor (Koch, 2005). The lakes were separated from one another by small mountains. The lakes were fed by runoff and snowmelt from the mountains, and flowed toward the largest lake, Texcoco. Due to evaporation, Texcoco was saline (Alcocer et al, 1996).

After the Spanish took over control in the sixteenth century, they soon found that the Aztec *water management* practices did not guarantee sufficient protection from floods. In these times, the city was only a meter higher than the average level of Lake Texoco. Floods were frequent, and the population grew steadily (Aguilar-Barajas et al, 2015). As a result, a large infrastructural undertaking (the Desagüe) was started to drain the area.

The main method of draining was the digging of canals, which alas was not sufficient to prevent further floods. After the Great Flood of 1629, construction of the *Grand Canal* began; consisting of one main canal and three secondary canals. It was completed over two and a half century after initial construction, but still did not prove efficient in safeguarding Mexico City from flooding. From the eighteenth century onward, flood protection strategy focused on constructing additional outlets to transport surplus water via open channels and tunnels. The lakes, in turn, dried out completely. Only some small lagoons are left in Xochimilco and Zumpango. The drainage deprived the city of nearly all its capacity to store surface water, and has led to a grave overexploitation of the aquifers (Aguilar-Barajas et al, 2015).

3.1.3. Floods

Mexico City, being the capital of Mexico, serves an important political, financial, cultural and urban role within the country. As such, future floods may have disastrous effects on the economy, public health and safety, and livelihood of the city as a whole. As the population increases, so does the urbanisation (in the form of new e.g. pavements, asphalt and infrastructure), which in turn decreases the water infiltration capacity, leading to increased Hortonian overland flow.

Lankao (2010) states that the abundant water supply and the susceptibility for flooding are the result of three specific elements in the structure and functioning of the hydrological cycle:

- Firstly, the mountains surrounding the basin consist mainly of basalt and andesite rock and therefore are highly permeable to water. The permeable formation causes high aquifer recharge levels as well as myriads of springs and recourses.
- The hills and mountains are covered richly in different types of vegetation, predominantly oak and pine, but also grasses and shrubs (Angel, 1973 as cited in Lankao, 2010). The forest served as shield against water erosion of the soil. Vegetation also created a dynamic equilibrium between water filtration, evaporation and run-off to the bottom of the basin.
- The lake system, which also contributes to the equilibrium, since it dampened the impacts of floods.

3.1.4. Influence of climate change

Climate is one of the most influential factors on Mexico City's water system. Periods with wet years and flooding events are alternated by periods with serious droughts, sometimes lasting for over a decade. Between the years 1450 and 1900, the Valley experienced over 136 droughts (Mendoza et al, 2005 as cited in Lankao, 2010). In the last century, the mean temperature in Mexico City has increased with 1.6 °C. This is largely caused by the urban heat-island effect, which in turn is (at least partly) a result of land use change.

Jauregui et al. (2001, as cited in Lankao, 2010) predict that in the future, the hydrological and climatic conditions of the Valley and the basin are expected to change further as a result of global warming. Changes in means and extreme events may disrupt the balance in the system. Temperature wise, an increase of mean temperature of 4 °C is predicted by 2080. This will be accompanied by a predicted decrease in mean precipitation of up to 20 per cent. Disruptions in the hydrological cycle will likely affect Mexico City's aquifers that provide its inhabitants with fresh drinking water: the expected increase in evapotranspiration, alongside decreases in precipitation runoff and aquifer recharge will decrease the availability of fresh water (ibid). Furthermore, alterations of extreme droughts and heat waves with short episodes of extreme precipitation may occur more frequent.

Climate change has caused an increase in mean rainfall in Mexico City, together with an increase in frequency and intensity of extreme events like floods, droughts and heat waves. In the twentieth century, downpours and storms increased from one or two to six or seven per year (SMA, 2008 as cited in Lankao, 2010).

3.1.5. Lack of and declining infrastructure

Mexico City is rapidly urbanising and has to act fast and efficiently in order to prevent the 'water crisis' to develop into a water fiasco. Currently, the largest issues with the infrastructure are the following.

SACMEX (2013), Mexico City's public water service, who serves more than 8.8 million inhabitants, indicates that there still are shortcomings in distribution and lack of infrastructure. The organisation faces significant challenges like aging infrastructure, problems with subsoil and subsidence and hydro-meteorological risks. Despite efforts to meet the needs of water services, SACMEX fails to deliver in full and the service quality is deteriorating at an alarming speed (ibid). In some scenario's water crises of unimaginable magnitude and consequences are predicted: aging infrastructure may deteriorate water sanitation and provision to unacceptable levels, increasing the vulnerability for possible failures.

Problems discharging flood and household water

The disappearance of the lakes and overexploitation of aquifers thanks to a rapidly increasing urban environment has caused the fragile ground under the city to subside. Continuing subsidence can have a myriad of negative external effects. Existing infrastructure can be damaged as result of the terrain getting more uneven. Subsidence also causes issues with (waste) water management, which can result in floods – often in periods with high precipitation. In the past, ground subsidence has caused a decrease of the inclination of the tunnels that transport water out of the city: they are dependent on gravity, and as inclination decreases, so does the tunnels capacity (Aguilar-Barajas et al, 2015).

External dependence and leakage

For drinking water, Mexico City is partly dependant (30%) on the Cutzamala and Lerma systems. However, especially the Cutzamala system has decreased in reliability over the past decades. It transports water from the Cutzamala River in the Southwest to Mexico City. The Cutzamala River is located 120 km (!) outside the Federal District, and estimates are that 40% of the water is lost before it reaches its destination (SACMEX-Redagua, 2013).

Dependence on outside water is also a large bottleneck for the drinking water supply in Mexico City. From the Cutzamala River, the water is pumped up to an altitude of 2700 meters near Los Berros, where it passes a potabilisation plant. The water still has to travel 100 kilometres (by gravity) from there to Mexico City. The infrastructure, consisting of pipes and tunnels, is 30 years old and needs constant maintenance. Earthquakes are able to completely destroy the system, as once before happened in 1985.

No connection

It is estimated that nearly one million inhabitants of Mexico City (a lot of which live in Xochimilco) are not connected to the water system. These people are reliant on other (illegal) methods of acquiring (ground)-water, which leads to overuse of the underlying aquifer, leading to further subsidence (ibid). The largest problem is that communities without direct connections to the sewer system deposit their waste in the main sewer entrances. As a direct effect, they clog the waters entry point to the central drainage network, effectively reducing drainage capacity when storms hit.

3.2. Modelling flood behaviour

Flood modelling can have a wide range of functions and uses. For instance, we can define (early) warning areas and forecast water levels. Furthermore, flood mapping can raise community awareness, and zoning flood plains can aid in the appropriate development of certain areas.

3.2.1. Input

The first necessity in modelling is acquiring the appropriate input data. The creation of a Digital Elevation Model (DEM) is the first step. The *Earth Explorer* tool, courtesy of the United States Geological Service, can be utilised to collect radar-data from a pre-defined area. The majority of data is open source and free to use for the general public. More detailed and advanced spatial intelligence often requires a clear statement of intent that the data is used for scientific purposes and not for commercial activities.

The Earth Explorer allows users to select a square zone containing the required area (Xochimilco), thereafter the available data sets are visible; ranging from vegetation monitoring, land cover to aerial imagery. For now, ASTER GLOBAL DEM is selected.

ASTER (The Advanced Spaceborne Thermal Emission and Reflection Radiometer) is a Japanese sensor, one of the five remote sensory devices located on the Terra satellite that is in Earth's orbit since 1999. Aster provides high resolution images 14 different bands of the electromagnetic spectrum, ranging from visible to thermal infrared light. The global digital elevation model was developed by U.S. National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade and Industry (METI). This DEM is the most complete
map of the Earth, with roughly 99% of the surface accounted for (BBC News, 2009). The terrain elevation measurements have a resolution of roughly 30 by 30 meters. The data is split up in sizable GeoTIFF-files, square digital elevation 'tiles' of 60 by 60 kilometres (22.702 tiles in total). The tiles carry the geographic coordinates and are initially referenced to the WSG84 geo-id.

While ASTER provides a solid product, it is not flawless - the DEM may contain anomalies and artefacts that reduce its usability, large elevation errors on local scale may occur and this needs to be addressed prior to the actual flood modelling.

With ArcGIS, Xochimilco can be separated from the rest of the digital elevation model. A shapefile with the administrative boundaries of the 2456 municipalities of Mexico, including the 16 boroughs in Mexico-City, is employed. This dataset is developed by INEGI, the National Institute of Geography, Statistics and Informatics of Mexico. Additionally, the projection of the data has to be adjusted from a Geographic Coordinate System to a Projected Coordinate System, in this case WGS 1984 UTM Zone 14N. This will alter measuring unit from degrees ('circular Earth') to a 'flat' Earth projection. The cell size employed corresponds to the image size of the satellite imagery (30x30). With Xochimilco *clipped* from the rest, figure 3.5. is the result.

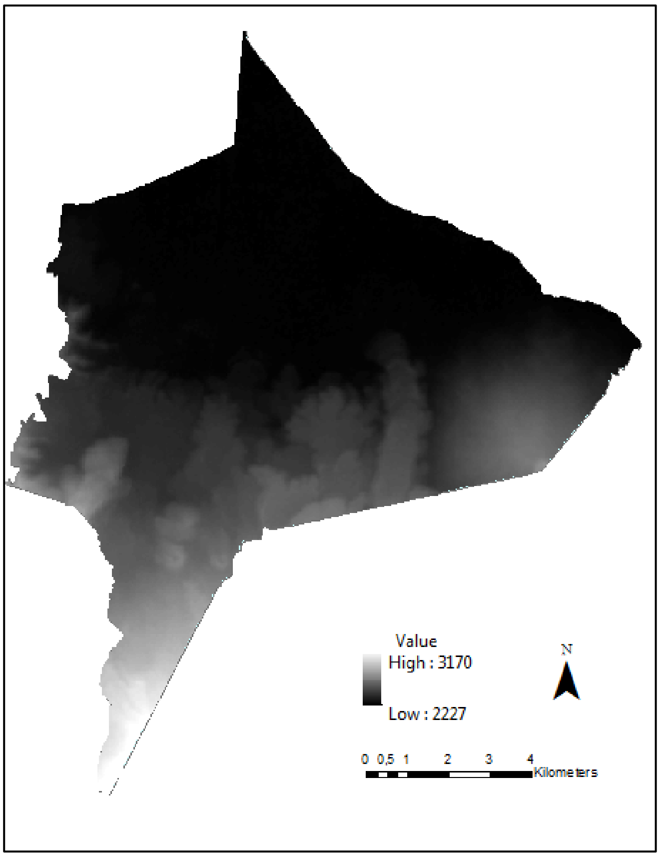

Figure 3.5. Digital elevation model of Xochimilco

The software used for flood modeling, the D-HYDRO Suite is developed by Deltares. D-HYDRO is simulation software, aimed at coastal areas, estuaries, rivers and urban areas. It allows users to simulate (amongst others) floods, hurricanes, waves, water quality and heavy precipitation. The software is aimed at a wide group responsible for design, execution and management; be it consultants, technicians, modelers or policy makers. One of the core assets of the D-HYDRO Suite is the D-Flow Flexible Mesh module, which is able to render one-dimensional, two-dimensional and three-dimensional hydrodynamic simulations on a grid.

For Xochimilco, two-dimensional flood modeling will be used. 2D-modelling usually calculates water depth and 'depth averaged' water velocity on a grid or mesh. This requires a digital terrain model (the DEM) and/or the bathymetry (underwater topography) of the bodies of water.

3.2.2. Adaptation of the DEM

In order to visualize the effects of precipitation events on Xochimilco, D-HYDRO will be utilized to simulate precipitation and the 2D water spread in urban areas. Ideally, the resolution of ASTER's imagery would be as high as possible (1 by 1 meter data, for example). This is unfortunately not the case; the 30x30 meter resolution can be observed as an 'average' height of each given cell. In other words, a lot of details – e.g. patches of trees, water streams, and buildings- are 'ignored'. Ultimately this means that with limited satellite data, flood modeling in D-HYDRO is a rough approximation and carries, to some extent, a **margin of error.** Practically speaking this will mean that we can observe which parts of a street or alley will flood, but not on the detailed level of a single house or building.

Rather than holding onto a cell size of 30 x 30, within ArcGIS the DEM is adapted to a cell size of 10 to increase the amount of detail.

To further enhance the DEM to 'compensate' for the missing spatial data, the DEM can be slightly modified manually to represent reality better. Some quite common adaptations than can be performed are **(a) 'burning in' bodies of water** to lower them in comparison to their initial position, and **(b) raising urban areas** (constructions, houses) to a higher point.

(a) Burning in bodies of water using Raster Calculator

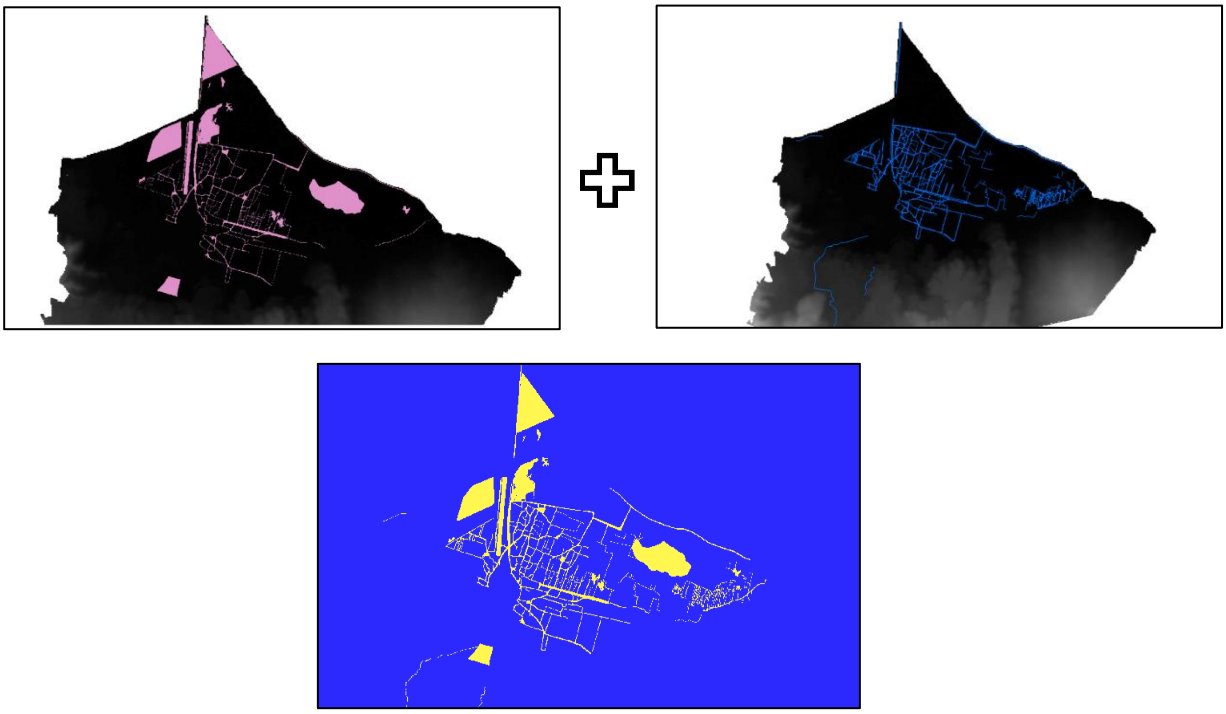

Figure 3.6. Merging two raster shapes

Two different water shape files (with some overlap) were found on online databases, therefore the initial step was to merge them, and afterwards assign all cells with water a value of 1, and all cells without water a value to 0. The value of 1 meter is chosen on a semi-arbitrary basis, on the assumption that (i) the height difference between the 'shore' and the top of the water is, on average, just one meter, and (ii) this holds for the whole area. In reality, this number would range from as few as 10 centimeters to some meters in the river valleys.

The resulting raster, which has the same spatial extent and projection as the DEM-raster) was then subtracted from the DEM, effectively lowering all cells with water 1 meter.

(b) Raising urban areas using OpenStreetMap

To research urban areas, one can make use of OpenStreetMap (OSM), which is open source data that is available at no cost to the general public. OSM's website explains "(…) *project that creates and distributes free geographic data for the world. We started it because most maps you think of as free actually have legal or technical restrictions on their use, holding back people from using them in creative, productive, or unexpected ways.*"

OpenStreetMap is a collaborative project to create a free map of the world, and considered to be a prime example of *volunteered geographic information*. OSM has over 2 million registered contributors, who can contribute to the project with different methods; amongst others manual observations, GPS devices and photography.

The required parameters that are needed to be 'burned in' the DEM have to be acquired from pre-existing tags and user inputs. Unfortunately, the data that is currently available is not specific enough to modify the elevation model in an appropriate manner: the level of detail of Mexico-City is limited to a general classification of what area is urban and what is not. Ideally, the highest level of detail – every house, construction and building and its respective size – would be available, but some cities and regions lag behind on other urban regions of the Earth. With available data edited into QGIS software we can make a general zonation of Xochimilco, as seen in figure 3.7.

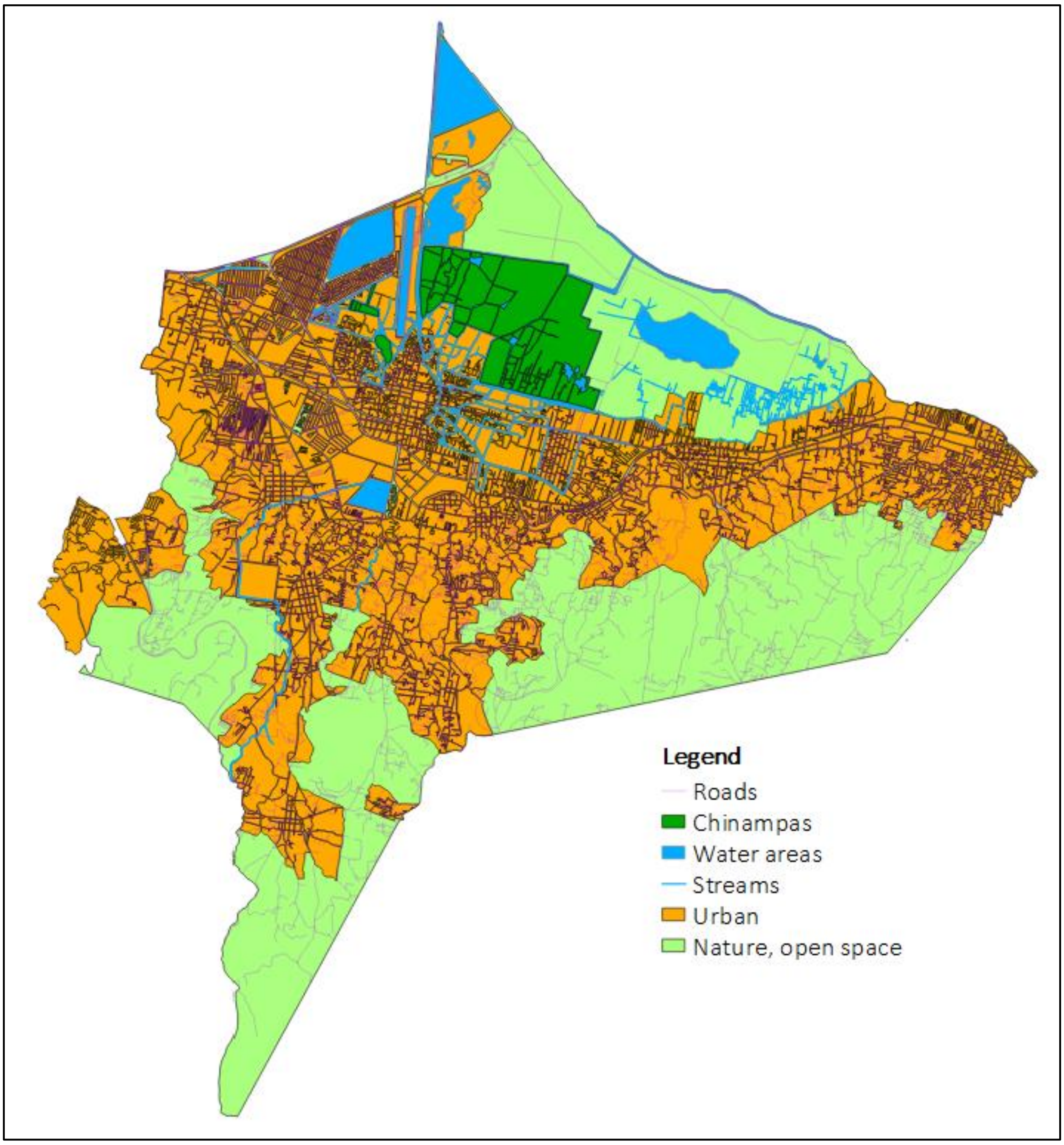

Figure 3.7. Zonation of Xochimilco areas using data from OpenStreetMap

3.2.3. Utilising the D-HYDRO Suite in Xochimilco

The number of severe storms (more than 20 mm of precipitation per hour) in Mexico City has increased in recent decades (Magaña, 2003). The changes in weather patterns in the Mexico City basin have resulted in a higher risk to intense precipitation and flooding. Mexico City has a rainy season that lasts roughly from late May until early October. Rainfall differs spatially; especially the south-western part of the city experiences the heaviest rainfall due to the interaction of easterly winds with orography (ibid). Furthermore, the southern parts of the city have to deal with runoff water originating in the mountains.

A test model is run to validate whether the D-HYDRO Suite computes a flood map with realistic outcome. The basic assumption is that all precipitation falls **within Xochimilco**. Of course, this is unrealistic since the laws of nature are not limited to human-made topographical boundaries. Furthermore, **external topography** outside Xochimilco, where precipitation could possibly leak to due to differences in altitude, is disregarded.

(Magaña, 2003), considers 20 mm/hour a severe storm. Initially and for test purposes, we consider a 'normal'-sized precipitation event of 10 millimetres in 1 hour at a continuous rate of 0.833 mm per 5 minutes.

The resulting flood map (water depth, figure 3.8.) presents a general impression; the zone below the red line is mountainous and steep; less water will accumulate there. The zone above the red line houses is relatively flat and has the most urban areas; and therefore is more interesting for the resilience problem. The bar on the right represents the water depth in meters, ranging from 0 to 0.25 meter. For visibility, water depths up to and including 2 centimetres are not displayed. In general, a 10 mm precipitation event will lead to small, local water nuisance up to around large puddles of 15 cm deep. For more insight we zoom in to the Xochimilco Chinampa-zone (the purple section in figure 3.9.).

The Chinampa zone, characterised by heavy agricultural use, is mildly affected by the precipitation event. As visible in figure 3.9. water starts accumulating into shallow puddles of about 10 centimetres deep. The average *puddle* has an extent of approximately 40 by 40 meters, a considerable size with regards to agriculture and potential losses due to drowning of crops.

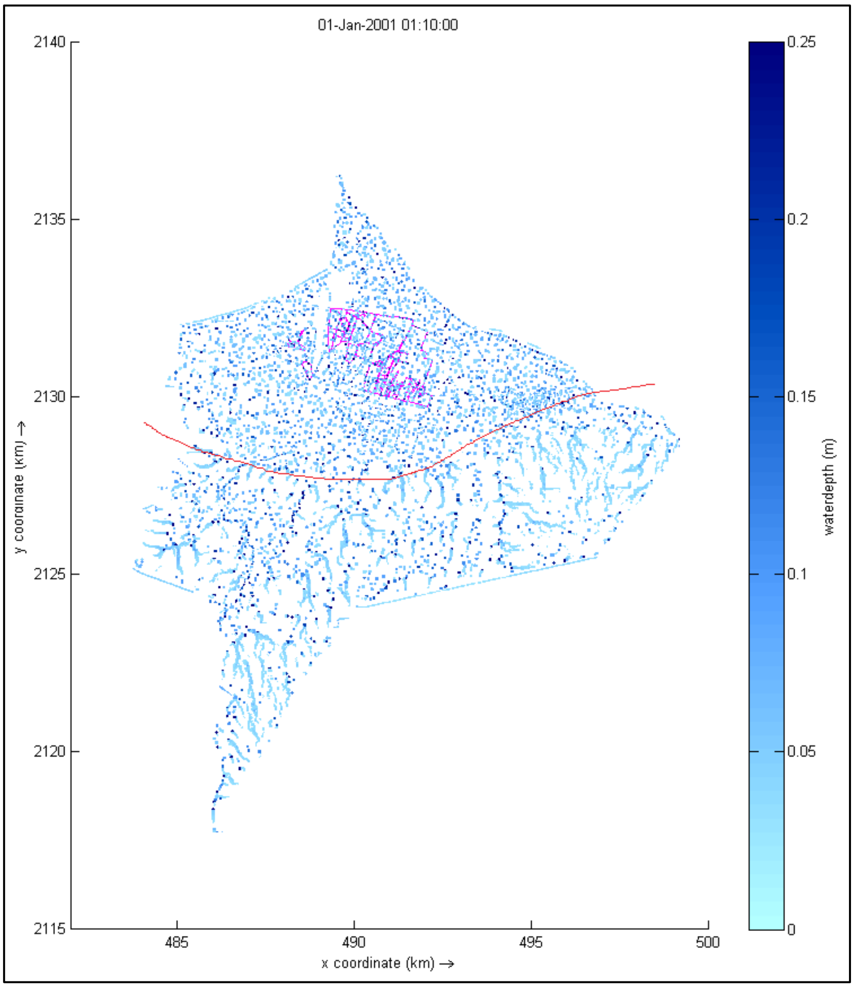

Figure 3.8. Water depth map – 10 mm/hour event

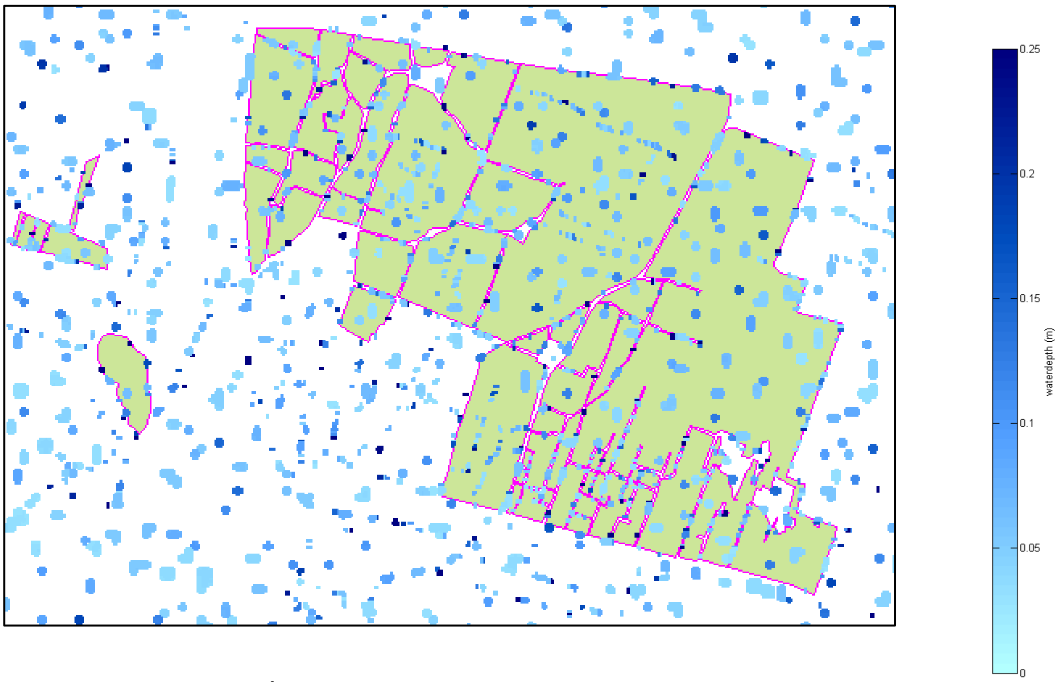

Figure 3.9. Water depth map – 10 mm/hour event – Chinampa zone

3.2.4. Run I: Modelling a 'severe storm'

The input in the D-HYDRO Suite will now be amped up to 20 millimetres in a one hour time frame; the precipitation event will have a continuous rate of 1.666 millimetres per 5 minutes. The resulting water depth map is visible in figure 3.10. As expected, the 20 mm/hour event clearly has a slightly larger impact than the former 10 mm/hour event. More areas (local depressions) are inundated, and the 'border' between the mountainous area and the lower lying urban areas is sharper than prior. Locally and in extreme cases, water depths of about 40 cm can be reached.

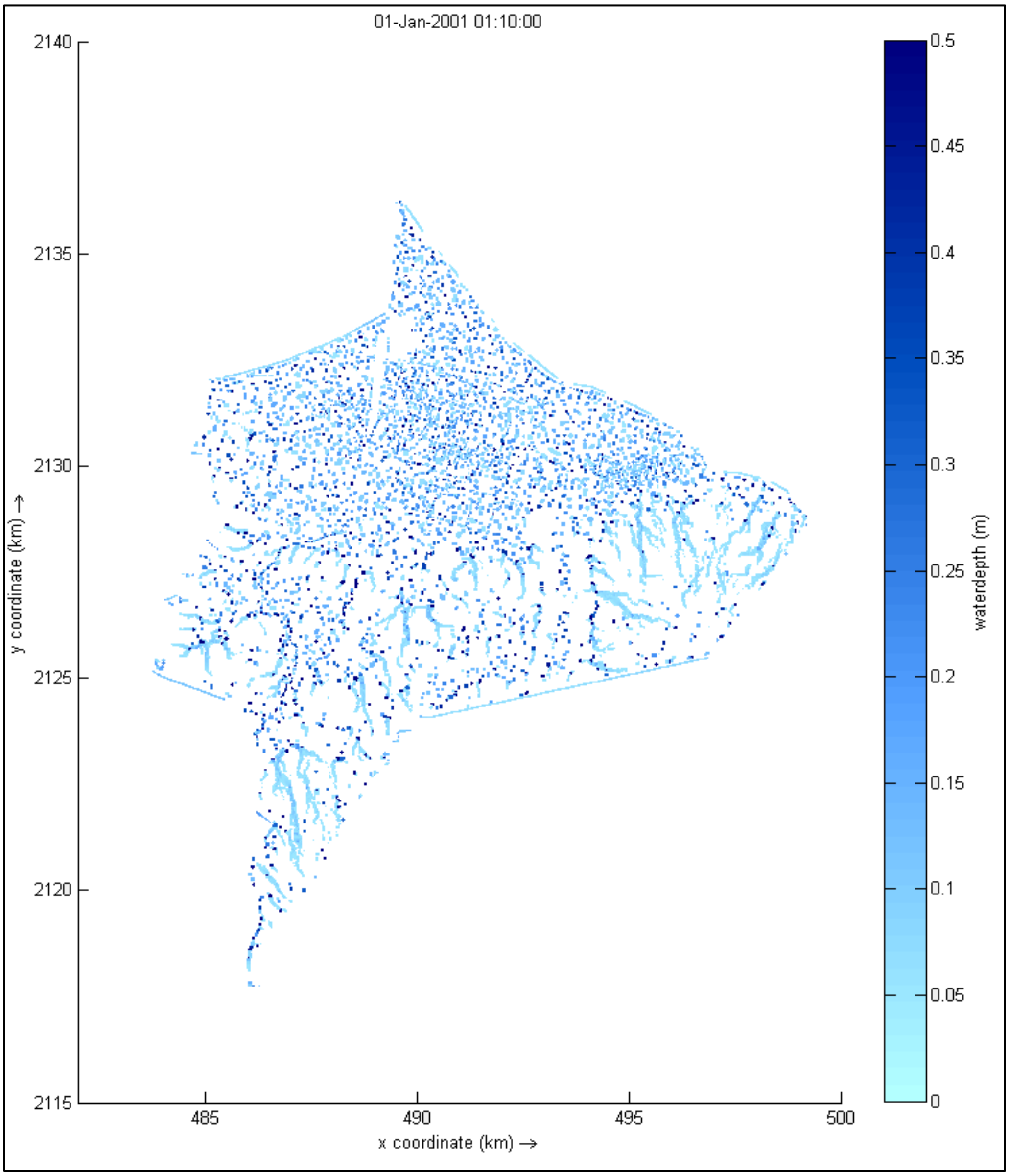

Figure 3.10. Water depth map – 20 mm/hour event

3.2.5. Run II: Modelling of a serious flash flood

Precipitation events larger than 60 mm in 24h are not unusual in the south-western part of the city. Magaña et al. (2003) state that extreme events in the western part of México City should be more than 25 or 30 mm in 24 hours. For the eastern part of the city, more than 15 mm in 24 hour already constitute an extreme event. The largest precipitation event in the southern part of the city was 164.9 mm in 24 hours on September 22, 1983 (Mendez Antonio et al, 2009).

In México City most rainfall occurs during the afternoons of summer time with intense precipitation frequently developing from east to west. Typically, during these events the intense precipitation begins in the afternoon, around 16:00 h local time (ibid).Floods in Mexico-City can be triggered by hurricane events. In 2016, Hurricane Earl threatened south Mexico and Mexico City with torrential rainfall. Prior to the event, hurricane expert Dan Kottlowski warned for torrential rainfall events of 100 to 200 mm, and locally in the south of Mexico possibilities of 300 to 450 mm. While the backlash of a hurricane typically can last longer than 24 hours, we will consider the possibility of 200 mm of rainfall in 24 hours, which is significantly more than the record for 24 hours (164.9 mm). The distribution of precipitation in time is displayed in figure 3.11.

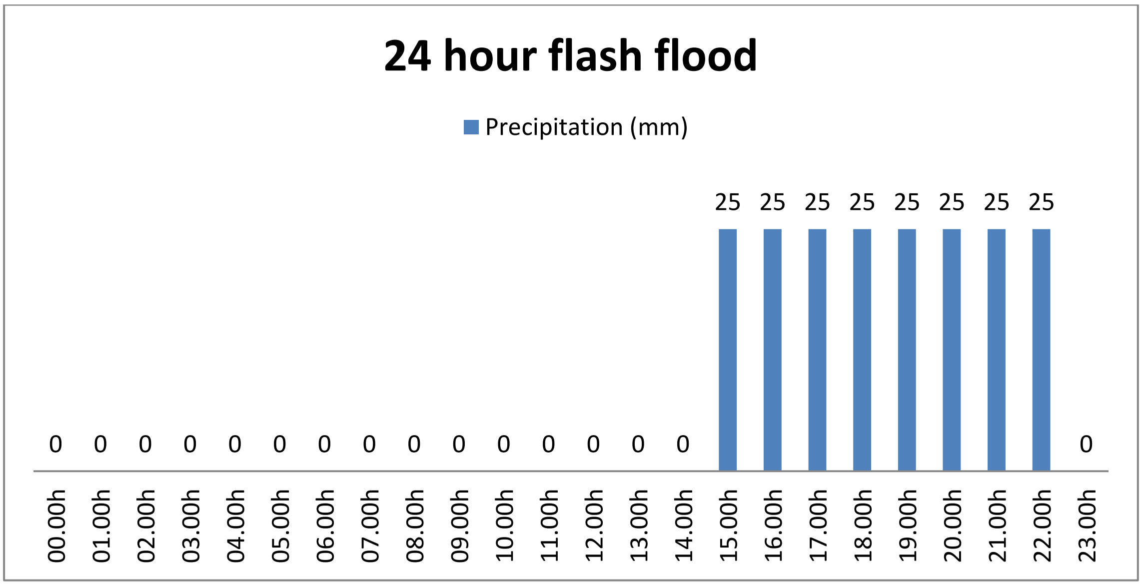

Figure 3.11. Modelling of a 24 hour flash flood with on the x-axis time and the respective rainfall

The resulting flood map can be observed in figure 3.12. At first look, we can already see that this torrential rain event has had great effects on Xochimilco. In the mountainous south, there is still some mild run-off visible (around 10 centimetres) that originated during the last rain hour. A large share of the water accumulates in northern direction, at the transition zone from mountain to the flat, urban zone: there, water depths of sometimes more than 4 meters are recorded. In most of the urban areas, floods reach a height of around 1.5 meters. To assess specific parts of Xochimilco, we need to zoom in further.

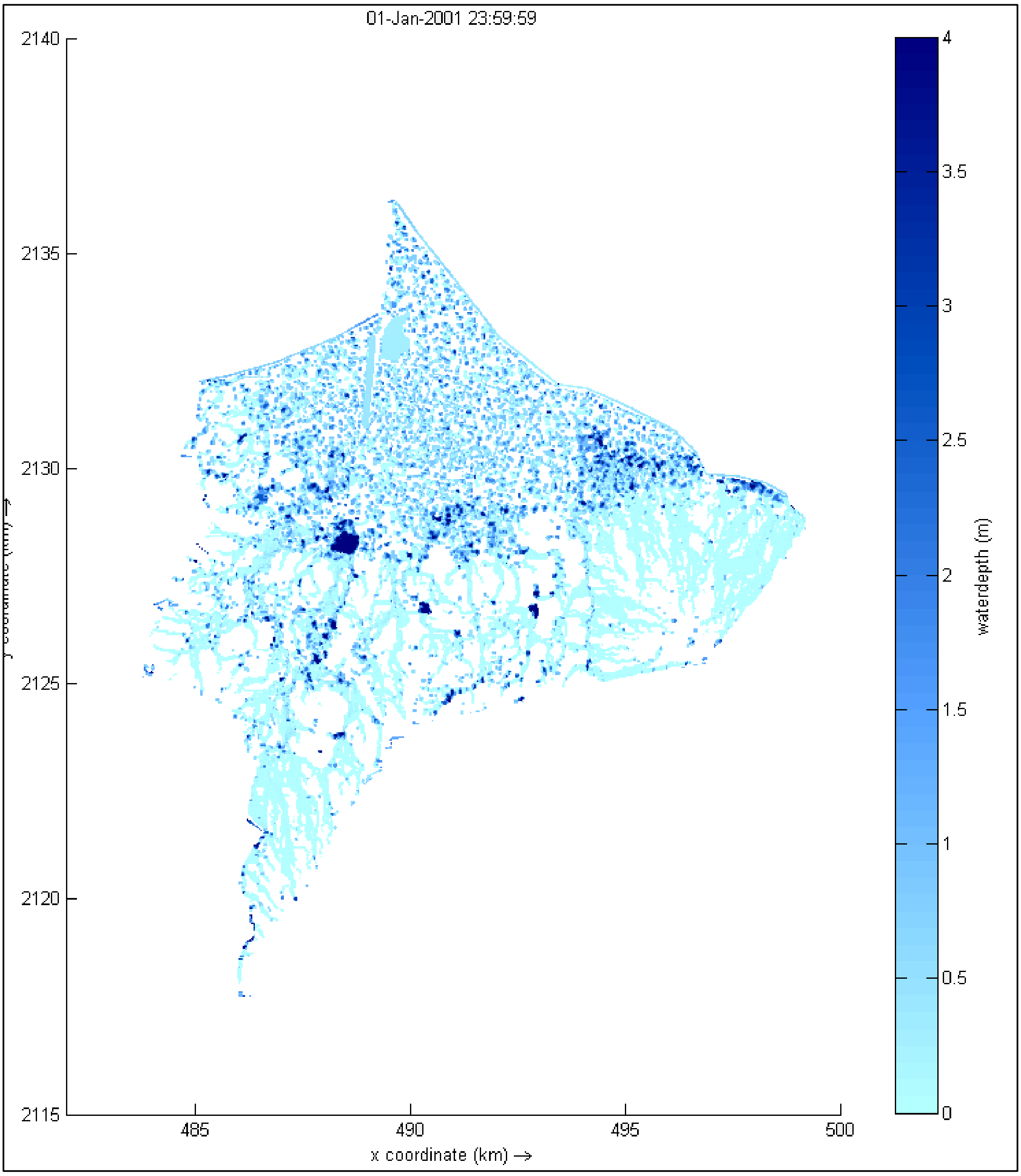

Figure 3.12. Water depth map – 200 mm/24 hour event

3.2.6. Spatial effects of the flash flood

In figure 3.7, a zonation of Xochimilco is visible. Herein, a division is made between water, urban and nature areas. In order to create a *specific risk map*, the urban area can be further divided. Aside from Xochimilco's chinampas, the UNESCO works hard to protect the whole heritage area, as depicted in figure X. To assess the impact of the 200 mm / hour flood on specific zones of the protected area, the **historic district** of Xochimilco is highlighted, as well as the predominant urban areas that feature **illegal settlements.**

In figure 3.13, three different water depths are displayed, respectively of the Chinampa zone (green), the touristic/historic centre (purple) and the urban area with large illegal settlements (yellow). The Chinampa zone, with is situated North of the other two zones, displays similar patterns as when confronted with a light 10 mm/hour event. The water accumulates in stretches of land that easily reach some square kilometres. The average water depth is about 1.5 meter, but can reach up to three meters in the lowest depressions of land. Given their relative northern position in Xochimilco, the chinampas face a mild threat.

This does not apply to the historic district and the illegal settlements; they lie closer to the south: the mountain run-off zone, and encounter larger difficulties. Especially large parts of the illegal settlements get flooded, in worst case scenarios up to 4 meter. Whole neighbourhoods would have to be evacuated. The historic district on its turn has water depths up to 1.5 meter, and is located just barely outside the largest depression, which is visible on figure 3.14.

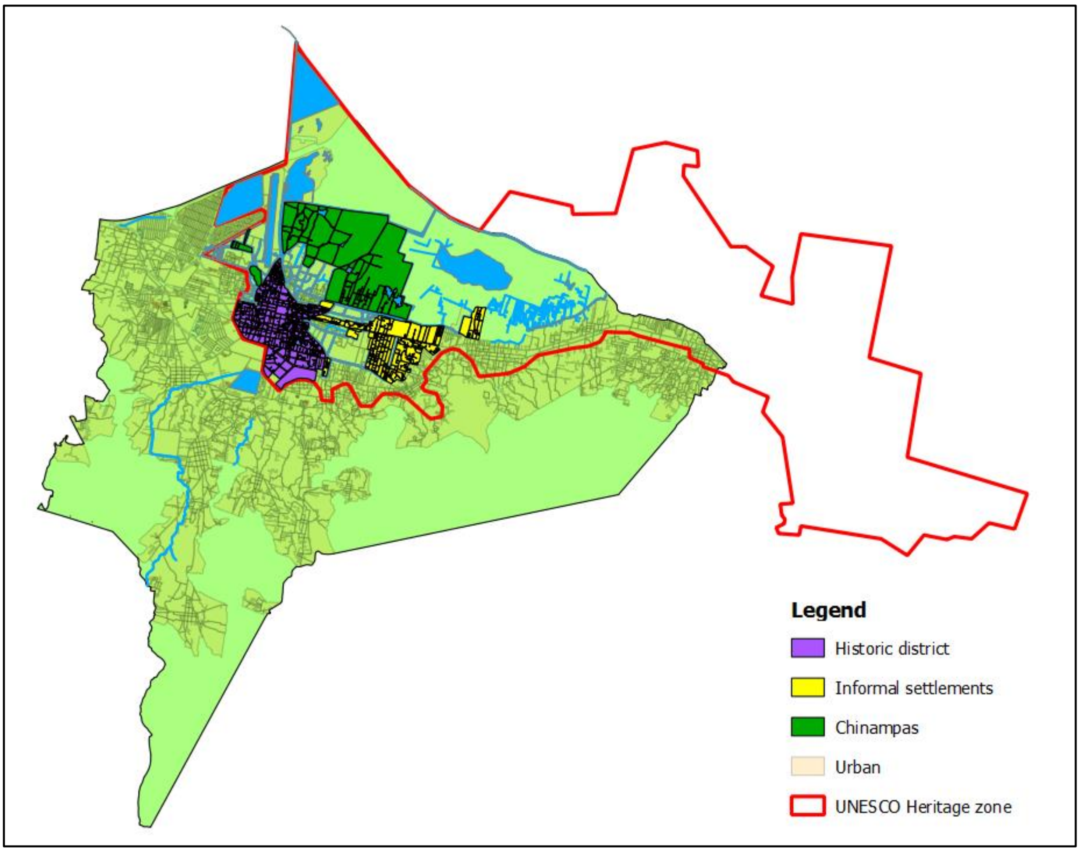

Figure 3.13. Further Zonation of Xochimilco's urban area, featuring the historic district and illegal settlements

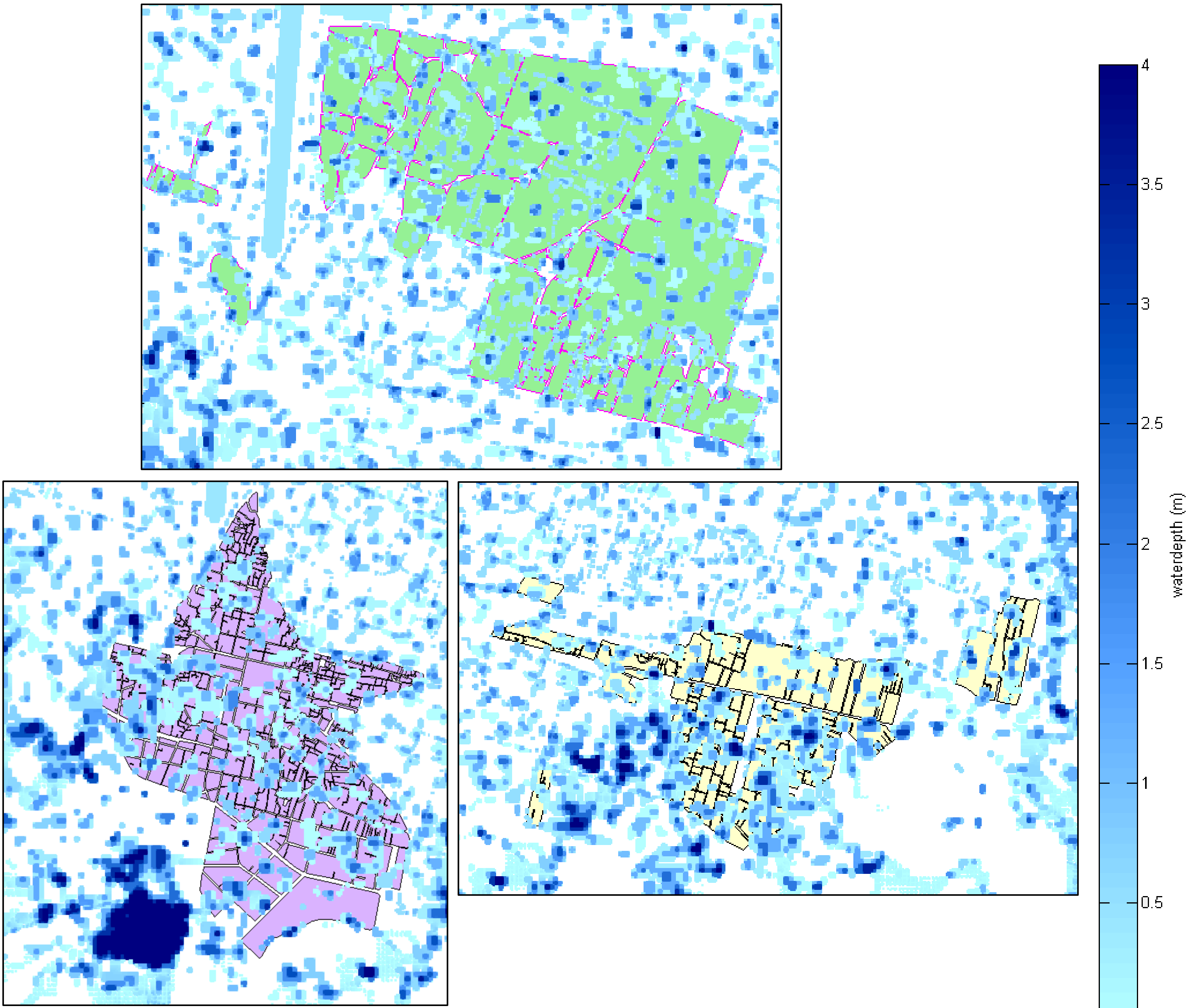

Figure 3.14. Water depth maps of respectively the Chinampa, touristic and illegal settlement zones

3.2.7. Quick scan critical infrastructure

Floods are able to harm critical infrastructure. Critical infrastructure is a term usually used by governments to refer to assets that are essential in the day-to-day functioning of society and economy. According to the European Commission (2004), critical infrastructure are 'those physical and information technology facilities, networks, services and assets which, if disrupted or destroyed, have a serious impact on the health, safety, security or economic well-being of citizens or the effective functioning of governments.'

Criteria what counts as critical infrastructure may differ; therefore we utilize the definitions set forward by the Government of the Netherlands (Ministry of Safety and Justice, 2015) who have set out an elaborate classification of sectors and services. They are divided into two categories, A and B. Category A encompasses infrastructure that reaches a certain threshold for one or more of the following criteria: economic impact (drop in gross domestic product), physical impact (deaths), societal impact (inhabitants struggling to survive), or cascading effects. Category B has the same criteria, but with lower thresholds for the first three. The critical infrastructure is ranked the following:

Category A

- National transportation and distribution of electricity
- Natural gas production
- Oil supplies
- Storage, production, or processing of nuclear materials
- Drinking water supplies
- Water management

Category B

- Regional distribution of electricity and gas
- Flight and airplane management
- Maritime and inland shipping management
- Large scale storage, production or processing of petrochemical resources
- Financial sector (banking services, electronic transfers between banks and between banks and the public)
- Communication with and between emergency services
- Police mobilization
- Government services that depend on reliable, available digital information and data systems

While not on the list above, public health (hospitals and ambulances) is also generally considered critical infrastructure. For the Xochimilco, the following public elements are deemed critical: four hospitals or health clinics with emergency services, one Xochimilco fire department, one District Attorney/police station, one correctional facility and the train rail infrastructure with corresponding terminals. Figure 3.15 displays their location.

Public Health

A. Hospital San Juan – Calle Pino 1, San Juan, 16000 Xochimilco

B. Hospital Materno Pediátrico – Prolongación 16 de Septiembre, Xaltocan, 16090 Xochimilco

C. Centro Médico Santa Fe – Av. México Pte, San Gregorio, 16600 Xochimilco

D. Grupo Corpus Especialidades Médicas – Lovelia 2 Planta Alta, Xaltocan, 16090 Xochimilco

Safety

E. Estación de Bomberos – Esquina Capulin, Prol 16 de Septiembre, Xaltocan, 19310 Xochimilco

F. Fiscalía Desconcentrada de Investigación – Gladiolas, San Pedro, 16090 Xochimilco

G. Reclusorio Preventivo Varonil Sur – Circuito Javier Pina y palacios, San Mateo, 16800 Xochimilco

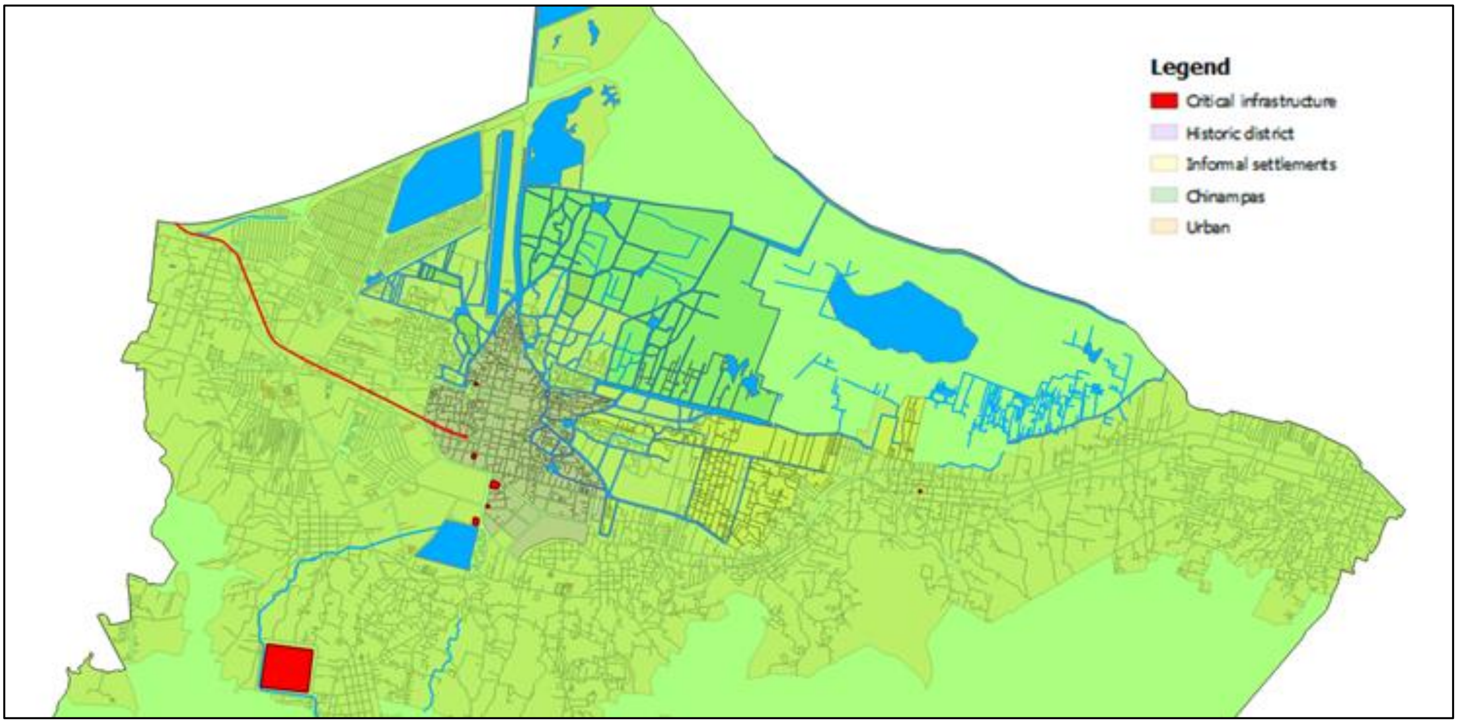

Figure 3.15. Critical infrastructure elements

Within the historic descript, multiple critical buildings will encounter water nuisance, as displayed in fig 3.16. The fire department (E) is located on the edge of very large water mass. More precipitation would certainly cause problems. The same holds true for the largest hospital (B), which is partly flooded and the health care centre (D). The District Attorney/Police Department of Xochimilco (F) is entirely flooded.

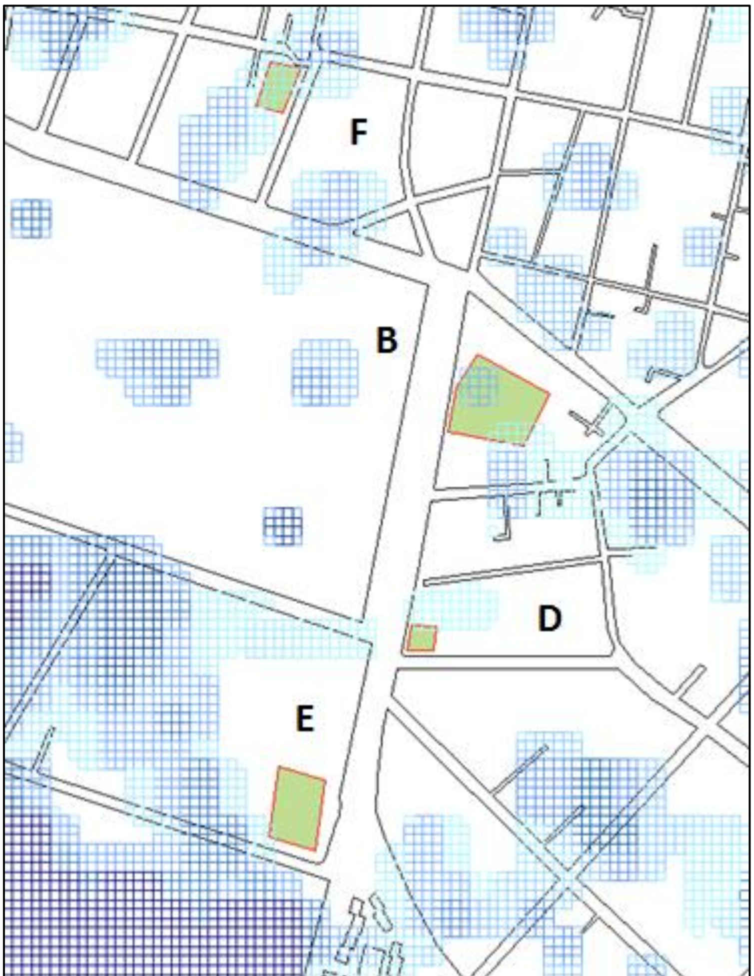

Figure 3.16. Critical infrastructure (i)

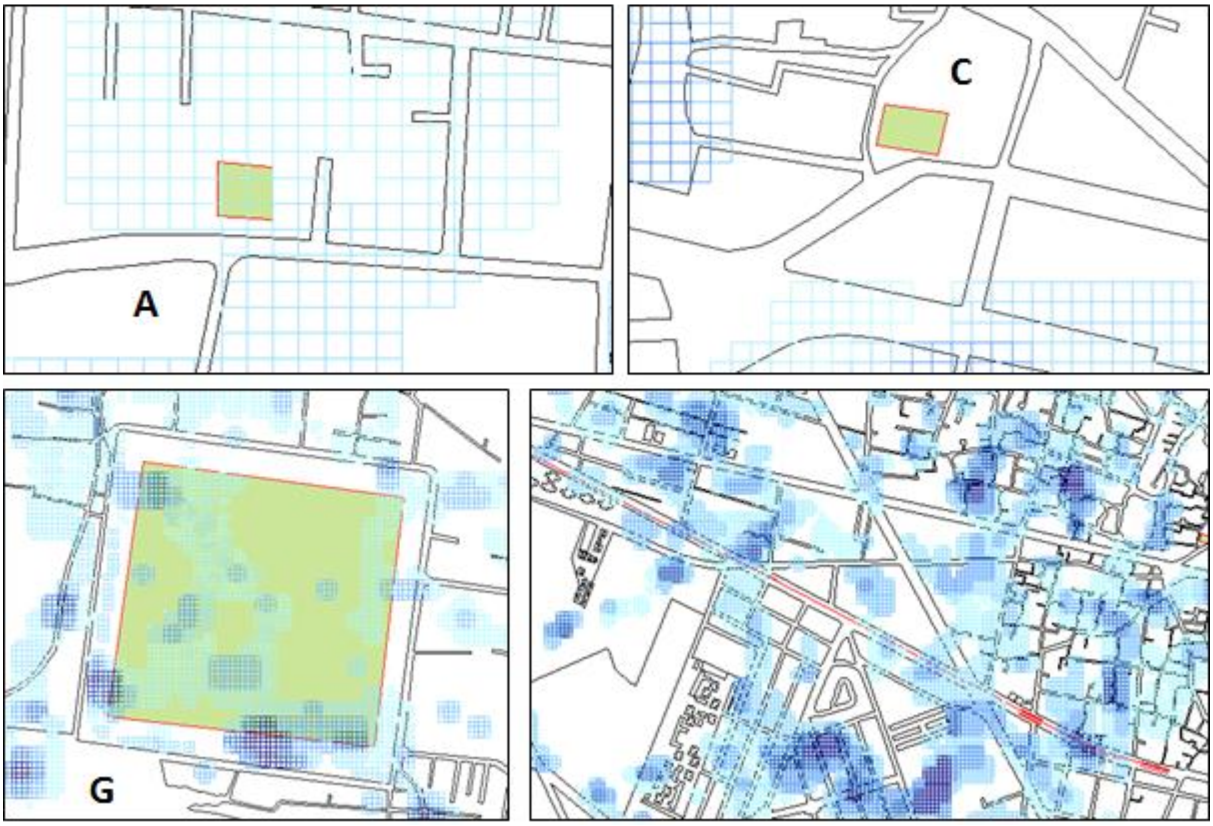

Figure 3.17. Critical infrastructure (ii)

Outside the historic district, the damage done is significant as well. One smaller hospital (A) will be entirely flooded. A small health clinic located further to the east (C) will not be harmed. The correctional facility (G) is party flooded, and inmates will have to be relocated elsewhere in the city. A large part of Xochimilco's only public transport (the train tracks to the northern part of Mexico-City) will be flooded. Most train stops will be inundated, and in the case of a large precipitation event the train service will stop functioning altogether.

3.3. Assessment current resilience

Using the four criteria set out in chapter 2, and applying knowledge on Xochimilco's floods and Mexico City's water system, an assessment will be made concerning Xochimilco's current resilience. Using the current resilience as base measuring point, methods and adaptation can be explored for increasing future resilience.

The ability to avoid impact; the first criterion is quite possibly the hardest to *pass* for Xochimilco, with its estimated 415.000 inhabitants, who predominantly live in the northern parts. In figure 3.17., the large overlap between urban areas and flood zones is displayed. In other words: water will reach the risk zones, and since a lot of infrastructure is vulnerable to floods, 'impact' will occur. There are currently no plans to construct *hard defences,* like a dike infrastructure. Slowly but surely the old storm water infrastructure is being expanded to accommodate more flood water. This is costly however, and will only contribute marginally to the flood issue. Storage of water in the mountains, where Xochimilco floods largely originate, is being investigated but not yet in operation.

The alternative, moving infrastructure outside the waters reach, is next to impossible. Xochimilco is quite impoverished; a large share resides in illegal housing, and a lot of assets cannot move because they are culturally or historically bound to a fixed location; for example the historic district which houses a multitude of archaeological artefacts, and the chinampas, who are economically attractive as they attract tourism.

The ability to limit impact, the second criterion implies that a flood will hit (large) parts of Xochimilco, but that the damages and impact are limited as a result of precautions taken beforehand. There are no indications that an (early) warning system has been established. Early warning systems are a combination of tools and processes within institutional structures. It should be coordinated by local or regional governments or agencies (Comision Nacional del Agua, 2012).

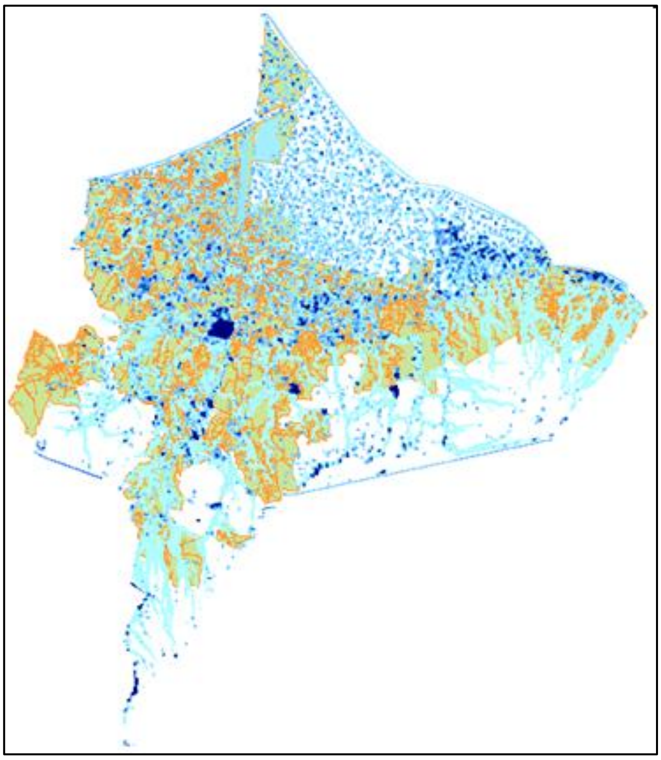

Figure 3.17. Urban zones vulnerable to floods

Severe precipitation events can also be triggered by tornadoes. These events are usually predicted some days in advance and this knowledge is spread by word-of-mouth, old media (radio and television), or new media (internet and social networks). Additionally, no evidence can be found that Mexico City has employed structured detailed evacuating systems with specified routes to minimise human casualties. In limiting the (financial) damages to their houses, the inhabitants of Xochimilco have often adopted quite primitive and non-structural solutions like barricading their houses with sand bags to avoid water intrusion.

The ability to recover from impact, the third criterion is largely influenced by societal, political and economic factors. Probably the biggest is Mexico's *governance patchwork,* and one of the most dominant reasons why Mexico City is not resilient: the responsibilities concerning water are spread out over a myriad of governing entities and other institutions. The key player within water resources is the federal government which regulates the use of water resources, finances investments, and transfers water from other basins through *Conagua* (the national water body), for instance the Cutzamala system.

Then there is Mexico State (one of the 32 federal entities), which buys water from Conagua, transports it through its own infrastructure and sells it to 57 municipalities within the federal borders. To make it more complex, each municipality has its own government that is in charge of distribution and sanitation. Finally there is Sacmex, the municipal water operator of Mexico City (part of the environmental ministry Semarnat) which provides drinking water, drainage and sewerage plus wastewater treatment.

Wirth (1997) accuses governments have hardly responded to environmental degradation. Ironically, it is the other way around: governmental policies are largely responsible for degradation itself. The government was responsible for aquifer depletion (and thus land subsidence) and furthermore it had failed to establish an ecological protection programme. To make matters worse, it also encouraged population growth via social-economic policy.

The lack of proper governance also appears in another case study. A MSc.-thesis that focused on the impacts of urban growth on Mexico-City states that rapid urbanisation and population growth has had unpredicted effects on Mexico City. Implemented policies were often too numerous, uncoordinated and unsuited to local conditions (Anjollini, 2015). Clearly this system has too many divided responsibilities and a new, inclusive governance method will have to be drawn up.

Insurance-wise, there may be hope. While the exact numbers are not known, it is assumed a lot of inhabitants are not insured, given the fact they legally not even own a house. The government of Mexico City has however repaid damages caused by former floods, for instance the June floods in Iztapalapa. The Mexico City government has a risk insurance policy with Banorte Insurance, from the Banorte Financial Group (The News MX, 2016).

The ability to adapt, finally, is harder to access. The reactive component is established in the fact that Mexico City is actively pursuing a more sustainable and resilient path development, given the fact that they have joined 100 Resilient Cities. Within this context, the pro-active component is also present, since different climate change developments are considered which leads to different flood schemes and possibilities.

3.4. Measures, adaptations, and improvements

It may be considered quite absurd that from the perspective of environment, safety and sustainability, Xochimilco and Mexico-City are failures. Water, a natural resource that drops down to Earth in great numbers and, more importantly, free of charge (!) is discharged at an enormous speed. At the same time, the same natural abundance is being transported from far 120 kilometres away: this process is inefficient, very expensive, requires a lot of energy and even then is not enough to meet the water need of Mexico City's population. To illustrate: annual precipitation in Mexico City (around 710mm per year) is nearly the same height as The Netherlands (800mm per year), yet the water shortages are gigantic and the water price is one of the highest in the world (IBM, 2016), and the quality can be quite low (Sacmex, 2013).

3.4.1. Ability to avoid impact

Within this category, huge improvements can be made. For Xochimilco, we have established that a large share of the problems arise as a result of mountain-runoff. In urban water management, the principle 'Retain and Store, Delay and Reuse, Drain only when Necessary' is important when dealing with large masses of water (Wagonner & Ball, 2015). In Deltares' preliminary approach (figure 3.18.) a general zonation of Mexico City is made. In the highest mountain areas, it is vital to store water as it is not densely urbanised and there is a myriad of space for future development. Furthermore, it is needed to replenish the aquifer. The same holds true for the hill slopes (more to the north) which is more densely urbanised. More to the north, in the urban core of Xochimilco, storage is of key importance. The effect of storage is tri-fold: (i) less discharge for the already failing waste and storm infrastructure, (ii) increase of available drinking water benefits public health and (iii) there will be smaller reliance on an already depleted aquifer, and on water from the Cutzamala system.

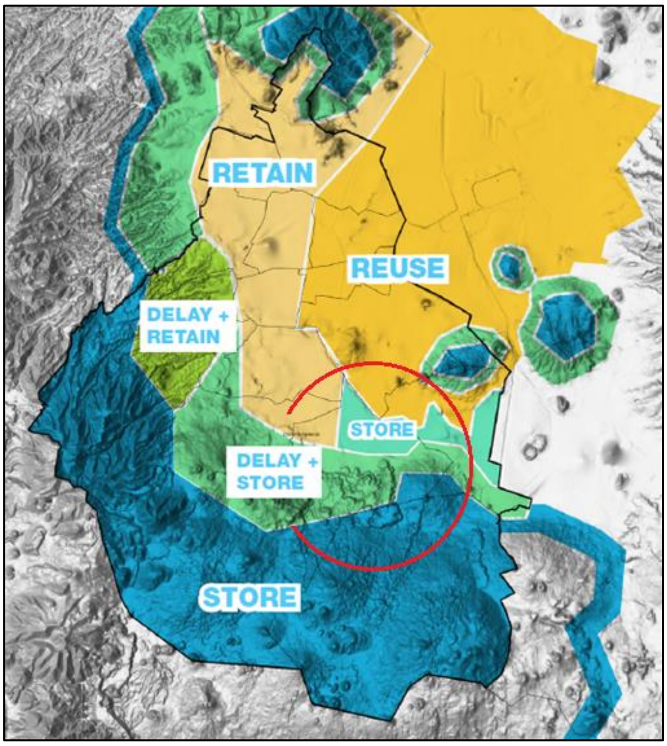

Figure 3.18. Deltares preliminary approach, Xochimilco is indicated in the red circle

There are a multiple methods to increase storage possibilities. Rain harvesting is one of the most promising measures in storing rain water. Inhabitants of Xochimilco who install a rainfall harvesting system can reap the rewards for five to eight months. The Mexican non-profit group Isla Urbana helps constructing constructions on roofs. The cisterns, which are capable of storing 5.000 litres of water not only collect but also filters the water through two filters. After the sediment is removed, the water is safe to drink. The downside: the systems are pricy, up to 5000 USD. Private citizens pay around 20% of the installation, Isla Urbana has to cover the rest through government subsidy and private donations.

Isla Urbana installed the first system in 2009, and since then has installed over 2,600 in Mexico. In one year, nearly 57.000 litres of rainwater can be captured by one system alone. A system needs to be installed on a roof with dimensions of 80 square meters. Rainwater harvesting must be developed further, since “we are over-exploiting the aquifer 100 percent,” says professor Luis Zambrano (Mexico’s Metropolitan Autonomous University). He predicts that at one moment in time, there will be no more water left. Estimates are that that will happen in 40 years, which will be a huge problem (Associated Press, 2016).

Other methods to increase storage are for example to dig new waterways or a system of ditches. Since the run-off from the mountains is a large influx, it is also possible to construct recreational water areas at the foot of the hills, for example *manatiales*, warm water sources (figure 3.19.). This will also increase recreational and touristic value.

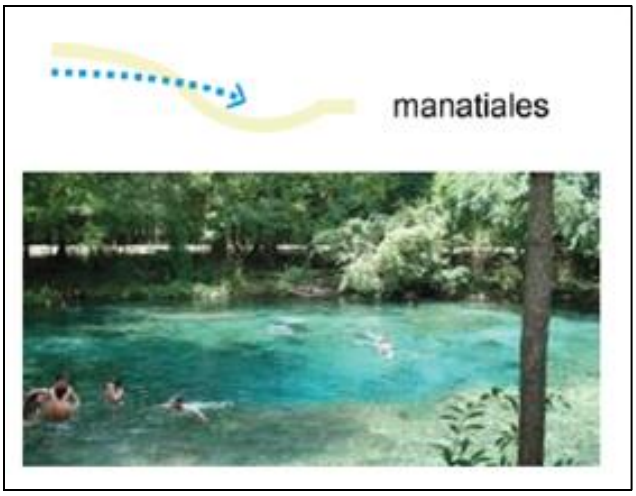

Figure 3.19. Construction of new storage capacity downhill, a spring

Increasing resilience is not purely a physical challenge, but also a mental one. It is important that water awareness and sustainable use of water resources is incorporated into Mexico’s primary education system. The youth of today are the adults of tomorrow. The adults of today however, should be reached in other ways. Via large scale public campaigns local governments should raise awareness and force a paradigm shift in the sustainability discourse.

Within the *ability to avoid impact,* storage has a large edge over increasing discharge possibilities (adding infrastructure), since these methods are very expensive whilethe water should stay in the area, not leave it.

3.4.2. Ability to limit impact

A lot of damages and financial impact can be avoided by flood-proving new buildings and adapting existing buildings. The following solutions can protect buildings in Xochimilco and prepare people, buildings and installations. Primarily, the notion exists that every building should be self-reliant, i.e. they should not have to be connected to the 'network' of existing infrastructure and should operate as an independent factor.

Figure 3.19. Flood prove housing

In a utopian society with unlimited financial means, exciting new infrastructure can be drawn up. Figure 3.19 gives an example of *flood prove housing,* which is an innovative theme especially in the aftermath of Hurricane Katrina. The above architectural novelty is a design solution by Dutch firm Waterstudio. Houses on poles or even floating houses is a unique technology that can be applicable in regions where water dominates. For Xochimilco, new buildings can be constructed on pre-raised ground, which is a relative cheap approach. The buildings can be designed in such a way that they can withstand a flood and be used again after a thorough cleaning. This requires waterproof construction and well considered materials, equipment and infrastructure. Also, the utilities within buildings should be designed in such a manner that they are able to withstand a flood. Valuables should not be located on the ground floor, for example (Atelier Grounblauw, 2009). Buildings can also be sealed by installing bulkheads and hatches (ibid)(figure 3.19.)

Figure 3.19. Installing of anti-flood barriers

To limit future casualties, it is crucial that local authorities install early warning systems, which is also able to reach the cut-off impoverished communities in the non-legal settlements.

3.4.3. Ability to recover from impact

The biggest challenge at hand is to create a more inclusive form of *water governance*, where public participation and democracy are incorporated. The current system has too many governing layers, too many spread out responsibilities and is focused largely on increasing discharge capacity, while they should focus on alternative methods.

The question on how to 'fix' the water system has already given rise to a political divide in the population. The centre-right government of Mexico is a firm believer that privatisation is the preferred method to finance the infrastructural improvements. Initially it had proposed a new bill to change Mexico's General Water Act to allow private companies to take over the system, but in 2015 this was blocked by *grassroots* political and activist groups – normal citizens who feared for the worst. In March of 2015, protesters marched to the headquarters of Conagua to protest the government's plans, scanting "The water is ours, dammit!" The argument from opponents was that privatisation would only raise the cost without the guarantee of higher quality or better availability in return.

During this lack of government action, the system is still getting worse. One civil servant explains (The Guardian, 2015);

"If we don't get more resources, we face a crisis. This isn't pessimism, this is realism. Although we are now improving some parts of the system, other parts are getting worse because we don't have the budget and staff to maintain the system," he says. Asked if it is drought that he worries about, the engineer shakes his head: "No, what I fear is conflict between communities."

Mexico City's situation is quite absurd. For hundreds of years the water is discharged away while the area could have enormous amounts of fresh water. There is an artificial scarcity, but the nature of the challenges at hand does not appear to be of a financial or technical nature, but rather of governance.

3.4.4. Ability to adapt

Mexico City has learned from the past, and in joining the 100RC network a more pro-active attitude is employed. In Mexico City's Resilience Strategy (CDMX, 2016), the ultimate goal is that in the foreseeable future, all water in the Mexico Basin will be legally handled under the Comprehensive Management of City Water Resources (or GIRHU).

GIRHU should is responsible for integrated management of water resources and the response to risks and impacts related to pressures, whether related to climate change or social developments. Furthermore, GIRHU must guarantee equal access to water and let it be available for the entire population. Four separate goals are recognised.

- (2.1.) Reduce water scarcity and access inequality
- (2.2.) Promote sustainable use of the aquifer and contribute to water security planning
- (2.3.) Foster a civic culture on the sustainability of water resources
- (2.4.) Integrate green and blue infrastructure, and develop an urban design for the water system with features that enhance resilience

The challenges at hand for Deltares lie primarily in Goal 2.4. Said goal is split up in two separate *actions*;

- (2.4.1.) Promote the restoration of bodies of water and watersheds
- (2.4.2.) Develop rainwater catchment, retention, regulation and infiltration, and flood prevention alternatives

The first action encompasses the regeneration and the restoration of natural bodies of water, as well as watersheds since they can help prevent new floods. Furthermore, they can also serve as a buffer and encourage further adaptation that is needed to combat climate change induced droughts. This project will run from 2016 to 2025. Clean-up of watersheds and the production of green infrastructure carry multiple benefits that potentially make Mexico-City more resilient, since it meets basic needs, enriches natural assets and strengthens adaptive capacity when the water supply hits a new low.

The second action features the use of green and blue infrastructure and technology to capture rainwater and keep it for later use, or possibly inject it in underlying aquifers. The nature of these projects allows it to promote awareness and education regarding sustainable use of water. In the rain season, intelligent constructions may reduce the impact of floods significantly. Also, green spaces (parks and other recreational green facilities) may prove to have a positive effect on social cohesion ('inclusive'). 100 Resilient Cities has to realise however that 'social cohesion' is abstract and difficult to quantify. The time frame for this goal also stretches from 2016 to 2025.

Action 2.4.2. features activity 2.4.2.1, the creation of water conservation areas, green spaces and multifunctional parking lots. Notable example herein is the Parque de la Viga, a green-blue infrastructure project, which will be redesigned to help maintain the water balance in the area: the redesign of the park will allow rainwater catchment and storage and storage of water in the soil (ibid).

4. Discussion and conclusion

4.1. Conclusion

This thesis started with the research question;

To what extent is Xochimilco flood resilient at this moment in time, and how can modelling and water management increase resilience in the future?

Currently, Xochimilco (and Mexico City) in general is not flood resilient, and prone to the forces of nature. There are several geologic, natural and anthropological causes than account for this fact. Flood modelling can be a powerful tool to identify what areas are under risk, how big the risk is and how a flood develops over time. For instance, critical infrastructure can be protected in a more appropriate manner.

Resilience-wise, there is a lot of ground to cover. The good news is that there is a wide range of measures and adaptations that can be considered on short, medium and long term. The bad news is that it is has to happen fast via an inclusive, new form of governance. In theory, Mexico City can be completely self-reliant and become resilient in multiple facets, but time is of the essence. When it is too late, there can be a huge societal collapse.

4.2. Discussion

It is quite unfortunate that the resolution of the satellite data used to create a Digital Elevation Model, and subsequently used to create flood depth maps was limited. Ideally, the resolution was 1 meter by 1 meter. In this thesis, a courser 30x30 meter was employed. The effect hereof is that flood maps are less specific – we can predict where the floods appear *approximately,* but not with great accuracy. This implies that some critical infrastructure may be flooded when the model predicted it not to, and vice versa. Furthermore, Mexico City needs more user input for OpenStreetMap, so in the future the risk zones can be specific up to the point of an individual house, and not a general 'urban zone'.

Resilience wise four flood resilience criteria are employed to give a general *feeling* of how an urban system can be adapted and changed. Resilience is an abstract concept, and there is, no numerical quantification of resilience, nor shall there be in the near future. The practical implication hereof is that a lot of further research will define it differently. However, the semantic aspect of *resilience* is limited. I reckon that while all definitions differ, there is a large common ground and overlap between the different scientific *frame of references*. In other words: while the criteria may differ, it seems very unlikely that one set of criteria is so fundamentally different from the rest, that Mexico City would be considered 'resilient' at the end of its respective reasoning.

As for future research, I highly suggest the development of a new inclusive bottom-up governance system rather. Furthermore, storing water is of prime importance: an exploration must be made how new storage systems can be made available to the impoverished general public. Since the water system is a public matter, maybe it should be funded public as well, in the form of taxation.

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