STORM WATER MANAGEMENT IN GUADALAJARA

Bachelor Thesis

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Preface

This report is the finishing product of my bachelor assignment, conducted at IITAAC in Guadalajara (Mexico). During a period of four months, I have worked here on my bachelor thesis and a research for the minor 'Sustainable Development in Developing Countries'. Together, they form a research on the water related problems of Guadalajara: the bachelor a technical research on storm water management and the minor a more socially oriented research on the awareness of water related problems and the influence these have on people.

A special aspect of my time at IITAAC is that they were founded very recently. This means I have seen the very beginning and have even helped with organising and installing the office. I am honoured that I have been part of the beginning of IITAAC and happy to see that they are already growing. Furthermore, I learned a lot during my research. Not only in terms of general working experience but also more specifically about doing research, working with hydraulic models and sustainable water management. And I had a great time. For both, I want to thank a number of people. First Arturo Gleason, for his supervision, his help and advice and for giving me the opportunity to attend a rainwater harvesting course in the United States. Next, Esmeralda Mendoza: thank you for explaining your work, for help with finding new information and for our cooperation in general. You were not only invaluable during my work, but it was also really nice working together. Apart from these two persons, I also want to give my general thanks to everybody at IITAAC: on the job for the help and the great atmosphere, outside the job for teaching and showing me more of Mexico and the great time we had.

And last but not least, my thanks to Joep van der Zanden and Cesar Casiano Flores, my supervisors from the University of Twente. Joep, thank you for the good guidance and detailed feedback. You really helped with both the quality of the research and the report. And Cesar, although you were my supervisor for the minor, you did something very important for my bachelor assignment as well: you brought me in contact with Arturo, and in that way started my job at IITAAC and the great time I had in Mexico. So thank you.

Summary

Guadalajara is the second city of Mexico, with more than 4.5 million people. Every year, floods cause over 30 million euro of damage, pollution, health problems, structural damages and sometimes even loss of human lives. To solve all these problem, additional knowledge on the bottlenecks in the hydrologic system and possible solutions is needed. To generate this knowledge, IITAAC has built a hydrologic model of a part of the San Juan de Dios subbasin, a river basin in the centre of the city. This model consist of two situations: the actual, current situation and a scenario with proposed measures to decrease the problems.

The objective of the research was to improve the existing hydrological model of Guadalajara, migrate it from EPA SWMM to PCSWMM and use it to propose new solutions for storm water management in Guadalajara. The validation process used to improve the model started with a sensitivity analysis. After this, Sargent's framework of the modelling process was used for validating and improving the model. This means that the modelling process was divided into the internal quality, data quality and output quality.

The first step of the validation was a sensitivity analysis. This showed that the results are especially sensitive to junction depth, conduit depth and outfall elevation. These are aspects where checking the data is important. However, it is difficult to obtain more data, which makes conclusions less reliable.

Checking the internal validity resulted in several changes to the model. Storage units have been lowered to enable them to fill up and the initial volume of El Dean has been lowered. The size of conduits has been changed at some points, most importantly between El Dean and its outfall. Junctions have received a pondable area to make sure that when they flood, no water is lost from the system. And corrections to their elevation have resulted in the elimination of bottlenecks.

Validation of the output is difficult due to a lack of data for the real situation. However, some remarks can be made. The model seems to underestimate flooding around El Dean and the Canal del Sur. Without modelling the current situation correctly, it is unlikely that the exact effects of measures can be calculated correctly. The consequence is that the model should mainly be used for comparing the effectiveness of measures. Designing measures and assessing their results on an absolute scale would require a more exact model.

For the actual situation, improving the model did not significantly change the maximum volume of flooding, it decreased flooding after 24 hours from 70 percent to 35 percent of the total rain volume, it made storage units function better and increased outflow. For the situation with proposed measures, mistakes with the surface storage and an unrealistic low outfall dominated the results. The measures seemed to result in a 25 percent decrease of runoff and a total absence of floods. Correcting this lead to a more natural situation with outflow, floods, storage and infiltration.

Concerning the impact of the measures, the proposals decrease the total occurring flood volume from 75 percent to 45 percent of the rain. Even more impressively, flooding after 24 hours decreases from 30 percent to less than 5 percent of the total rain volume. However, as upstream flooding is decreased, more water flows to the downstream part of the subbasin. This causes El Dean to flood more. Furthermore, the decrease and flooding and increase in outflow is good for this subbasin, but it can cause problems in downstream areas.

After checking the model implementation of the previously proposed measures, new proposals for water management in the area have been designed. The newly designed proposal consists of two main solutions: building storage basins and increasing conduct size. The storage basins decrease peak flows, the bigger conduits increase the system's capability to cope with high flows. This proposal decreases flooding with 45 percent and flooding after 24 hours with 75 percent. This means that it performs better than the old proposal, while using less extreme measures.

Regarding the reliability of the results, the difficulties of obtaining data and differences between real world observations and model results have repercussions. General conclusions, like 'increasing conduct size has in the downstream part than in the upstream part' are still viable. However, results should not be interpreted as very exact, and care should be taken with proposing very specific measures.

Apart from the big infrastructural measures used in the proposal, some more small-scale measures have been examined. From these additional measures, permeable pavement is the most useful. With the ubiquitousness of roads, they can seriously help to increase infiltration and decrease runoff. However, it is also an expensive measure that would take a long time to implement. Infiltration trenches contribute very little, but because they are easy to implement, they are still a sensible solution. Rainwater harvesting systems are not really useful for stormwater management. Because of their low volume and the necessity to convince people to implement them, they are an inefficient solution for storing rainwater, and should only be used with other objectives in mind.

Based on the research three recommendations are made:

1. Use also other rain events than the currently used rain in the research.
2. Increase the size of the research area. This decreases the influence processes just outside the research area.
3. Gather more information on the structure of the sewage network. A ground penetrating radar would probably be a good way to do this.

Contents

Appendices

1 Introduction

1.1 Problem indication

Guadalajara is a Mexican city that has grown rapidly in recent years, growing from 3 million inhabitants in 1990 (INEGI, 2005) to 4.4 million people in 2010 (INEGI, 2013). The unregulated urban sprawl has resulted in numerous problems, including the water supply and the drainage of water after heavy rain. Floods in Guadalajara cause over 30 million euro of damage per year. Apart from these costs, the floods cause several other problems, including pollution, health issues, structural damages and even loss of human lives (García-Salas, Rueda-Lujano, & León-Rodríguez, 2010). An example of a flood in Guadalajara is shown in figure 1. In the past, rainfall posed less problems because infiltration was easier and streams acted as natural drains. However, due to extensive urbanisation the problems have increased (Gleason J. , 2008). In addition to the problem of floods, Guadalajara has problems with the supply of fresh water and contamination of surface waters (WMO & Conagua, 2011), (Redacción Informador, 2009).

Figure 1: A flood in Guadalajara (Enrique, 2013)

To solve all these problem, action should be undertaken soon. To do this, additional research of the actual situation, the bottlenecks in the hydrologic system and possible solutions is needed. To generate this knowledge, IITAAC has built a hydrologic model of a part of the San Juan de Dios subbasin, a river basin in the centre of the city.

1.2 Zone of study

Guadalajara is the capital of Jalisco, a state in the western part of Mexico (located at the red dot in Figure 3). With 4.4 million people, it is the second largest metropolitan zone of Mexico and an important economic centre (INEGI, 2013). It has a subtropical climate, with wet summers and dry winters. The rain is about 940 millimetres per year, with most of the rain falling between June and September (Climate-Data, sd). Furthermore, being in a subtropical area, the rain is characterized by a high intensity. A summary of the climatological characteristics is visible in Figure 2.

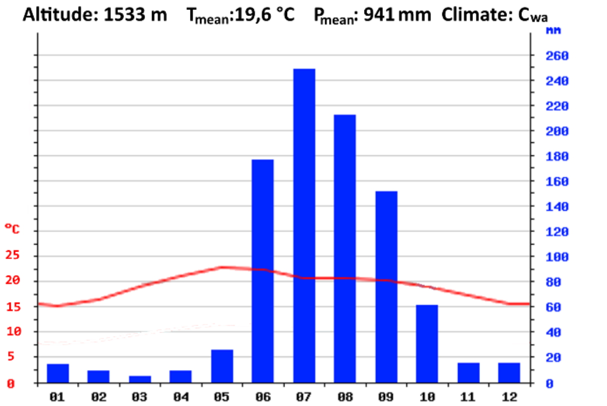

Figure 2: The climate of Guadalajara (Adapted from: Climate-Data, sd)

Figure 3: The administrative hydrological regions of Mexico and the location of Guadalajara (SEMARNAT, 2005)

Mexico is divided in 13 administrative hydrological regions (Figure 3). Guadalajara lies in region 8, the Lerma-Santiago-Pacifico region. This is the basin of the Lerma River, a river of 750 kilometres that crosses five states and ends in Lake Chapala. Lake Chapala is drained by the Santiago River, which flows to the Pacific Ocean. Guadalajara is part of this Santiago basin. The subbasins in Guadalajara are the White River (Rio Blanco), Atemajac and El Ahogado (see Figure 4). The Atemajac in turn is divided in the San Juan de Dios subbasin in the centre of the city, and the Oriente and Osorio subbasins more to the east of the city (see Figure 5).

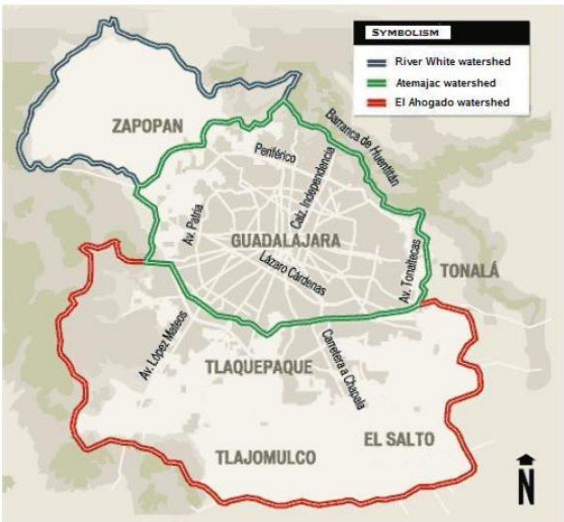

Figure 4: The river basins in Guadalajara, the Atemajac water basin being the green one (Gleason J. , 2008)

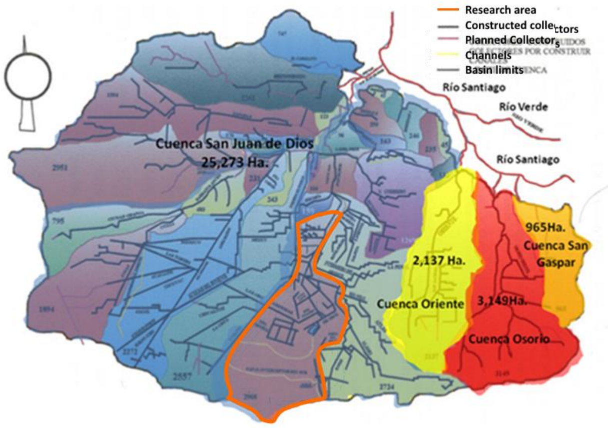

Figure 5; The subbasins of the Atemajac basin, with the San Juan de Dios basin at the left and the research area in orange (adapted from Gleason, 2011)

The modelled area itself is an upstream subbasin of the San Juan de Dios river basin. It has a surface area of 21 km^2, and there are 58.000 houses in the area. Important elements in the area are El Cerro del Cuatro, Cerro Santa Maria, the Canal del Sur and El Dean (see picture 5). The Cerro del Cuatro and Cerro Santa Maria are hills in the south of the area. The Canal del Sur is a canal that drains of rainwater. And El Dean is a park with a big pond, also used as a storage basin for rainwater.

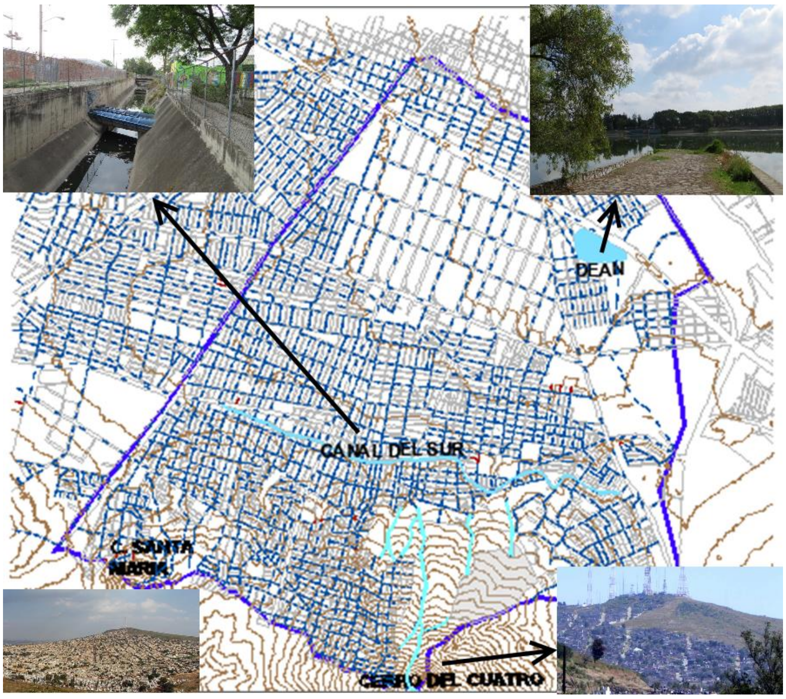

Figure 6: The research area with its defining elements

1.3 Problem definition

The runoff process in an urban environment differs from the runoff in a natural environment. Most natural environments have a pervious soil, so rainwater can infiltrate the soil. This water will reach rivers as groundwater flow. If the ground is impervious or saturated, the water will flow as surface runoff. Even the surface runoff and river runoff in natural environments are relatively slow, due to the roughness of the surface and the meandering nature of natural streams. In urban areas, the presence of large impervious areas means the infiltration capacity is lowered. This is exacerbated by vegetation clearing and soil compaction (Booth & Jackson, 1997). The influence of the amount of impervious surface on infiltration is shown in figure 4. Furthermore, the hydrologic system is changed by building a sewer system which transports runoff rapidly to stream channels. These natural channels in turn are often also made more smooth and efficient, and transport the flood wave faster downstream (Booth & Jackson, 1997).

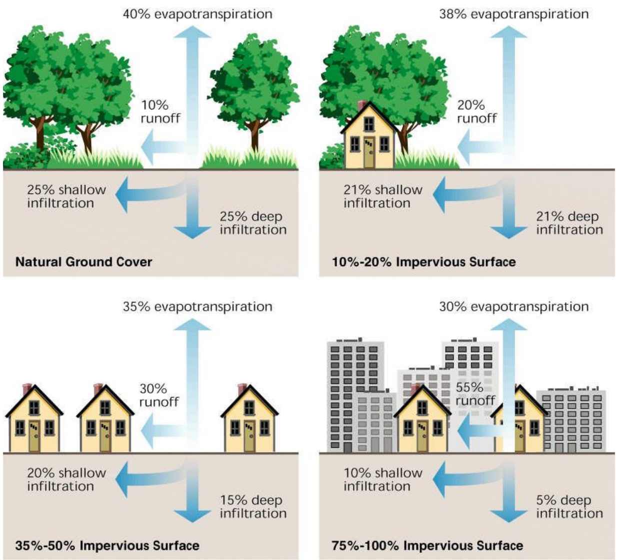

Figure 7: Impervious surface and infiltration (Schöninger, 2007)

Because surface runoff on itself is faster than subterranean flow and because the surface flow is made even faster, urbanizing an environment affects the hydrological system greatly. Common effects of urbanisation are an increased runoff peak, increased duration of high flow magnitudes, increased runoff volume and a dramatically increased frequency for high runoff flows (Booth & Jackson, 1997) (Goonetilleke, Thomas, Ginn, & Gilbert, 2005). These changes lead to higher levels of sediment and pollutants, and alter the characteristics of the ecosystem (Goonetilleke, Thomas, Ginn, & Gilbert, 2005).

In turn, these hydrological changes affect the urban system. The higher runoff is likely to overwhelm sewage systems, causing the system to overflow. This means floods, causing damage, great inconveniences for the population and potentially dangerous situations. When the sewage system is a mixed system – and most systems in Guadalajara are – this is further exacerbated by the mixture of rainwater and wastewater flowing through the streets. This contaminated water poses a severe health risk to a city. In Guadalajara, this is even worsened by the fact that contaminated water percolates into the soil, contaminating aquifers as well (Gleason J. , 2008).

In Guadalajara, floods are common during the rainy season, especially in the older parts of the city (Overseas Security Advisory Council, 2012). As a result, each year about 5 people die because of storm water runoff and floods, 2800 houses and 650 commercial establishments are negatively impacted and the damages amass to 30 million euros (García-Salas, Rueda-Lujano, & León-Rodríguez, 2010).

At the moment, it is widely known that there are problems. However, there are still questions about the exact hydrological situation in Guadalajara. It is unclear what the bottlenecks in the system are and which alternatives exist to resolve the floods. There are two ideas for possible solutions: small scale actions and big infrastructural actions. Small scale actions include rainwater harvesting and the implementation of infiltration systems. Big infrastructural actions are for instance the modification the drainage system or the construction of retention ponds. However, it is unclear how much these ideas can help, and how they should be implemented exactly. IITAAC is working to generate more knowledge on the hydrological situation in Guadalajara, in order to propose solutions for the problems. They have a hydrological model for a part of the city, but this model has to be improved. Furthermore, they want to migrate the model to a new software program, because the current program is difficult to work with and lacking in visual output capabilities, making it more difficult to understand results.

1.4 Objective

The objective of the research is:

To improve the existing hydrological model of the San Juan de Dios basin in Guadalajara, migrate it to a new program and use it to propose and evaluate solutions for storm water management.

1.5 Research questions

To achieve the objective of the research, the following research questions have to be answered:

1. How well does the model of a part of the San Juan de Dios basin describe the hydrological situation of Guadalajara that currently arises during heavy rain?
2. Are IITAAC's proposed measures implemented correctly in the model?
3. What solutions are needed to decrease or resolve the floods in the area?

1.6 Reading guide

Chapter 2 will start with a theoretical framework for validating models. Chapter 3 continues with the methodology used. This includes a description of the model and software used. The next three chapters give the results of the research. Chapter 4 gives the results of the sensitivity analysis. Chapter 5 outlines the results of checking and improving the model with EPA SWMM and rebuilding it with PCSWMM. In chapter 6 the new designs for storm water management measures are shown. Chapter 8 ends with a conclusion and discussion.

2 Theoretical framework

For validating the simulation models, the framework of Robert Sargent (1998) has been used. As Sargent explains, a model consists of a problem entity, a conceptual model and a computerized model. The problem entity is the problem or situation to be modelled. The conceptual model is the mathematical or logical representation of the problem entity. The computerized model is the implementation of this model on a computer. This is shown in Figure 8.

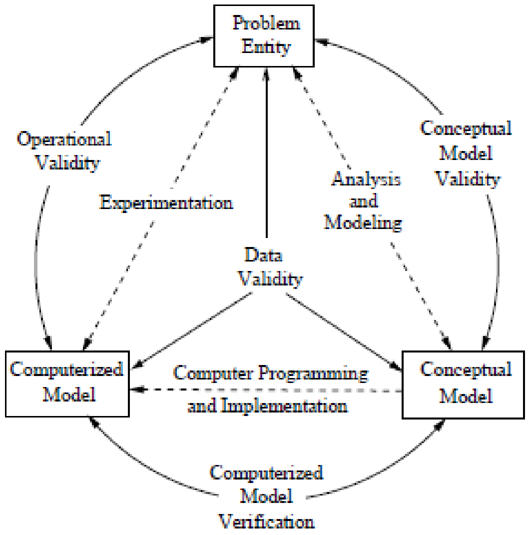

Figure 8: Sargent's simplified version of the modelling process. (Sargent, 1998)

The verification and validation steps are visible within this figure. Conceptual model validation means controlling if the theories and assumptions used for the conceptual modal are correct and if the model represents the problem well enough for its intended purpose. Computerized model verification means checking if the conceptual model is implemented correctly on the computer. Operational validation, or output validation, means checking if the outcome of the model represents the problem accurately (enough). And finally, data validation means checking if the input used for the model is the right data, and if it is correct. (Sargent, 1998)

For this research, conceptual model validity and computerized model verification will be regarded as the same. This will be called internal validity. The model used is not developed from scratch, but is based on an existing program (EPA Storm Water Management Model). This means that the assumptions and rules underlying the conceptual model are often indirect and part of the program. The goal is to validate the model of IITAAC, in other words the input into the program. So the assumptions within EPA SWMM are no part of the research. For the use of the program, it is difficult to differentiate between assumptions about the situation and the input into the program. Consequently, in this research validity is characterised as data validity, internal validity and operational validity.

3 Methodology

The methodology consists out of three parts. In order to understand the research, one has to know the model. So the methodology starts with explaining the software used. The second part will explain the scenarios used in this model. So the first part of the methodology will briefly explain the model. Because the validation process consists of two stages (old and new program) applied to two model scenarios (actual situation and with proposed measures), subsequently this process will be explained more clearly. The last part will explain how the theoretical framework of Sargent can be applied to the model.

3.1 Description of software used

The main part of this research is checking and improving models. The nature of these models determines the process needed, so the first part of the methodology will be to describe de models. The model visible in Figure 9, is made using the open source program 'Storm Water Management Model' (SWMM) of the United Stated Environmental Protection Agency (EPA). This program is used for analysis and design related to storm water runoff and combined and sanitary sewers in urban areas. As mentioned in section 1.2 the model was set up for an upstream subbasin of the San Juan de Dios river basin. It consists of an area of 21 km^2, with 60.000 houses and a little bit of industry.

The model is made in EPA SWMM. It consists of the following elements:

- Subcatchments: the areas in which the model is divided. All the water from a subcatchment flows to the same point. This is either a node or storage unit (see below).
- Conduits: this is the name for conducts in EPA. They can either be tubes, or natural channels.
- Junctions: these are the places where two conducts connect. Furthermore, they are the only places where rainwater enters the conveyance system (i.e. manholes).
- Outfalls: the place where water leaves the system. There are four outfalls in the research area (making it not a classical river basin, in the sense that normally a basin is defined as the area of which all the water flows through the same point). As the boundary of the research area is artificial, the sewage pipes continue outside the research area. As such, the outfalls physically represent the continuation of the conducts.
- Storage units: storage basins, where water is stored. They can either be natural basins or artificial constructions for storing water.

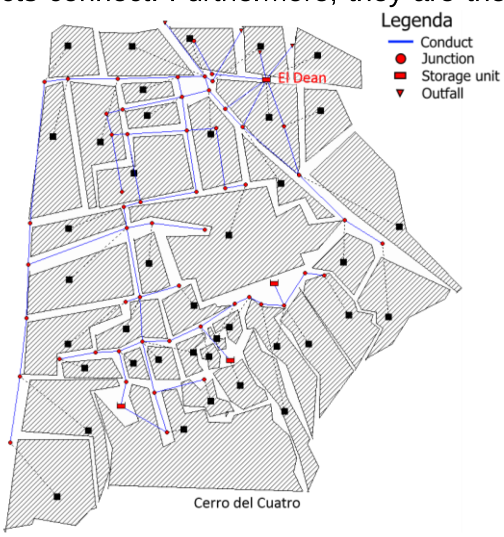

Figure 9: EPA SWMM model of research area

After the model is checked and improved in EPA SWMM, it is rebuilt in PC SWMM. There are two reasons to switch to another program. The first reason is that the current program is technically capable enough, but lacks in user-friendliness. By switching to a new program, IITAAC hopes for easier work and better results that can be presented in a more understandable (graphical) manner. This applies both to the current project and to future projects. The second reason is that you can notice new things when you are really building a model, instead of only checking it. When rebuilding the model, you have to make more choices about how to do something, and this makes you think more about the choices made in the previous model. And besides, you might simply notice new parts that are modelled strangely or could be done better, because you are using all the data for the new model.

PC SWMM is a commercial software program developped by CHI (Computational Hydraulics International). CHI calls their program a spatial decision support system for US EPA SWMM (CHI, sd). It is a commercial program based on EPA SWMM that adds new capabilities. The fact that is is based on EPA SWMM means that it uses the same engine for calculations and can even open EPA SWMM files. The most notable improvement over EPA SWMM is that PC SWMM has GIS capabilities. This means for instance that Open Street Maps and Google Earth are integrated in the program. Furthermore, it can import geo-referenced files for both adding spacial information (for instance elevation layers) and adding entitities (for instance junctions). Other improvements is that it is more visual, that results can be exported easily and that is is more user-friendly to work with in general.

3.2 Discription of scenarios

The model is used for two different situations, or scenarios. The first is the actual situation: the situation as it currently is. The second situation is based on the actual situation, but some measures are proposed to decrease or solve the problems. The measures consists of three steps. The first step is preventing rain from becoming runoff. This is done by implementing rain catchment systems at houses, schools and buss stations. Furthermore, more green is added along the main roads to increase infiltration. The second step is to slow runoff down, and decrease peak flow. This is done by twelve new storage basins, which are used to temporarily store rainwater. And thirdly, the transport capacity is increased by enlarging conducts and building new conducts. A map of the model in the proposed situation is shown in Figure 10.

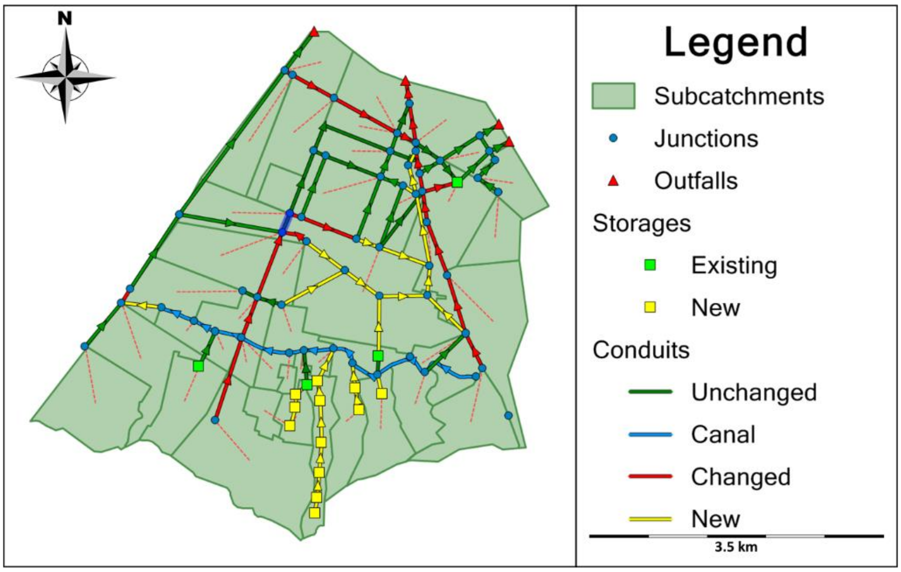

Figure 10: The proposed situation

For both scenarios a rain with a return period of ten years is used. This period is chosen, because it sufficiently rare that extreme situations arise, but at the same time it is not so rare that it is unneccessary to prepare for such an event. The rain with a return period of ten years has an intensity of 58 milimetre per hour in Guadalajara (Secretaría de Comunicaciones y Transportes). As this is only the peak of the rain, lighter rain will most probably fall before and after this peak. Therefore, the total rain event used has a duration of four hours and an intensity of 72 millimetres (Mendoza González, 2013).

3.3 Description of validation steps

Because the validation process is a bit complex, with multiple software programs being used for multiple model situations, the process is visualized in Figure 11. The first stage of the validation is to check and improve the models using EPA SWMM. This is the same program that was used to make the models. The first step is to validate and improve the model of the current situation in EPA SWMM with the framework of Sargent. How this framework was applied, is explained in more detail in section 3.4. Furthermore, a sensitivity analysis will be performed in this step to determine to which variables the model is most sensitive. Additional care has to be taken in the case of these variables, because a mistake here will have more effect on the model results. Furthermore, for these variables it would be good to collect more data (during this research or in the future).

The second step is to validate and improve the model of the proposed situation in EPA SWMM. Of course, the changes of step 1 will also be applied to this model situation. Subsequently, the model will be checked and improved. The focus in this phase is on the parts that are done differently in the two model situations. The results of these process are explained using Sargent's framework. However, because we are just looking at the differences with another model, it is not necessary to go through his framework completely. (For example, as the model is based on the same data, it is not necessary to check the source of the data again.)

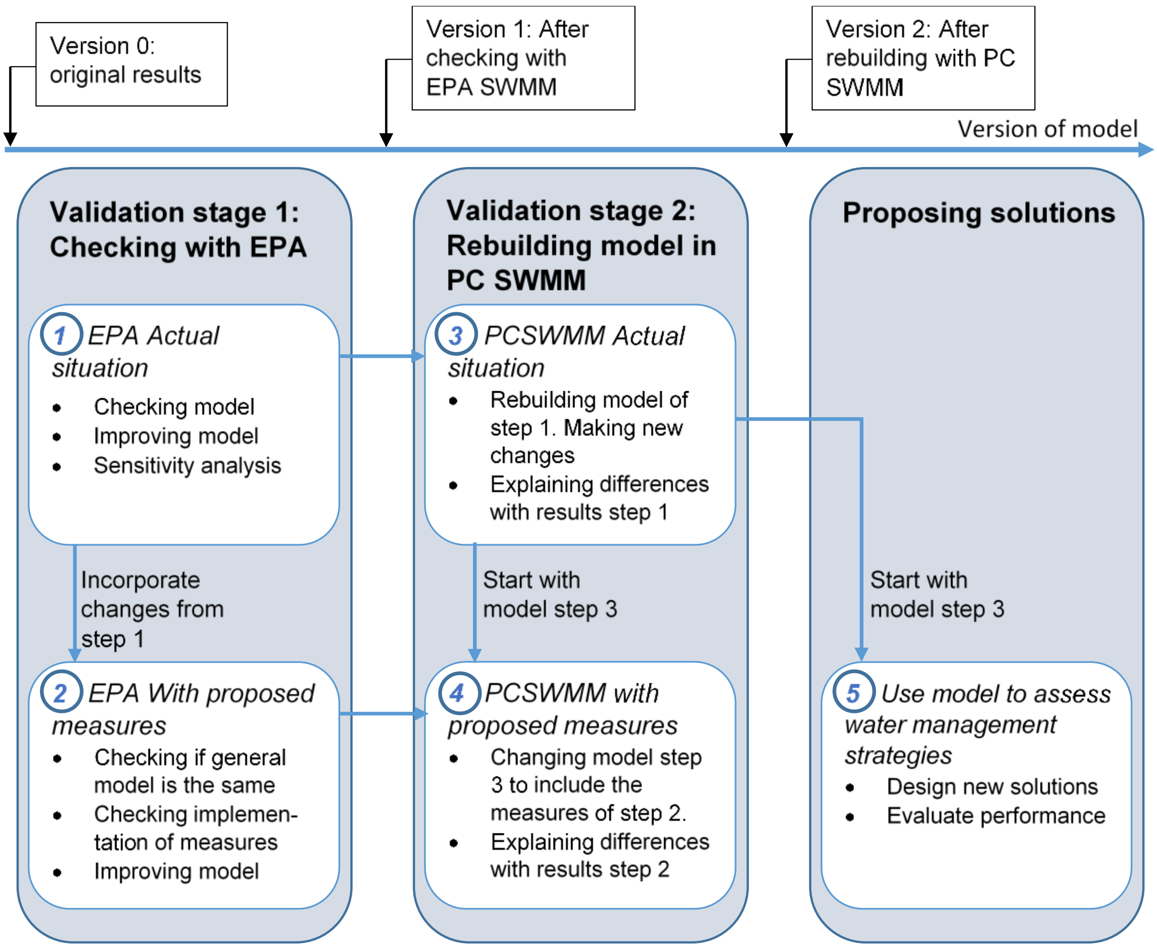

Figure 11: Workflow validation and design process

The second validation stage is performed with a different program: PC SWMM. Within this stage, the first step is to rebuild the model of the actual situation in PCSWMM. Because the process is here to remake the model, changes are made when parts are 'discovered' that can be done better, rather than by systematically checking the model. Consequently, Sargent's framework was not used for remaking the model. The results of the model will of course be compared with the results of the model of step 1.

In the fourth step, the model of step 3 will be changed to incorporate the proposed measures for improving the situation. Of course, the differences in the results between step 2 and 4 will also be explained.

The last step will be to design new solutions and use the model to evaluate their effects on flooding. For this, the model of the actual situation (the result of step 3) will be used as a starting point.

3.4 Applying the validation framework

Like indicated in the theoretical framework, Sargent's framework will be used. The last chapter indicated where it will be used. This chapter will explain more about how it will be applied. Like said before, three aspects of the models will be examined:

- Data validity
- Internal validity
- Output validity

In the case of data validity, the first step is to assess if the data is sound. This means determining if it is detailed enough, recent enough and checking for missing data, strange outliers or improbable data. A more thorough but still qualitative method is to also look at the way data is collected and to see if mistakes are made there. A more quantitative validation is possible by comparing the data to other datasets. These can either be existing datasets, or data obtained by taking new measurements. In this research, data validation is mainly limited to the first option, because other data to compare against does not exist or is not shared by other organizations, while the alternative of taking our own measurements would be too difficult and time-consuming.

For checking the internal validity, all the input in the model will be checked. This starts with the general settings, and determining if they are suitable for this kind of model, or that other settings would lead to a more accurate model. After this, the structure of the network will be compared with available sources. When not available, it will be checked whether the physics of the water systems are adequately represented by the model (so no missing connections, too big changes in elevation, not functioning parts of the network etc). After the structure of the network, the properties of the objects in the model should be checked as well. This includes properties like the imperviousness and roughness of subcatchments, size of conduits and volume of storage units.

A last step is comparing the outcome of the model with reality. Although hard numbers of flow rates and runoff volumes are not available, information about inundation or water depths in certain parts is available. This can be used to compare the model results with what happens in reality.

All these steps will first be performed for the model of the current situation. The resulting changes will, where applicable, be incorporated in the model with the proposed measures. Subsequently, the unique features of the model with the proposed measures will be validated.

4 Results: sensitivity analysis

The first part in the validation is the sensitivity analysis, to know what parts of the model are most important to check[1]. In this chapter the results of the sensitivity analysis will be discussed.

The sensitivity analysis is done to determine for which changes the model is most sensitive; which changes of the model have the greatest effect on the outcome of the model. These are the variables that need extra attention. For the sensitivity analysis, changes to the following 'model results' have been examined:

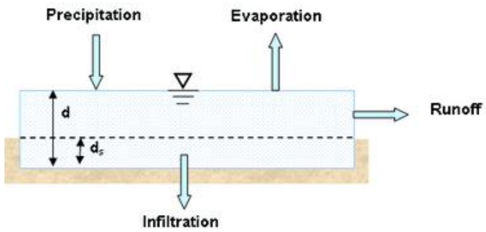

Figure 12: Conceptual view of surface runoff in SWMM (US Environmental Protection Agency, 2014)

1. *Infiltration*
   Water that infiltrates into the soil
2. *Surface storage*
   The thin layer of water that does not run off, but is stored on the subcatchment surface by ponding or surface wetting (see Figure 12).
3. *Runoff*
   All rain, minus infiltration and surface storage
4. *Outflow*
   The water that flows through the outfalls and leaves the modelled area.
5. *Flooding: ponding*
   If there is too much water in the conduits and junctions, some junctions will overflow. Ponding means that the water that flows from the junction, is stored above the junctions. As the water level decreases, this water will return into the system.
6. *Flooding: lost*
   The difference between flooding: lost and flooding: ponding exists only in the model, both are flooding in the real world. Ponding only happens if a pondable area has been set in the program. If no pondable area has been set, the water of floods simply leaves the system. This is called flooding: lost.
7. *Additional volume storage units*
   The additional volume is the total storage volume minus the initial storage volume. Unless explicitly stated otherwise, the term volume storage units in this report will refer to the additional storage volume, and not to the total storage volume.

Sensitivity can be calculated in the following way:

$$sensitiviy = \frac{\%\,\Delta input}{\%\Delta output} \qquad or \qquad sensitivity = \frac{\Delta input}{\%\Delta output}$$

The first formula is used if a relative change to the input variable is meaningful. Otherwise, the second formula is used. This is for instance the case with the elevation of junctions. Elevation is measured from an arbitrary level (sea level), and it is not useful to decrease the elevation of an individual unit with 10 percent.

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[1] To be more precise, the sensitivity analysis was performed on a partially improved model. To make the results more precise, easy improvements of the model were applied beforehand. These are for instance the values of parameters that are the same for the entire model, like surface storage and conduit roughness. However, the more detailed changes were made after the sensitivity analysis . These are for instance individual unit properties and changes to the structure of the network.

The results of the sensitivity analysis are given in two ways. The first is the sensitivity of whatever output changes most. The second is the maximum change in output for output 4 to 6. This is done, because measures are taken with the objective of solving problems. Therefore, you want to know how much the problems change. Flooding is a problem. Outflow is a problem as well, because it causes flooding outside the model area. However, infiltration, surface storage and storage in storage units are no problems, they are solutions. Therefore, they are not included in the second sensitivity results. For runoff, there is a different reason it is not included. Runoff is all the water that runs over the land, or in other words: it is all the rain except the infiltration and surface storage. It consists of outflow, flooding and water stored in storage units. Therefore, it cannot have the biggest relative change; at least one of its components will always have a bigger change (as long as the components do not change equally). In Table 1, the results of the sensitivity analysis are shown.

Table 1: Sensitivity analysis

Category input	Input		Most changed output (all outputs regarded)		Most changed output (only problem indicating outputs regarded)	
	Name	**Change**	**Name**	**Change**	**Name**	**Change**
Catchment	Manning's N (imp and perv)	-10%	Surface storage	-3.9%	Flooding: lost	0.9%
	Dstore (imp and perv)	-10%	Surface storage	-7.1%	Max ponding	-0.5%
	Imperviousness	-10 %-point*	Total infiltration	87.1%	Flooding: lost	-14.1%
Junction	Junction depth	-10%	Flooding: lost	-19.8%	Flooding: lost	-19.8%
Conduits	Size	-10%	Outflow	-19.3%	Outflow	-19.3%
	Roughness	-10%	Outflow	8.9%	Outflow	8.9%
	Energy loss coefficients	-10%	Outflow	1.0%	Outflow	1.0%
Outfalls	Elevation outfall 90	-2 m	Outflow	5.4%	Outflow	5.4%
	Elevation all outfalls	-1 m	Outflow	9.5%	Outflow	9.5%

*The imperviousness of the subcatchments is where possible decreased by 10 percentage points. If this leads to an imperviousness lower than 0, it is set to 0

NB. Catchment imperviousness and outfall elevation are the only inputs that vary per object (resp. catchment and outfall), the others are set to the same value for every object

As apparent from the table, changes to the conduit size, junction depth, imperviousness and elevation of outfalls have the biggest influence on the system results. However, the table only gives the sensitivity on a certain point. Because the sensitivity can be different for other changes, it is also calculated for other changes. This analysis can be found in Appendix B and supports the conclusion that the abovementioned variables are the most sensitive inputs.

There are two factors that decide if it is important to improve the data of a certain aspect. The first aspect is the sensitivity of a system. Here, the conclusion is that conduit size, junction depth, impervious area and elevation of outfalls are important aspects. The second part is the quality, or accuracy of the data. If the data is less accurate, improvements to the data is more useful. In the case of the imperviousness of subcatchments, data is reasonably good. Because the big impervious areas like parks and hills are known, a 10 percent difference between data and reality would be big. In the case of conduits and junctions, there is no data available to check is the size is at least logical. It is possible that they are (locally) twice as big in reality as in the data.

Conduit size, junction depth and outfall elevation are the aspects where both a high sensitivity and a high likeliness of significant mistakes are met. Consequently, these are the aspects where better data would help most. The junction determines in the model sets how deep below ground the conducts are located. And the outfall elevation is the elevation of conducts at the border of the research area. So if the model terms are translated to real life meanings, the size and elevation of conducts are the areas where better data would help most.

Unfortunately, these are also the aspects for which it is difficult to obtain better data. The municipality and water service companies do not have the data or do not want to share it. And because the objects are all underground objects, it is more difficult to take measurements yourself to check the data. A non-invasive technique like Ground Penetrating Radar would probably be the best way to obtain more data. Appendix F contains more information about how this could be used.

5 Results: checking and improving the model

In this chapter, the results of the validation will we described. First, the models are checked and improved. This is successively done for the model of the actual situation and the model with the proposed measures. Subsequently, the model results are discussed. First, the original model results are compared with the results of the validated models for both the actual situation and proposed measures. Lastly and most importantly, the final results of the actual situation are compared to the final results of the proposed measures to evaluate how well the proposals perform.

5.1 Validating the model of the actual situation

The first step is validating the actual model. For this, Sargent's framework has been used, and the data validity, internal validity and output validity have been checked consequently. The validation process consists of two stages. The first stage is to check the model with EPA SWMM. The second stage is to rebuild the model in PC SWMM. Almost all changes of this second stage pertain to the internal validity. Some could be argued to belong to data validity, but also for the sake of readability all changes have been categorized regarding the internal validity.

5.1.1 Data validity

Like indicated in the methodology, it is difficult to validate the data, because alternative data is not available. Oftentimes, there is no official data at all, and estimates are used. However, some remarks can be made. The most important one is that it would be good to keep searching and asking for more information, because this would make the model more reliable. This is especially true for the sewage network, because right now parts of it are not known.

A more specific remark is about the structure of the sewage network. From the available maps, it is not always clear whether tubes are connected at places where they cross, or that they are built in different elevations. Another remark is that the maps contains data on the size of sewers, but it is not always clear to what part a size refers, and where the new size starts.

5.1.2 Internal validity

For the internal validation, all the input in the model was checked. This resulted in a lot of changes to the model. Many of these changes were not about big mistakes, but more cases of variables where other values are more likely. However, some were really mistakes with significant influence on the model.

Like said, two programs have been used during the process of checking and improving the model. The changes resulting from checking the model with EPA SWMM are shown in Table 2. For a sense of what the numbers mean: the total precipitation is approximately 1.5 million m^3.

Table 2: The important changes resulting from the EPA SWMM validation and their influence

Object	Change	Reasoning	Influence
Conduits	Roughness: manning's coefficient from 0.01 to 0.014	0.01 is lower than all materials, 0.014 is likely for concrete pipe, cast iron pipe, brick pipes and cement pipes (US Environmental Protection Agency, 2014).	Outflow lowered from 200,000 to 155,000 m^3.
Storage units	Elevation	The elevation in the program is the elevation of the bottom of the units, and was implemented like it concerns the top of the unit, preventing water from flowing in.	Storage volume increases greatly, from maximum 75,000 m^3 to maximum 300,000 m^3.
El Dean: initial depth	Lowered from 6.5 to 5.5 meters (of total 8 metres)	Corresponds better with observations during visit to El Dean, and with information in AutoCAD maps of the area	100,000 m^3 less initial volume, 100,000 m^3 more potential storage
Conduit from EL Dean to outfall	Increased size from 1 to 2.2 metres	The size in the AutoCAD map is 2.2 metres.	Increase outflow by 110,000 m^3, decrease flooding likewise
Outfalls	Removed outfall 67	Does not exist in AutoCAD maps of network	Increase outflow with 75,000 m^3, decrease flooding likewise
	Changed elevation of outfall 90	The elevation was 5 meters higher than the nearest conduit, which caused it to do nothing.	
	Added outfall in north-west corner	It exists in AutoCAD	
Junctions	Add pondable area	Without pondable area, water from floods is lost from the model. It is more realistic if it can return into the system.	Decrease flooding: lost by 150,000 m^3. Increase flooding: ponding by 80,000 and outflow by 70,000 m^3.
	Lower junction (number 30) by 6 meters	It was 5 metres higher than the previous junction, causing the entire runoff of subcatchment 3 to become flood.	

Other changes that have had less influence are changed energy loss coefficients of conduits, added maximum flow rates to conduits, changed maximum depths of some conduits and small changes to the network structure.

After checking the model with EPA SWMM, the model was rebuilt in PC SWMM. This lead to new insights about parts that were done incorrectly or can be done better. The resulting changes are shown in the table below. Appendix C contains an elaborated version of this table with more explanations.

Table 3: The important changes resulting from rebuilding the model with PC SWMM

Object	**Change**	**Reasoning**	**Influence**
Subcatchments	Slope higher (from an unweighted average of 2.8 percent to 4.4 percent)	Half of the subcatchments had a slope of 0.5%. This is what SWMM automatically assigns and indicates that the correct slope what never assigned.	Lower surface storage and infiltration and higher maximum flooding volumes. This is because runoff becomes faster and runoff peaks become higher.
	Soil: from the same soil everywhere to loamy soil in the upper part and sandy soil in the lower part.	Based on INEGI soil maps (as cited in Mendoza González, 2013)	Lower infiltration
Storage units	Initial depth of 25 percent added	Previously, only El Dean had an initial depth. It seems unlikely the other storage units are completely empty at the start of the model run.	Decrease in storage volume
Nodes and conduits	A bottleneck west of El Dean disappeared, due to changing slopes and elevations	Following the maps of the network and the elevation data	Outflow increases, total flooding decreases and flooding around El Dean increases
Conduits	Smaller sizes in the upstream part	Following information	Higher volume of flooding: lost
	Adding a conduit	A missing conduit was suspected	Flooding: ponding decreases by 100,000 m^3.

5.1.3 Output validity

Running the model gives a lot of output values. However, most of these values cannot be checked against reality, because the real situation is unknown. This is the case for the flow rates and depths in most conduits, the total outflow and the volume in storage units. Nevertheless, some facts are well known, especially of what places are regularly flooded.

The most important part is the neighbourhood around El Dean. Naturally, it is a lower lying area, and a lot of water flows to El Dean. If there is heavy rain, more water flows to the area than the lake can store, and the area floods. The water on the streets reaches heights between 0.5 and 1 metre during not too extreme rains. However, in the model El Dean floods approximately 0.5 metres during an extreme rain event (frequency of once per 10 years).

There are two possible explanations for this difference. The first one is that the modelled area is in reality no independent unit. It is a integrate part of the city and its water system. Water that leaves this model area will flow through conduits further downstream. If these also contain water (and they will after a rain), water might not flow as easy through them in reality as through the outfalls in the model. Consequently, outflow is modelled too high (and flooding too low). Because the Dean is connected directly to an outfall, it would be heavily influenced by this. A second reason is probably that the streets not only flood because the lake overflows: they also flood because a part of the water flowing to the lake flows through the streets instead of the sewers. This behaviour is not part of the models.

The same pattern of underestimated flooding is visible with the Canal del Sur. The canal is known to flood during heavy rain, but in the model it does not. For most links, the water stays about 1 meter below the top. Here, another explanation is possible. The canal in the model has a regular cross section. In reality, bridges, tubes with drinking water, litter and other obstacles block the water at places. These might explain why the canal floods in reality. Furthermore, it is possible that the elevation data used is incorrect, and that a locally lower elevation causes flooding along some parts of the canal.

5.2 Checking the implementation of the proposed measures

The model of IITAAC is not only made to examine the current situation, it also contains proposed measures that can improve the situation in El Dean. The effects of these measures are of course influenced by the changes to the general model. However, the implementation of the measures themselves in the model has also been checked and changed. Because the method used is very similar to the general validation of the model, this part has been moved to appendix D**.** Here in the main text only the most important conclusions are given.

The model with the proposed measures contains two important mistakes. The first one is that the height of depression storage was changed from 2 and 5 milimetres in the actual situation (for respectively impervious and pervious area) to 50 milimetres in the situation with measures. This unrealistically high value led to an increase in depression storage from 25.000 m^3 to 380.000 m^3. This decreased the runoff likewise. Because the runoff was the most important output used in reporting the effects of the measures, this led to hugely overstated benefits for the measures.

A second problem in this model concerns the outfalls. An unrealistically low outfall was added, and this was connected to an enormous conduct (10 by 4 metres). Together this lead to an outflow that is so high, that flooding was totally absent one day after the rain (the modelling period) and the volume in the storage units was lower at the end of the model run than at the start.

When these mistakes were corrected, a more natural situation with outflow, floods, storage and infiltration arose. Furthermore, the combination of the continued influence of changes to the model of the actual situation and other smaller changes to the implementation of the measures also altered the results. The most important consequence this had is that outflow increased and flooding decreased.

5.3 Comparison of actual situation results: original vs improved

In Figure 13, the original and validated models are compared. First, this is done for the actual model. Version 0 refers to the original results, version 1 to the results after checking the model with EPA SWMM and version 2 to the results after rebuilding the model with PC SWMM.

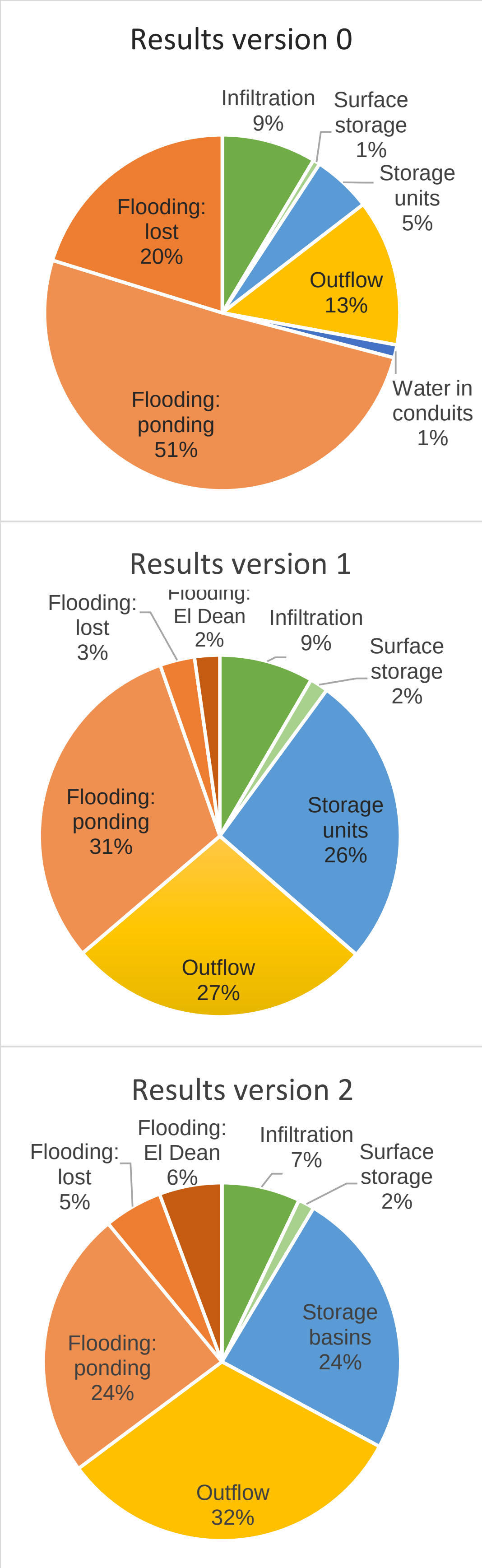

Figure 13: Results of actual situation, with the original results (version 0), the results after checking the model with EPA SWMM (version 1) and after rebuilding the model with PC SWMM (version 2).

The differences between version 0 and version 1 can be explained as follows:

- The storage volume is higher, because the elevation of the storage units has been lowered (making sure they can fill until the top), and because the initial volume of El Dean has been lowered.
- The outflow is higher, because the outflow of El Dean has received a bigger conduit connecting to a lower (elevated) outfall. This is done to make it equal to the information in AutoCAD-maps of the system. Also, a new outfall has been added, but this has less influence.
- The flooding is lower. The total amount of rain remains the same. The storage volume and outflow increase, so something else has to decrease. This is the flooding.

The differences between version 1 and versoin 2 can be explained as follows:

- The infiltration is lower, because of the higher slopes and different soil characteristics
- The outflow is higher, because a barrier before the outfall has been removed.
- The volume in storage units is lower, because setting an initial volume has lowered their (free) capacity.
- Flooding: lost is higher, because making conduits smaller has added some bottlenecks.
- Flooding: El Dean is higher, because earlier flooding locations are eliminated. This water can now reach El Dean.
- The final flooding: ponding (so after 24 hours) is lower, because making the infrastructure according to information has both eliminated a low junction and added a new conduit, removing a bottleneck.
- The total occuring volume of ponding (not visible in graphs), which is actually more important than the result after 24 hours, is higher, because the higher slopes mean runoff is faster. It has risen from 820,000 to 1,030,000 m3 (resp. 55% and 69% of the total precipitation).
  The total amount of flooding is expresed as percentage of the rain volume. If water causes flooding in multiple places, it counts multiple times. So a total flooding of more than 100% is possible.

In summary, the changes from the EPA validation step result in a higher storage volume, a higher outflow and less flooding. The PCSWMM validation step results in a higher maximum flooding volume but less flooding after 24 hours, an increased outflow and higher flooding around El Dean. Furthermore, infiltration and surface storage decrease. The results of all these changes is that the final model has almost 5 times more storage volume, 2.5 times more outflow and 2 times less flooding.

Although the situation is still serious, the current results say that it is better than previously thought. However, at the same time the comparison of model results with real world observations indicates that the model is too optimistic in the case of flooding around El Dean and El Canal del Sur. Combined with the fact that data is oftentimes not available or not detailed enough, this leads to the conclusion that the model functions more to give a general overview of the situation than a detailed description, and that this overview might be too optimistic.

5.4 Comparison of proposed measures results: original vs validated model

Next, the outcomes of the model with the proposed measures can be compared. The results before and after validating are visible in Figure 14**.** Before validating, the mistake with the surface storage and an unrealistic low outfall dominated the results. After validating the model with EPA SWMM, this was corrected. Consequently, the surface storage and outflow decreased and a more natural situation with outflow, floods, storage and infiltration arose. After validating with PC SWMM, the most important outcome changes were a significantly higher outflow, lower flooding volumes and less infiltration. This is almost completely caused by the continued effect of alterations introduced in the model of the actual situation and more thoroughly analysed in Apendix E**.**

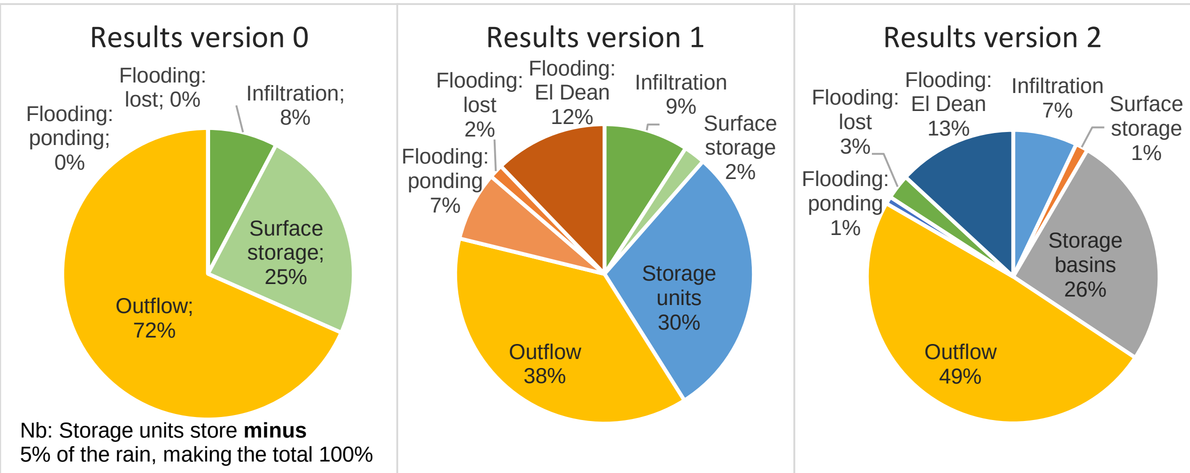

Figure 14: The water balance of the model with the proposed measures. Shown are the original results (version 0), the results after checking the model with EPA SWMM (version 1) and after rebuilding it with PC SWMM (version 2)

Of course, these results are also influenced by the quality of the model in general and changes to the modelled actual situation. Amongst others, this means that it is hindered by a lack of data and might give results that are too positive. This does not mean that the results are incorrect, but it does mean that the uncertainty is fairly high. As such, the general effect of the measures can probably be trusted, but it is unlikely the model predicts their effect exactly right.

5.5 Comparison of final results: actual situation vs proposed measures

The last step is to compare the final results (after rebuilding the model with PC SWMM) of the actual situation with the results of the proposed measures. (Figure 15). This tells us how well the solutions perform.

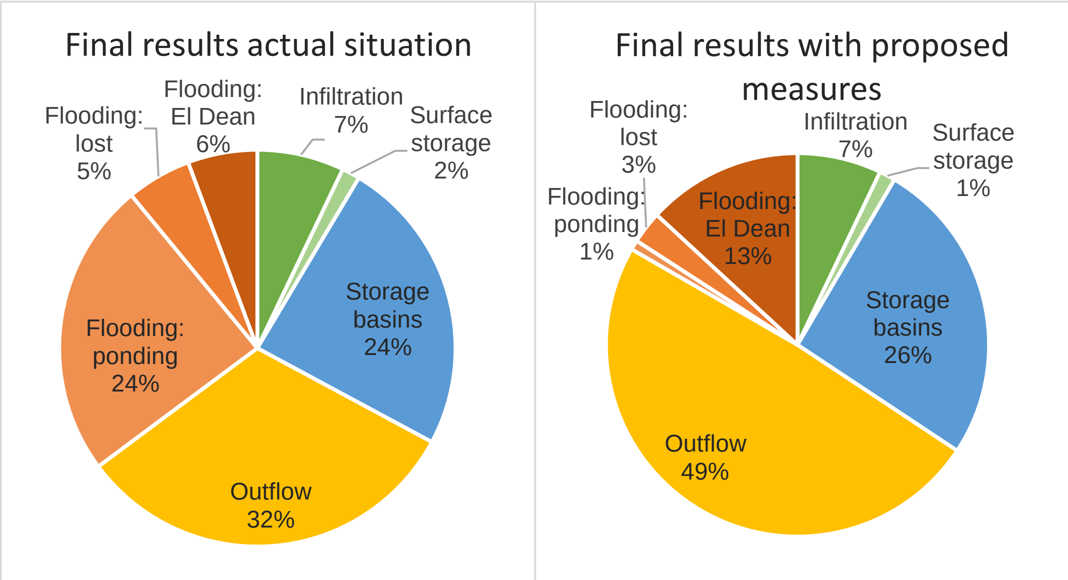

Figure 15: Comparison of the final model results: left the actual situation, right the model with results with the proposed measures

The differences between the results are:

+ The storage volume is higher, because new storage units have been added.
+ The total flooding is less, because that water now remains in storage units, or flows out of the research area.
+ The infiltration is marginally more, because some green areas have been added around the roads. However, this is too little to be visible in the graphs (increase of 0.7 percent-point). The same thing applies to the rain barrels, catching 0.4 percent of the rain.
• The outflow is higher, because many conduits have been enlarged to increase the transport capacity. This is good from the perspective of this area, but it can cause problems in other parts of the city.
- The flooding of the area around El Dean is higher, because the bigger conduits can transport more water to El Dean.

In conclusion, the proposed solutions help substantially to decrease problems in the area. However, at the same time this is primarily caused by large changes to the infrastructure. In the case of storage basins, they help by retaining water longer. In the case of conduits however, they help by transporting water faster. This solves problems in this area, but could also cause problems in other areas. The proposed small scale actions, like rain catchment systems and local reforestation are indeed small scale. They contribute, but in the same time they do not have a significant impact on the runoff. As a result, only the conclusion that flooding is decreased by the proposals is really correct. If runoff is defined like in the software used (meaning all precipitated water except infiltration and surface storage) the conclusion that the proposed measures decrease runoff is incorrect. If it is used in the meaning of all water that flows through the conducts, the measures (mostly the storage basins) do indeed lower the runoff. However, their impact is considerably less than previously thought.

6 Results: solutions to Guadalajara's storm water management problems

The model of the runoff and flooding in the area is made with the objective of designing solutions that can improve the situation. In the past chapter, the previously proposed measures have been evaluated. This is the first step for designing new measures, and it gives an idea of the performance of various measures. The next steps are to make a more systematic overview of the various options, with their characteristics and the possibilities within this area. Based on this information, a new proposal can be made.

6.1 Possible measures for storm water management

In this section, five possible measures are examined. Two big infrastructural measures are new/bigger conducts and storage basins. And three more small scale measures are rainwater catchement systems, infiltration trenches and permeable pavement.

6.1.1 Infrastructure: new/bigger conduits

When it rains, water is conveyed to the sewage system and transported to water treatment plants or natural water bodies. When the transport capacity of this system is insufficient for heavy rain, the first reaction people have is to increase the capacity. This means increasing the size of existing conducts, or building new conducts. This measure is fairly easy to implement in a small area, but it is important to realize that it affects a bigger area. Transporting water faster to other areas can cause flooding in other parts of a city. Furthermore, it can cause problems along the river that receives the runoff from the city.

Increasing the size of collectors is reasonably easy and can be used on any scale. Furthermore, as opposed to for instance storage basins, it does not require a lot of space in a city. As a result, it is a useful and much used measure. However, given its disadvantages, it should never be the only measure used. Instead, it should be used together with measures that do not negatively affect other areas.

6.1.2 Storage basins

Storage basins are used to store a part of the rain. They decrease (peak) flow, which means that within cities smaller conductors and (in mixed sewage system) treatment plants can be used. Furthermore, this can also result in lower flows in rivers outside of cities. Besides their hydraulic function, they can also fulfil a recreational or aesthetic function (for instance when they are combined with parks).

A prime disadvantage is that a lot of space is needed to build storage basins. City centres have little empty space, which makes it difficult to use large areas for incidentally used storage areas. It is possible to nonetheless use this little empty space, or to opt for more expensive space saving solutions. This can for instance be in the form of underground storage facilities under squares or parks. Another disadvantage is that storage basins are less robust than for instance increasing the size of conductors. Storage basins might not work when needed, because they are still full from a previous rain.

The conclusion is that storage basins are helpful for slowing down runoff and storing water, and they should certainly be used. In the research area, this is primarily possible in the upper part of the subbasin, where there are hills and open space. Furthermore, some parks could also offer the needed space. However, in the implementation, care has to be taken that they are not prematurely filled. This would probably mean using active control elements, and not solely relying on gravity.

6.1.3 Rainwater catchment systems

Rainwater catchment systems are systems that catch and store rainwater from houses and other buildings in rain barrels, cisterns or other storage units. Just like storage basins, this has the advantage that it can decrease peak flows. As an added advantage, the water can be used later when it is needed for irrigation, washing things, showering or even drinking. Furthermore, they improve awareness on water related problems. As such, it is a promising solution that can both function to improve access to water and decrease flooding. However, it is hard to implement them on a sufficient scale. This has several reasons:

- In general, households will only install one rain barrel. If a house has an area of 100 m^2, and it rains 2 cm, this corresponds with a volume of 2 m^3. However, rain barrels have sizes of approximately 200 litres. So this means they catch about 10 percent of the rain (not even of a very heavy rain, but a quite normal one).
- Companies might install bigger tanks. But even if their (relative) capacity is ten times as high, they can still only store an average rain of 20 millimetres, and not an extreme event.
- Not all houses and companies will install rain barrels or other forms of storage.
- In general storage units will not be empty at the start of a rain. People want to use them to provide water, which means they have to contain some water. And if it has just rained, they may even be full.

In the area are 58.000 houses. If you assume the average rain barrel is 200 litres, 50 percent of the houses installs them, and 50 percent of the volume is available (empty) at the start of the rain, they can catch 3000 m^3. If companies install tanks that can store 20 millimetres of rain and the assumptions of a 50 percent installation rate and 50 percent of empty volume still apply, they also store a volume of about 3000 m^3. Together, this is equal to approximately 0.4 percent of the rain in the area, and less than what one basin of 60*60*2 metres could provide. This shows that it is difficult for catchment systems to contribute significantly to decreasing runoff. Therefore, their primary objective should be to provide water. After all, for decreasing flooding it is easier to build one basin of 60 by 60 metres, than to convince 30,000 houses and half of the companies to install catchment systems.

6.1.4 Infiltration trenches and swales

Infiltration trenches are ditches filled with rocks. These trenches collect and store runoff, and let it slowly infiltrate into the soil (US Environmental Protection Agency, 2012). Ideally, they are built along contour lines to prevent them from transporting water. Vegetative swales are shallow channels slow down and capture runoff and let this infiltrate into the soil (US Environmental Protection Agency, 2012). The difference between both types is that infiltration trenches are filled with rocks, while swales are open channels, usually covered by grass. Furthermore, swales tend to be more shallow but wider. Because infiltration trenches and swales do not only store water but also facilitate infiltration, they do not only help against peak flows, but also provide water for vegetation and recharge aquifers. Figure 16 and Figure 17 show an example of an infiltration trench and vegetative swale.

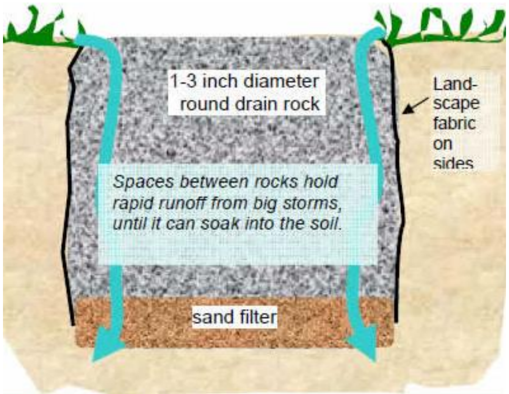

Figure 16: Example of infiltration trench (rainwise.seatle.gov)

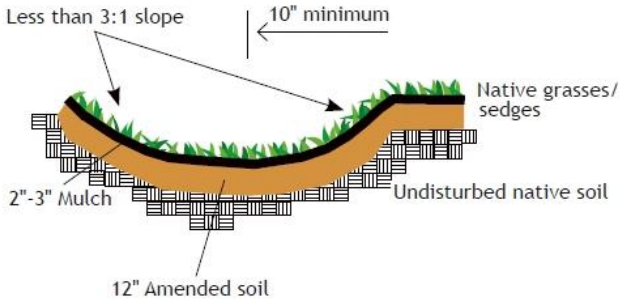

Figure 17: Example of vegetative swale (vtwaterquality.org)

Within the research area, the area in the upstream part of the subbasin is suitable for trenches and swales. The hills here are not covered by buildings and roads, so there is sufficient space. Their potential will be calculated by using a proposal of building an infiltration trench every 60 metres in the total natural area. This means their total length is 15 kilometre. With a cross section of 60*60 centimetres, they would be able to store a volume of 2300 m^3, of which 700 m^3 can infiltrate in one day.

6.1.5 Impermeable pavement

Impermeable pavement is pavement that allows storm water to drain trough the pavement. Underneath the pavement a storage layer is built. This allows water to be stored and slowly infiltrate into the soil below (US Environmental Protection Agency, 2012). Like other infiltration-improving solutions, this offers benefits for both storm water management, nature and aquifers. The advantage of permeable pavement is that it can be used widely in a city, without occupying extra space. A disadvantage is that the construction process is quite expensive: removing the road surface, replacing a soil layer by a gravel layer and then making the permeable top surface. In comparison to for instance storage basins, this is a lot more work. Furthermore, the permeable top layer is at risk of getting clogged by dirt, especially when the area with permeable pavement is regularly flooded. This reduces permeability, and can have the result that a part of the rain is not stored anymore, but becomes runoff again. An example of a permeable road is shown in Figure 18.

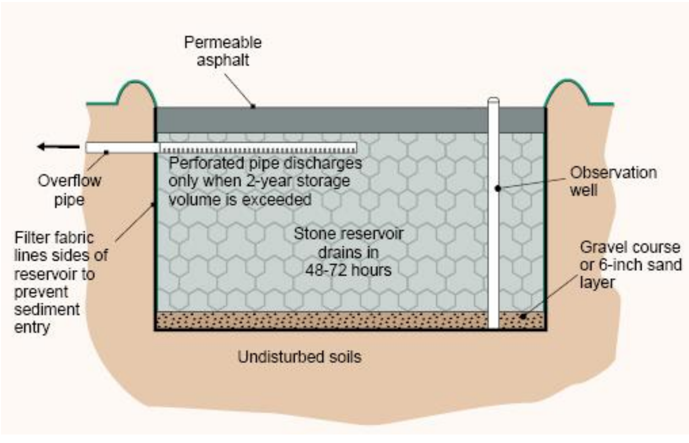

Figure 18 Example of permeable road (Nieber, Erickson, Weiss, Gulliver, & Hozalski, 2010)

In the researched area, there is a total of about 500 kilometres of road[2]. These roads are on average more than 8 metres wide[3]. If the pavement has a top layer of 10 centimetres with a

[2] Based on a Google Maps based estimation of the average size of blocks (the city has a gridlike street pattern) and the area of the research zone.
[3] Based on a Google Earth based analysis: roads have in general at least one lane and parking space at both sides. Such a road is more than 8 metres wide.

porosity of 15 percent and a storage layer of 30 centimetres with a porosity of 40 percent, it can store 135 millimetres of rain (all numbers are common for permeable roads, according to EPA SWMM, numbers, according to EPA SWMM Help, 2014). 135 Millimetres is almost two times the amount of rain used in the model (72 mm). And if infiltration during the rain is taken into account, even more water could be stored. To reach full capacity during the rain event used, the roads have to receive water from other areas. The first candidate to supply this water is the pavement next to the road, as water can automatically flow to the road. In a more elaborate system, one could even chose to connect the drains of houses along the road to the storage layer below the road. In this case, the storage layer can even be enlarged to store more water.

If the storage capacity of the previous example is fully used, such a system could store and infiltrate 540,000 m^3. This is equal to 35 percent of the rain. So although the ubiquitousness of roads in a city means the project would be immense, the benefits are of a comparable magnitude.

6.2 New proposal form storm water management

Based on the results of the model and the analysis of different possible measures, a new proposal has been developed. This proposal has the structure of a main proposal and some additional options.

6.2.1 Description of main proposal

The main proposal is to build more storage basins and enlarge existing conduits. This proposal is visible in Figure 19. Differences with the previous proposal (Figure 10, page 8) are that less conduits are increased in size and that no new conduits are added to increase the capacity of the network (they are only added where necessary because of the creation of new storage units). Another change is in the size of the conduits. In this proposal, conduits are increased to a circular tube of 2 metres, or a rectangular conduct of 3 by 2 metres. In the old proposal, the biggest conduit was 10 by 4 metres, more than 6 times as large.

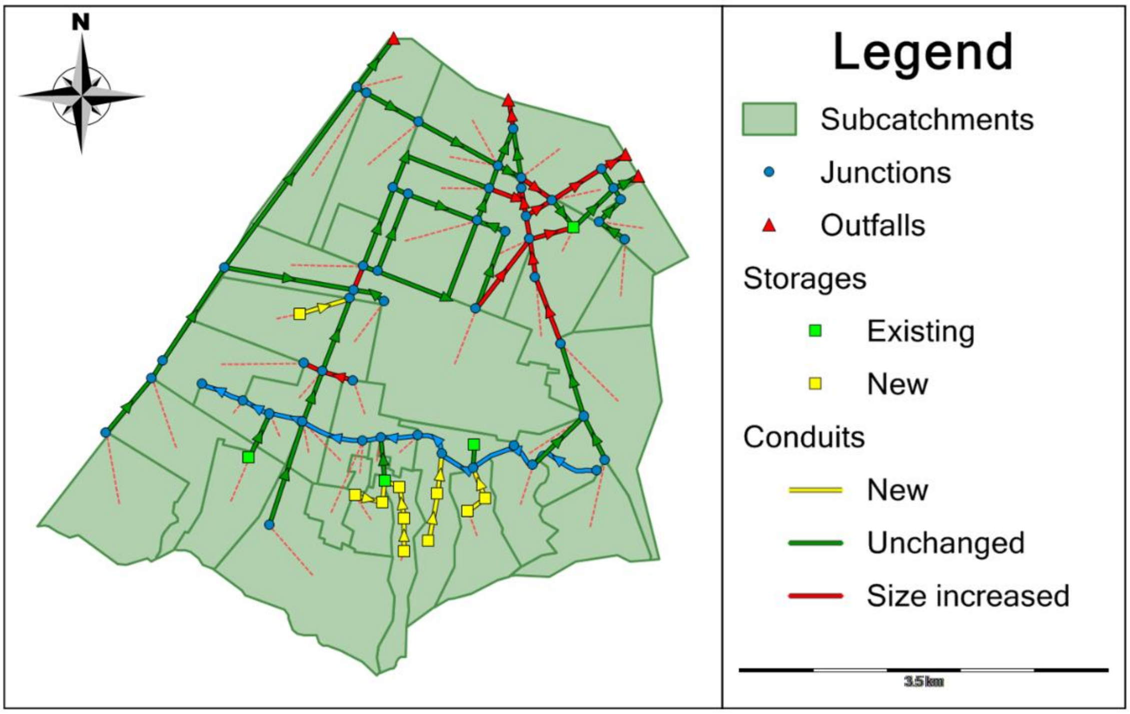

Figure 19: New proposal for storm water management

The structure of the storage units is quite similar: mainly in the upstream area. One difference is that in this proposal, one storage unit will be built in a park in a more downstream part of the subbasin. And of course the exact implementation is different. In this model, the proposal consist of 10 storage basins, each with an area of 3600 m^2 and a depth of 2.5 metres, resulting in a storage capacity of 90,000 m^3. In the previous proposal, there are 12 new storage basins, each having a depth of 4 metres and an area of between 800 m^2 and 4250 m^2. This results in a storage capacity of 98,000 m^3.

6.2.2 Results of proposal

The result of the newly proposed measures is that flooding is greatly decreased and outflow greatly increased. Outflow is up to 60 percent of the rain, from 32 percent in the actual situation and 49 percent with the old proposals. Total flooding after 24 hours is down to 8 percent, from 35 percent in the actual situation and 17 percent with the old proposals. The total amount of flooding is down from 79 percent in the actual situation and 63 percent with the old proposals to 45 percent with the new proposals.

Because of the added storage basins, the maximum volume of the storage basins is slightly higher than in the actual situation: 27 percent instead of 25 percent. However, it is slightly less than with the old proposal. And the storage at the end to the day is even less. This indicates that the new proposal works: in both the actual situation and the old proposals El Dean is still flooded after 24 hours, so the lake is also still at full capacity. With the new proposal, the lake is already emptying, explaining the lower storage after 24 hours. This is also visible in the floods around El Dean. With the new proposal, maximum flooding of El Dean is down to 5 percent from 6 percent in the actual situation and 13 with the old proposals.

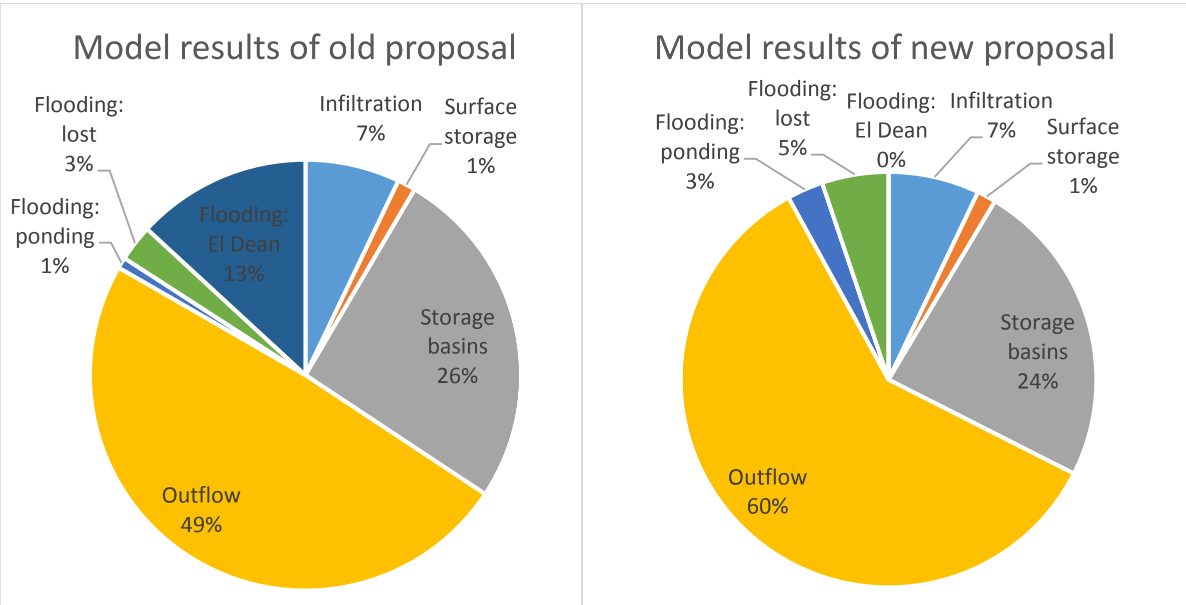

Figure 20: Comparison of model results of old proposal and new proposal

6.2.3 Additional measures

The abovementioned measures are the most important part of the proposal, because they are the measures that could contribute significantly within a (from an infrastructural perspective) reasonably short timeframe. In this part, some alternative or additional measures will be proposed.

6.2.3.1 Permeable pavement

Permeable pavement can contribute greatly to reduce runoff. However, like said before, it is a lot of work to implement on a great scale. Consequently, it makes financially more sense to replace roads with permeable pavement when major repairs are planned, than to replace all the roads in one big project. Additionally, a per area analysis would be needed to asses if it is a viable solution, or that the risk of clogging is too high. The result of this procedure is that it is more a long-term process than a clear construction project, and that it is unknown what scale is feasible. Therefore, it is not included in the main proposal, and only given as an additional measure.

6.2.3.2 Infiltration trenches

Infiltration trenches can contribute a lot less than permeable pavement, because they are only possible in areas with free space (as opposed to every place with roads), and because they are built in lines instead of on complete areas. However, this also makes them a lot easier to implement. On the area where they are implemented, they catch less than 2 percent of the design storm. On the scale of the entire subbasin, this is negligible. This is why they are not included in the main proposal and main calculations of the proposal. However, the other side of only needing 2 percent of the design storm is that only a small fraction of the design storm is needed for them to function. So even if there is just a little bit of rain, they increase infiltration with the same amount.

So for storm water management they are not really effective (little effect) but they have a reasonable efficiency (also not a lot of work to implement). Combined with their benefits of infiltration for both vegetation and aquifers, it seems advisable to implement them from the perspective of integrated water management.

6.2.3.3 Rainwater catchment systems.

Rainwater catchment systems store rainwater, and make it available for later use. They can also decrease the peak flow of storm water events. However, like shown in section 6.1.3, they would probably store less than 6,000 m^3. Although this is more than the infiltration trench, it is also a lot more difficult to implement it. 30,000 Households and half of the companies have to be convinced to install a system. As a result, it is a very inefficient solution for storm water management.

They certainly have benefits for providing (drinking) water and also serve to make people more aware of problems like water scarcity and water quality. And if catchment systems are included in the design phase of buildings, the can even be made on such a scale that they contribute more. So because of their other benefits, they remain an appropriate sustainable solution. However, within in scope of storm water management it is illogical to advise people to start building rain catchment systems.

7 Conclusion and discussion

7.1 Performance of the model

The first step of the validation was a sensitivity analysis. This showed that the results are especially sensitive to junction depth, conduit size and outfall elevation. These are aspects where checking the data is important and where more data would really help. However, it is difficult to obtain more data, which makes conclusions less reliable. This is also clear from the data validation, where checking data was difficult and existing data sometimes also difficult to understand. However, despite these problems some correction have been made to the data. Correcting inconsequent storage basins and missing slopes of subcatchment are the most important corrections made.

Checking the internal validity resulted in more changes in the model. Storage units have been lowered to enable them to fill up and the initial volume of El Dean has been lowered. The size of conduits has been changed at some points, most importantly between El Dean and its outfall. Junctions have received a pondable area to make sure their flooded volume is not lost from the system. And some corrections to the elevation have resulted in the elimination of bottlenecks.

For the output validity, validation is difficult due to a lack of data for the real situation. However, some remarks can be made. The model seems to underestimate flooding around El Dean and the Canal del Sur. Without modelling the current situation correctly, it is unlikely that the exact effects of measures can be calculated correctly. The consequence is that the model should mainly be used for comparing the effectiveness of measures. Designing measures and assessing their results on an absolute scale would require a more exact model.

For the actual situation, the conclusion before and after improving the model is the same: there is a lot of flooding. However, after improving the model the outcomes in terms of flooding are less severe. Flooding goes down from 70 percent to 35 percent of the total rain volume, storage units function better and the outflow increases.

For the proposed situation, mistakes with the surface storage and an unrealistic low outfall dominated the results. They resulted in a 25 percent decrease in runoff and a total absence of floods. When this was corrected, a more natural situation with outflow, floods, storage and infiltration arose. When comparing these results with the actual model, the proposals really help to decrease flooding (from 500.000 m^3 tot 250.000 m^3). However, as upstream flooding is decreased, more water flows to the downstream part of the subbasin. This causes more floods around El Dean. Furthermore, the increase in outflow is good for this subbasin, but it can cause problems in downstream areas.

7.2 Discussion of effects of measures

After validating the model, is was used to design new solutions for water management and assess their performance. The new proposal consists of two main solutions: building storage basins and increasing conduit size. The storage basins decrease peak flows, the bigger conduits increase the system's capability to cope with high flows. This proposal decreases flooding with 45 percent and flooding after 24 hours with 75 percent. This means that it performs better than the old proposal, while using less extreme measures (A less new conducts, B increasing less conducts in size and C proposing less extreme sizes of conducts).

However, the bigger conducts also result in a more rapid outflow, which can cause problems in other parts of the city. So to make sure problems are solved instead of displaced, at the same time measures should be taken at other places in the city.

From the additional measures, permeable pavement is the most useful. Due to ubiquitousness of roads, they can seriously help to increase infiltration and decrease runoff. However, it is also an expensive measure that would take a longer time to implement and its performance could decline over time due to clogging. Infiltration trenches contribute very little, but they are a sensible solution because they are also easy to implement. Rainwater harvesting systems are not really useful for storm water management. Because of their low volume and the necessity to convince people to implement them, they are inefficient as a storm water solution. So when building rainwater catchment systems, this should be with their other benefits in mind.

Regarding the reliability of these results, the difficulties of obtaining data and differences between the real situation and the modelled situation of course have repercussions. General conclusions, like 'more measures are needed in the downstream part of the subbasin' or 'real improvements to the situation are possible without resorting to conduits of riverlike proportions' are still viable. However, results should not be interpreted as the exact truth, and care should be taken with taking very specific measures.

7.3 Recommendations

Based on the research a number of recommendations can be made. The first is to do more research with different rain events. Currently, a rain event with a return period of ten years and a duration of one hour is used. It is possible that a rain with a higher intensity and shorter duration or a lower intensity and longer duration causes more problems. Furthermore, it is useful to know from which return period problems occur, and how possible measures perform with less or more extreme events. To do this, data would probable pose less of a problem, as the availability of precipitation data is a lot better than the availability of data about the structure of the hydraulic network. Therefore, it would be a good starting point to improve the research.

A second recommendation is to increase the size of the research area. Apart from an interest in the situation outside the current research area, this would also improve the accuracy of the current model. At the moment uncertainties about the border of the area influence the model. Firstly, the elevation of outfalls is uncertain. Secondly, the model is probably influenced because modelling conducts outside the research area as outfalls underestimates the resistance they exert on water flows. And thirdly, conducts along the borders of the research area transport water from inside and outside the research area. The flows from outside the area are unknown. When the research area is bigger, these problems occur further from the current area of interest and the results for the current area become more precise.

A last recommendation is to obtain more data. Data availability and accuracy was the main problem during this research. Because in some cases even water utilities do not have more data, the only way to obtain this is doing measurements. The conclusion of the sensitivity analysis was that it is most important to know more about the size and elevation of the conducts. The most practical way to obtain this data would probably be to use a ground penetrating radar.

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Appendices

Appendix A. Other tasks at IITAAC

Apart from this research, which I did for my bachelor thesis, I also did a research for my minor 'Sustainable development in developing countries' at IITAAC. That assignment was about the perception of water related problems, and the influence these problems have on people. So the first difference between both research tasks is the subject of the research. The minor research is centred on *people* (how do they perceive it, how are they influenced), the bachelors research is centred on the *problem* (which problems arise, how can they be solved). The second difference is the scope: this research is only about too much water, the minor's research is about all water related problems (too much water, too little water and water of a bad quality).

Next to the research tasks, I helped the organization with practical tasks as part of the minor. Because the organization is very new and has only recently acquired an office, they still needed to equip and organize this when I arrived. I helped them with doing this. Furthermore, I attended a rainwater harvesting course in the United States, and used this knowledge to teach others how to build a rainwater harvesting system. Besides, I helped with some small tasks, like small adjustments to the Storm Hunter (a truck equipped with measuring equipment and a rainwater catchment system, built to measure the quality and quantity of rain).

Appendix B. Aditional graphs to sensititivity analysis

This is the appendix to chapter 4. In chapter 4 the sensitivity of several system variables was calculated for a 10 percent decrease in value. Here, the sensitivity is also calculated for other changes. Mathematically, the sensitivity is equal to the slope of the line in the graphs below. The graphs support the conclusion of chapter 4 that the max conduit depth, junction depth, elevation of outfalls and (to a lesser degree) imperviousness of subcatchments have the highest sensitivity.

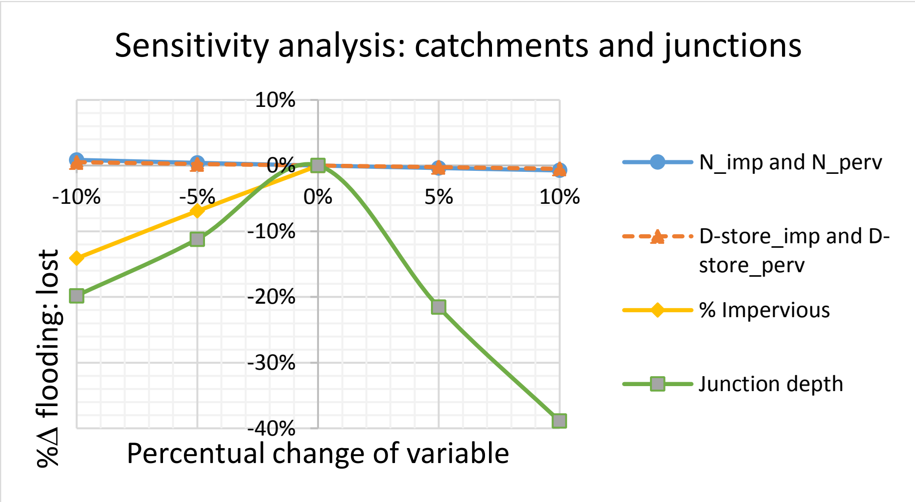

Figure 21: Sensitivity analysis, influence of catchment and junction properties on flooding: lost

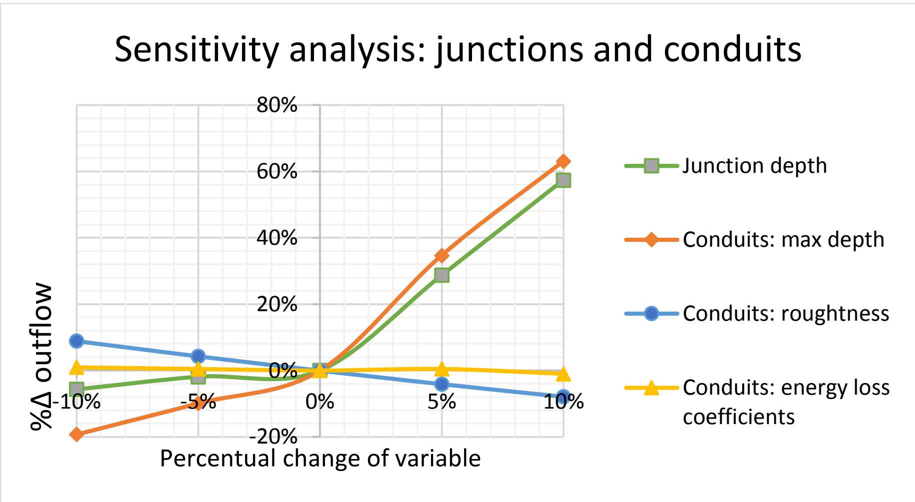

Figure 22: Sensitivity analysis, influence of junction and conduit properties on outflow

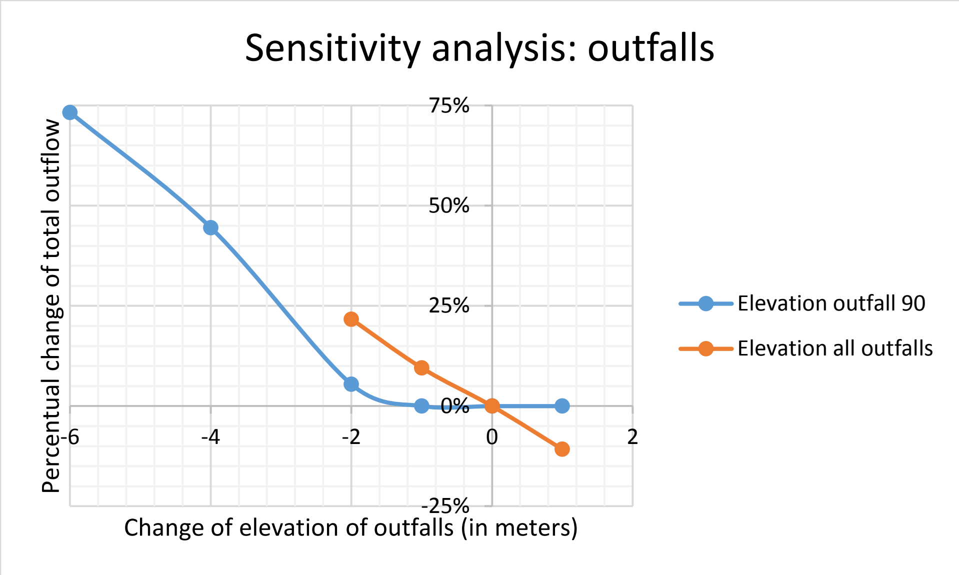

Figure 23: Sensitivity analysis, influence of outfall elevation on outflow

In most cases, the sensitivity is constant, as visible by the constant slope of most graphs. Notable exceptions are the junctions and the elevation of outfalls. In the case of outfalls, the explanation is simple. No water flows through outfall 90 until it is lowered by approximately 2 meters. After this, the relationship is quite linear. The case of the junctions is more special. Apparently, the current model leads to a maximum of water lost due to flooding. If the junction depth is lower, the volume of flooding: lost decreases and the volume of ponded flooding increases. A part of the water cannot reach the junction without a pondable area anymore, and it floods in junctions where flooding is possible. When the junction depth increases, the volume of flooding: lost decreases as well. In this case, the volume of the storage units and outflow increases. The increase in stored volume is mainly happening in El Dean, which is at the end of the modelled area. So apparently more water can flow to the end of the model area.

Appendix C. Explanation of changes to model of acutal situation after rebuilding it in PC SWMM

This table is an elaborated version of Table 3 in section 5.1.2.

Object	Change and reasoning	Influence
Subcatchments	Increased slope (from an unweighted average of 2.8 percent to 4.4 percent) Reasoning: half of the subcatchments had a slope of 0.5%. This is what SWMM automatically assigns and indicates that the correct slope what never assigned.	Lower surface storage and infiltration and higher maximum flooding volumes. This is because runoff is faster and runoff peaks are higher.
	Changed soil: from the same soil everywhere to loamy soil in the upper part and sandy soil in the lower part. This is based on INEGI soil maps (as cited in Mendoza González, 2013)	Lower infiltration The loamy soil in the upper part of the subbasin has a lower hydraulic conductivity; the sandy soil in the lower part has a higher conductivity. Most infiltration occurs in the upper part, which has more unused and pervious soil. The decrease in conductivity here decreases infiltration. The lower part of the subbasin is almost completely covered with impermeable roads and buildings. So the increase in the conductivity of pervious area barely increases infiltration. Together, the decrease in infiltration in the upper part and the barely noticeable increase in the lower part mean that infiltration decreases.
	Drawing them correctly, so they now form one fitting piece (in the old model there was a lot of space not belonging to any subcatchment)	Very low. Only the drawing changes, the area remains almost the same. And the area impacts the results.
Storage units	Initial depth of 25 percent added. Previously, only El Dean had an initial depth. It seems unlikely that the other storage units are completely empty at the start of the model run, so they have received an initial depth of 25 percent.	This decreases the storage volume (which is defined as the additional storage volume and does not include the initial volume).

Junctions and conduits	Modelled according to information. West from El Dean (see Figure 24), a bottleneck has almost disappeared. The slope in some conduits [most notable point 1] increased, a conduit was added [point 2] and junctions [point 3 and 4] that were lower than the outfall received a correct elevation. (It may seem like this was a deliberate effort to remove the bottleneck. However, it purely originates from following the data more exactly. The elevation of the junction and slope of the conduit both change as a consequence of using elevation data. The conduit is added because it appears on the map of the network.)	Outflow increases and the volume of flooding decreases. Furthermore, as the flooding at the specific points of the bottleneck [point 3 and 4 of Figure 24] decreases more than the outflow of the closest outfall [point 6] increases, the amount of water that flows to other places has to increase as well. Amongst others, this increases the outflow of other outfalls and increases flooding around El Dean.
Conduits	Decreased sizes in the upstream part. Based on the information some conduits have been made smaller.	Flooding: lost has increased. The conduits form bottlenecks now. Since the bottlenecks occur in the upstream (and sloped) area of the subcatchment, water will flow to another place and will not be stored on top of the junctions. Consequently, it seems incorrect to model flooding as ponding. As a result of this choice, the volume of flooding: lost is higher.
	Conduit added at point 5 in Figure 24**.** The runoff of one of the bigger subcatchments went to one junction connected to a small 0.76 meter conduct. Given that most conduits are between 1 and 2 metres, and that the diameter has a quadratic relation with the cross section, this is quite small. The small conduit forms a bottleneck, causing one third of the previously occurring flooding. So a missing conduit or incorrect subcatchment borders were suspected here. To correct this, a second conduct was added in de model.	The flooding at this point has been eliminated. This decreases flooding with 100,000 m^3.

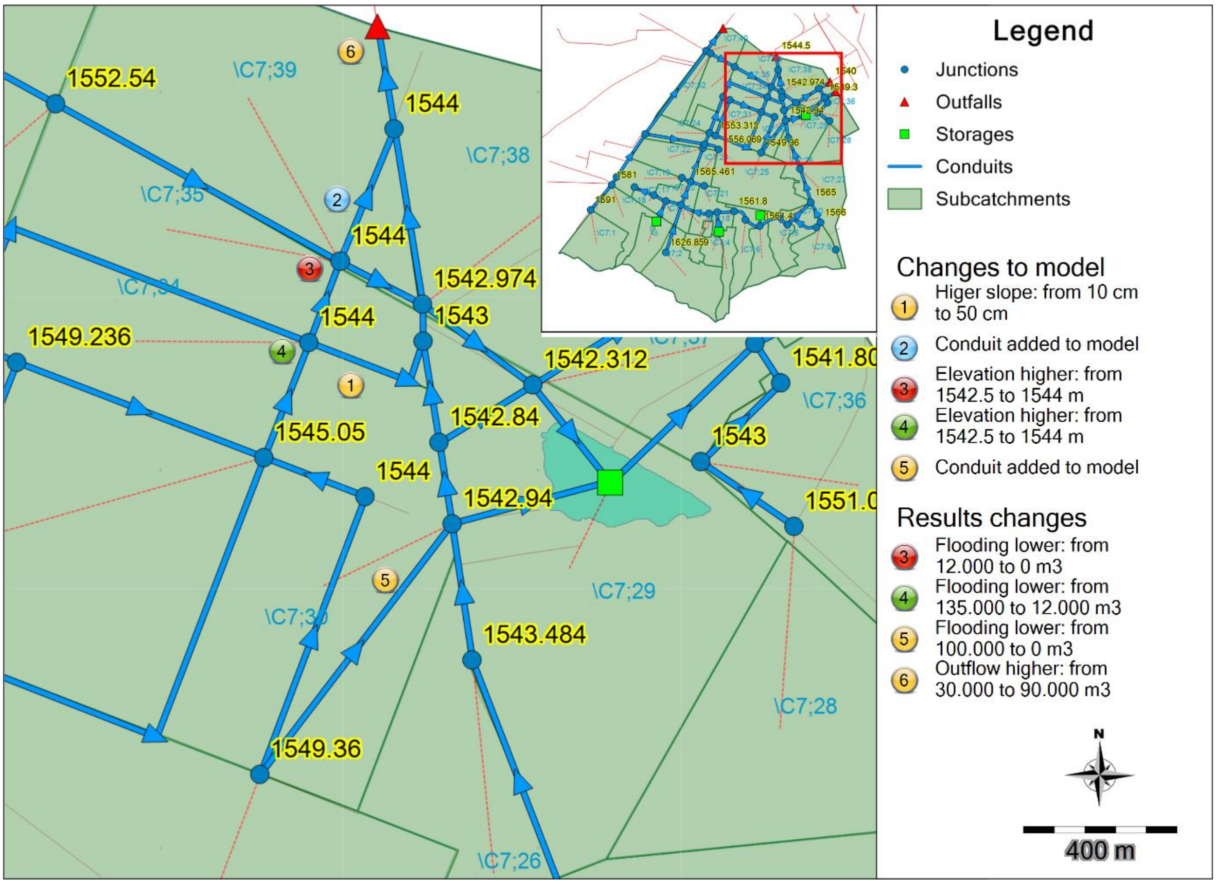

Figure 24: Changes west of El Dean

Appendix D. Explanation of changes to model with proposed measures

This is the appendix to section 5.2. Here, the changes to the model with the proposed measures are described in greater detail. Again, Sargent´s framework is used. Because of the hypothetical nature of this scenario, it is impossible to validate the outcome. However, the data validity and internal validity are controlled. Almost all change originate from validating the model with EPA SWMM. If a change originates from rebuilding the model with PC SWMM, this is specifically mentioned.

D.1 Data validity

The model with the proposed measures consists primarily of the old model, with changes for the proposed solutions. This means there is little new data used. However, it is possible to make one remark about data validity. The proposed measures do not only introduce new storage units, the old ones are still used as well. However, for some reason the volume of two of the old storage units has been decreased. For now, the storage volume has been restored, to make a comparison of the results possible. However, the fact that the data is consistent now does not make the data correct, and the fact that different values exist makes the data less trustworthy.

D.2 Internal validity

The model of the proposed situation had a few mistakes, which unfortunately have led to a too optimistic prediction of the effectiveness of the solutions. The first one is the depth of depression storage in both pervious and impervious areas. Depression storage is water that will stay on any area, being streets, gardens or other areas. This water will not become runoff, and will eventually infiltrate of evaporate. For the actual situation, the height of this depression storage was respectively 2 and 5 millimetres for impervious and pervious areas. In the proposed model, this was changed to 50 millimetres. This unrealistically high value led to an increase in depression storage from 25.000 m^3 to 380.000 m^3.

In the previous research, the runoff was the most important output used in reporting the effects of the measures. The runoff is equal to all the rainwater, minus the infiltration and surface storage. Consequently, the increase in surface storage was responsible for the reported 25 percent decrease in runoff. This led to the conclusion that the storage basins and infiltration-improving measures worked really well.

Another problem with the proposed model lies in the outfalls. A new outfall was proposed, to increase outflow and decrease flooding. This outfall was given an elevation of 1534; 7 metres lower than the nearest (original) junction. This would lead to a conduit slope of 8 percent, in an area with a slope of 1 percent. In other words, the system would be built really deep underground. This implementation of the new outfall lead to an unrealistically high outflow. This was exacerbated by the fact that conduit connected to the outfall was a rectangular tunnel with a cross-section of 10 metres wide and 4 high. Together, this lead to an outflow that was so high, that flooding was totally absent one day after the rain (the modelling period) and the volume in the storage units was lower at the end of the model run than at the start.

It seems easier to enlarge existing conduits, than to make totally new ones, especially because this has less consequences for the network outside the modelled area. With this idea, the new outfall was deleted. Of course, without the new outfall, the new conduits going to this outfall were deleted as well. To retain the spirit of the original proposals and to prevent that new bigger conduits in other parts of the area suddenly connect to the old small conduits, some other conduits have been enlarged.

Apart from new or enlarged conduits, a part of the strategy to solve the problems is to make more storage units. The new storage units are all planned in the hills in the south, because this is the only place where there is still nature, and room for the basins. However, in the current implementation they are not fully used. The outlets have been placed too close to the bottom, making it impossible for the storage units to fill up. This has been changed. In addition, an initial storage volume of about 25% has been set, because it seems unlikely that the basins will be completely empty at the start of the rain.

Another part of the strategy is to use rainwater catchment systems. However, there are two problems with their implementation in the model. The first problem lies in the conceptual model. The idea was that rain barrels can capture all the water that falls on a roof. However, rain barrels are quite small and in general houses install just one. As the barrels cannot store the total rain volume, the calculation should be based on the number of rain barrels instead of on the surface area of the houses. (See chapter 6.1 for a more detailed analysis on the potential of rain barrels). The old concept would have led to a too optimistic effect, if it was correctly implemented. However, the second problem is that the wrong parameters were changed, leaving the measures without influence. Both problems have been solved in the validated model, leading to a catchment volume of 6000 m^3.

The last change pertains to the junctions. This is the only change that was introduced after rebuilding the model with PC SWMM. In de programs, junctions connect conduits and form the point where surface water can enter the system (i.e. they represent manholes). Junctions have elevation and height information. In the example of Figure 25, the junction has an elevation of 1568 metres above sea level and a depth of 2 metres. This indicates that the ground level is at 1570 metres. For the conduits, their depth below ground is equal to the junction size minus the conduit size and conduit offset. In the case of the conduit in Figure 25, having a size of 1 metre, an offset of 0.5 metre and a junction depth of 2 metres, it is half a metre under ground.

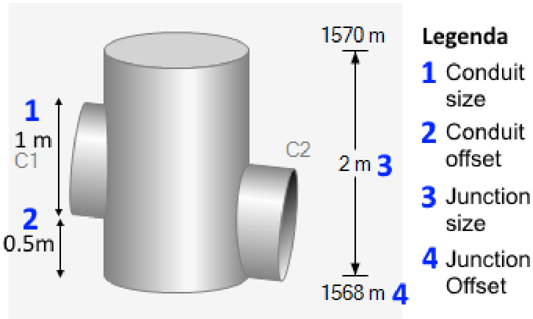

Figure 25: Cross section of junction with conduits

The consequence of this system is that junctions have to be bigger than their connecting conduits. In the proposed measures the conduits were enlarged, but the junctions were not. This would mean that the conduits are very close to the surface, or even placed above the surface. To correct this mistake, the size of the junctions has been increased where necessary, and their elevation has been lowered likewise. The same applies to the outfalls: where necessary, their elevation has been lowered. (Outfalls have no size of their own, but are equal to the connecting conduct. Therefore, their size does not have to be altered).

Appendix E. Comparison of results: model with proposed measures

This is the appendix to section 5.4. Here, the differences between the results of the model with the proposed model after checking it with EPA SWMM and after rebuilding it with PC SWMM are analysed.

The PC SWMM model with the proposed measures is of course influenced by new changes to the model of the actual situation. There are little additional changes in PCSWMM that are specifically made for the model with the proposed measures. As a result, you would expect the results to change approximately the same from the EPA version to the PC SWMM version as they do in the model of the actual situation. However, one complicating factor is that the continuity error in the PCSWMM version of the proposed situation is quite high (about 7 percent). On a total volume of 1.5 million m^3, this means approximately 100.000 m^3 too much is routed through the model. In the EPA model, this continuity error was much lower. It results in higher volumes for the entire water balance. The water balances are shown in Figure 26.

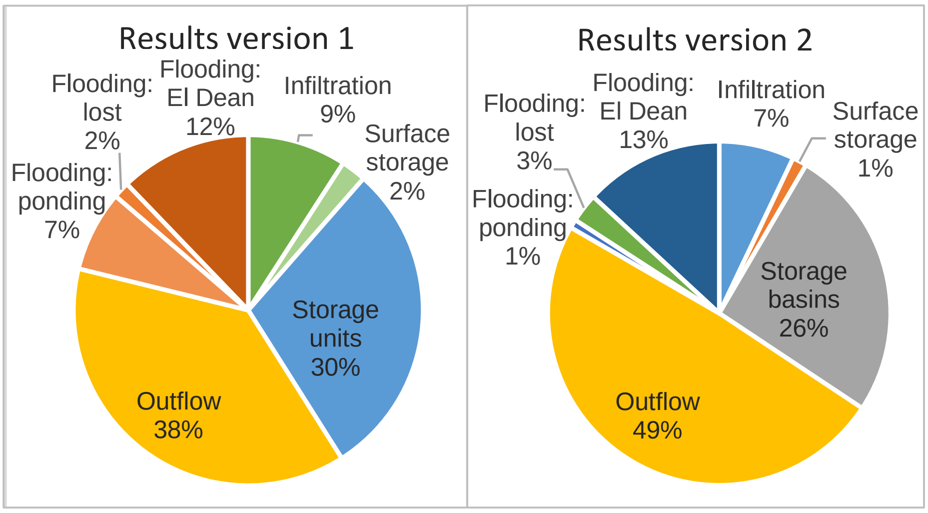

Figure 26: Comparison of the results of the model with the proposed measures. Left the outcome after checking it with EPA SWMM, right after rebuilding the model in PC SWMM

Changes that are approximately the same as for the actual model are:

- Infiltration and surface storage are lower, due to higher slopes and the introduction of a second soil group.
- The final (additional) volume of storage units is lower, because the initial volume is higher.
- Final flooding: ponding is lower, because of a removed bottleneck. The volume of ponding after 24 hours is lower for the proposed situation than for the actual situation. As a result, the decrease in volume when switching to PCSWMM is much more noticeable.
- Flooding: lost is lower. Although the size of the change is according to expectation, this result is reached by adding one place with flooding: lost, while removing another place with flooding: lost (a small conduit that forms a bottleneck is enlarged as part of the proposals).

Cases where the change for the model with proposed measures is different from the model of the actual situation are:

- Flooding: El Dean is higher, because earlier flooding locations are eliminated and more water can reach El Dean. This is as expected. However, the increase is smaller than in the actual situation, because in the proposed situation the flooding according to EPA SWMM is already high. This means the water level of El Dean is also higher and that water flowing into El Dean experiences more resistance. As a result of this higher resistance, less additional water flows into the lake, and the increase in flooded volume is less.

- Outflow: in the model of the actual situation, the outflow increased in PC SWMM because a floods causing barrier was removed. However, only a part of this volume became outflow. Another part causes flooding at other points. With the bigger conduits, the water does not form floods at other points, and the increase in outflow is bigger. Furthermore, increasing the conduit size to one outfall has lowered its elevation. As a result, the outflow of this outfall is greatly increased.

Appendix F. Using ground penetrating radar for mapping underground elements

According to the sensitivity analysis, better data is needed on the size and elevation of network elements like conducts. Because this data is not available, new measurements are needed. This is easiest if you do not have to enter the system and take measuerments manually. This means a non-invasive subsurface imaging method should be used. Ground penetraing radar (GPR) would be suitable: according to Richard Yelf (2007) GPR can be used for mapping pipes, cables and other buried objects.

GPR uses high frequency radar pulses which are transmitted into the earch. They are reflected by earth layers or objects within the ground and from the returning signal an image is made (US Environmental Protection Agency, 2011). It is capable of high resolutions for depths up to approximately 10 metres. The highest resolutions are possible with high frequency signals, but these penetrate the ground less (Yelf, 2007). Furthermore, resolution and penetration depth depend on the soil characteristics. Both are lower in soils with a higher electircal conductivity. This means the precense of clay or water decreases the quality of results (US Environmental Protection Agency, 2011).

For the research area, this means the results have a lesser quality in the upstream area of the subbasin, due the the presence of clay in the ground. Furthermore, the dry period of the year would me more suitable to to the research, as results are better in drier soils.