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BACHELOR THESIS

URBAN FLOOD MODELLING

RECOMMENDATIONS FOR CIUDAD DEL PLATA

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ABSTRACT

Due to climate change and urbanisation urban floods have been increasing in frequency and size. An urban flood is when a rainfall event exceeds the capacity of the drainage in an urban area, consequently flooding it. Urban floods are known to lead to erosion of soil, pollution of the area and significant economic damage. With the increase in flooding frequency, urban flood models have been gaining interest as thy are a tool to understand floods and mitigate them.

This thesis presents a list of recommendations for urban flood modelling in the Delta del Tigre district of Ciudad del Plata. This city in Uruguay is used as a pilot for a national water plan regarding drainage, flood protection, potable water and sewerage. The city was chosen because of its complex hydrologic situation involving impermeable soil and dykes. The soil forces water to run of instead of infiltrating and the dyke in the Delta del Tigre obstructs and at times stops the water from leaving the district. This leads to frequent flooding that, in addition to being very inconvenient, constitutes a danger for the residents in the city.

As part of a diplomatic treaty between Uruguay and the Netherlands the aid of Dutch experts was requested, taking advantage of the long standing record of expertise in flood protection and water management the Netherlands possesses. The Dutch Risk Reduction team, a team of experts that advices governments on how to resolve urgent water issues, was asked to give advise for resolving the urban flood issues while at the same time assisting in creating the directive for the national water plan. Working in this context, this thesis concerns itself with a subset of the advise, namely recommendations for the modelling of urban flooding as a consequence of heavy rainfall. It in particular focuses on understanding the flood processes that take place in this complex urban environment.

To give these recommendations a conceptual model was created and used. A conceptual model is essentially a blueprint for the construction of the model, containing all the necessary assumptions and methods of simulating the hydrologic processes. The challenges encountered during the creation of the conceptual model were used to identify the gaps in knowledge and to develop the recommendations. It was found that there is a lack of data, both in quality and availability. A section of the district lacks elevation data and the available measurements are distant from each other. The roughness coefficient, an important parameter for the flow of water, cannot yet be determined due to insufficient data on the surface shape and greenery. To cope with this a cell-based model has been recommended due to its usability and flexibility. It is usable in situations where the accuracy of data is low, while its flexibility allows for expansion in the future. A number of minor recommendations have been given in regards to the model, including the usage of simplified equations and the negligibility of smaller processes.

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In eternal gratitude
to my parents and grandparents

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Chapter 1

Introduction

Flood hazard has been called one of the most important and influential natural disasters to affect humans (Mascarenhas, Toda, Miguez, & Inoue, 2005). Flash- and river floods jump to mind when talking about important flood events, but another type of flood, urban flooding, is gaining importance. Urban flooding occurs when the surface runoff exceeds the capacity of the drainage system in an urban area (Nie, 2014). It is known to lead to the pollution of the environment, erosion of the soil surface and significant economic damage (Mark, Weesakul, Apirumanekul, Aroonnet, & Djordjevic, 2004; Nie, 2014; van Overeem & Steenbergen, 2015). Due to the increase in impermeable surface because of urbanisation combined with climatic changes, flood flows have become higher and "flashier" (Hollis, 1975). Stormwater drainage in urban areas often does not have the capacity to cope with this change and as a result there is an increase in the frequency with which urban floods occur (Huong & Pathirana, 2012). In the future this frequency is going to only increase, as simulations for a number of cities have shown that a combination of urbanisation and climate change will raise peak flow volume and increase flood risk (Semadeni-Davies, Hernebring, Svensson, & Gustafsson, 2008).

It does not come as a surprise that urban flooding has seen a lot of research over the past 30 years (see M. B. Smith (2006) for an excerpt of research papers in this field). Numerous papers concern the mathematical modelling aspect of urban drainage and flooding on topics such as dual-drainage and parameterisation (Hsu, Chen, & Chang, 2000; Huong & Pathirana, 2012; Leandro, Chen, Djordjevic, & Savic, 2009; M. Smith, 1993). Mathematical modelling has been described by Mascarenhas et al. (2005, p. 335) as "one of the most used ways to understand physical and environmental processes" and a very useful tool with which "one can get a whole view of what is taking place in the environmental system." It is an indispensable tool for the understanding, analysis, simulation and prediction of urban floods.

The simplification of reality to manageable simulations is an important aspect of mathematical modelling. Contrary to model code, which is defined as a generalised software package that can be used to create models, models are bound to a specific location (Refsgaard, 1996). The shape, complexity and contents of a model depend on the local features. Often practical factors limit the complexity and possible accuracy of models, forcing simplifications. Data is one of these factors. Depending on the availability and the detail of the data, simple or complex modelling approaches can be chosen. Detailed data warrants accurate and complex simulations of hydrologic processes, while incomplete or less accurate data sets pose another challenge, as reality has to be simplified conform to the detail level of the data. Researchers have taken different approaches to simplifications when modelling urban flooding for cities. Hsu et al. (2000) used a grid with two-dimensional simulation for the flood and simplified the sewerage flow to a network of links with one-dimensional flow. This approach of simplifying surface flow to two dimensions and sewerage flow to one dimension finds widespread use in urban flood modelling (Chang, Wang, & Chen, 2015; Hsu et al., 2000; Seyoum, Vojinovic, Price, & Weesakul, 2012; Takanishi, Noguchi, & Nakamura, 1991). Depending on the resolution (number of datapoints) and accuracy of the available data the surface flow is simulated with a denser (more accurate) or less dense (less accurate) grid. Mascarenhas et al. (2005) demonstrated another approach with one-dimensional simulation for both the surface flow and sewerage. The surface data of land and infrastructure is aggregated into homogenous "cells". This is a more extensive simplification of reality that can be used when less data is available.

1.1 Scope

While models for urban flooding have been created for numerous cities, no complete and validated model exists for Ciudad del Plata (van Overeem & Steenbergen, 2015). Ciudad del Plata is located in the south of Uruguay in South America, on the riverbed of the Rio de la Plata and in the delta of the Rio Santa Lucia. The city lies close to Montevideo, the capital of Uruguay. The basin of the Rio Santa Lucia houses 1.7 million inhabitants, which is about 50% of the total population of Uruguay.

Figure 1.1: Uruguay in South America

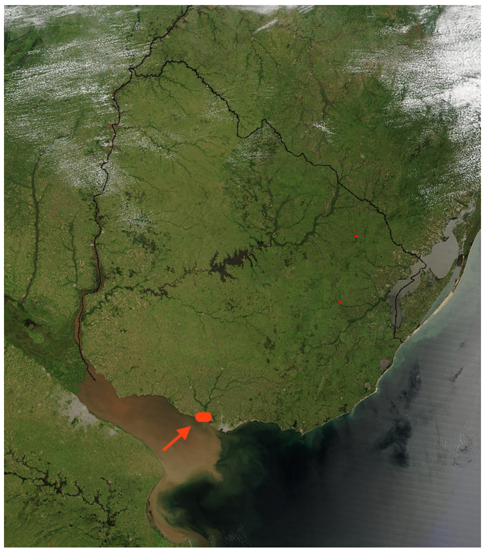

Figure 1.2: A satellite photo of Uruguay, Ciudad del Plata is highlighted

The city is a point of interest because it is being used as a pilot for a national water plan in Uruguay regarding drainage, potable water, sewerage and flood protection. Aside from Ciudad del Plata, two other cities participate in the gathering of information for the programme, but the situation in Ciudad del Plata is novel. It is the only city in Uruguay with dykes, while the Delta del Tigre district is enclosed by a dyke. This provides a challenging hydraulic and hydrologic situation when compared to the other cities. A dyke is barrier, meaning that it influences the flow of water. In this particular case it is for example an obstacle to the water that needs to flow out of the district during heavy rainfall.

There are two possible flood situations in Ciudad del Plata: either pluvial, as a consequence of rainfall, or fluvial, meaning riverine. Due to the low permeability of the soil, pluvial floods are frequent, occurring as many as five times a year (van Overeem & Steenbergen, 2015). The pluvial flooding event in Delta del Tigre is complicated by the presence of the dyke: in Delta del Tigre stormwater can only leave through culverts with non-return valves. When the water level outside the dyke rises, the gates close to maintain the integrity of the dyke, keeping water out. This blocks the outflow of water from the district as well, leading to quicker and heavier floods. Fluvial floods occur when southern wind blows the Rio de la Plata against the Rio Santa Lucia, forcing the water level in the Rio Santa Lucia to rise. Eventually the water overtops the dyke, flooding Delta del Tigre. Fluvial floods occur less frequently than pluvial floods: about once ever two years (van Overeem & Steenbergen, 2015).

The floods are an inconvenience and at times a danger to the residents. Moreover, a combination of both floods occurring at the same time leads to the largest inundations that are destructive (van Overeem & Steenbergen, 2015). Due to the dykes being relatively novel structures in Uruguay, the Uruguay government sought assistance from the Dutch government. The Netherlands has a long history of coastal flood and water management and has assisted other countries in the past. Especially the experience on dykes is valuable to Ciudad del Plata. To meet the request, the Dutch government sent the Dutch Risk Reduction Team, a team of experts that advices governments on how to resolve urgent water issues. The team was requested to provide support in the field of urban water management and flood protection, and to create a directive for the national water plan.

A part of the advise given by the DRR-team involves recommendations for modelling urban flooding. Director Nacional de Agua (the ministry of water, DINAGUA) seeks to better understand the key hydrologic processes behind the urban flooding in Ciudad del Plata. These include water routing, channel flow, surface runoff, culvert flow and eventual inundation of areas. It is also their wish to use models in the future as part of the design process for solving their urban water issues. While there have been first attempts at modelling the situation to better understand the flood dynamics, there is still much unknown.

1.2 Objective

This thesis aims to create a list of recommendations for urban flood modelling in Ciudad del Plata, which are a subset of the advise given by the DRR-team. The overarching objective is to aid DINAGUA in the creation of the national water plan by improving their understanding of key hydrologic processes.

1.3 Research questions

The research questions are as follows:

1. What are the key hydrologic processes of an urban flood in Ciudad del Plata?
2. How are these hydrologic processes linked?

3. What are the minimal data requirements for modelling the occurring urban flood?

1.4 Method

To achieve the objective and fulfil the purpose a *conceptual* model is used. The creation of a conceptual model is the step in the hydrologic modelling methodology that concerns itself with the understanding of hydrologic processes and their simplifications, containing among others assumptions and relations (Liu, Yu, Zhang, & Nie, 2011; Refsgaard, 1996). It is a blueprint for the creation of a model and serves well as a thorough analysis of the situation from which recommendations can be derived. More details on the form and contents of a conceptual model are given in section 2.3.

The Delta del Tigre district is used as the study area for the conceptual model. As the most complex area in Ciudad del Plata due to the dykes and its location next to two water bodies, it will be a representative area from which challenges and recommendations can be derived.

The steps that will be carried out are shown in table 1.1. Steps from the hydrologic methodology (appendix A) were combined with what authors perceived to be the contents of a conceptual model (Pace, 2000; Robinson, 2004).

Table 1.1: Method steps

Step	#	
Define purpose of the model.	**1**	**A.** Analyse the situation. **B.** Find out what the issue is. **C.** Derive the purpose of the model. **D.** List the model requirements.
Gather the necessary field data.	**2**	**A.** Find what the necessary data is. **B.** Compile the available data.
Create a conceptual model.	**3**	**A.** Derive the limitations that the data imposes on the model. **B.** List the key hydrologic processes. **C.** Analyse the boundary conditions in the system. **D.** Determine the assumptions that can be used in the model. **E.** List mathematical formulas and algorithms that can be used to describe these processes, constraints and boundary conditions.

Validate the conceptual model.	**4**	**A.** Validate the conceptual model's structure, logic, relations and processes. **B.** Validate the consistency. **C.** Validate the theories and assumptions.
Present the conceptual model .	**5**	**A.** Derive the recommendations for urban flood modelling.

1.5 Outline of thesis

Chapter 2 starts with a literature study that covers the hydrologic processes in general and gives an overview of urban flooding theory. At the end multiple works are used to define the conceptual model and establish its contents.

In chapter 3, the study area is then examined and the area's geography, climate, surface and soil are described. The chapter ends with the detailing of the urban flooding event as it is known. This details the features and descriptions of the locale that are necessary for the conceptual model.

Chapter 4 presents the conceptual model. The chapter is structured to mimic the first steps of the hydrologic methodology (definition of purpose and requirements, collection of data). Afterwards the contents are presented, including the choice of model, assumptions, processes and their simplifications. The chapter concludes with the currently known model parameters and the boundary conditions. The conceptual model is then validated in chapter 5.

The conceptual model and the recommendations are discussed in chapter 6. The final chapter, chapter7, concludes the thesis and sums up the most important findings, presenting possibilities for further research.

Chapter 2

Literature study

This chapter serves as a summary of the main principles in urban flood modelling. First an overview is given of the hydrologic processes that are involved and their definitions. The most important aspects of urban flooding are then treated, including dual drainage and ways that researchers have modelled different flow types. The recommendations will be derived from a conceptual model, so the final section uses previous research to define it and describe its contents.

2.1 Hydrology and process overview

Important hydrologic processes for floods are presented in this section. Figure 2.1 gives an overview of the processes that take place during an urban flooding event and their interactions, as described in Mascarenhas et al. (2005) and AMK Associates (2004). Processes that have a minor to non-existing influence on the flooding in Ciudad del Plata have been discarded from the figure to maintain focus and clarity. Because of that subsurface processes other than infiltration, such as percolation and groundwater base-flow have not been depicted. Furthermore, snowmelt has been left out due to the temperate climate in Uruguay. Section 3.1 gives more information on the geography and climate, and section 2.1 argues the removal of these processes from the (conceptual) model.

Definitions

Precipitation
: Precipitation refers to the liquid or solid phase aqueous particles that fall from the atmosphere to the earth's surface. It is also the amount of water that has fallen at a given point over a period of time (American Meteorological Society, 2012).

Interception
: Interception is "the process by which precipitation is caught and retained on vegetation or structures, which afterwards either reaches the ground as throughfall or is evaporated. As a general rule, this loss to runoff or stream discharge only occurs at the beginning of the storm." (American Meteorological Society, 2012)

Evapotranspiration
: Evapotranspiration is the combined process of evaporation and transpiration

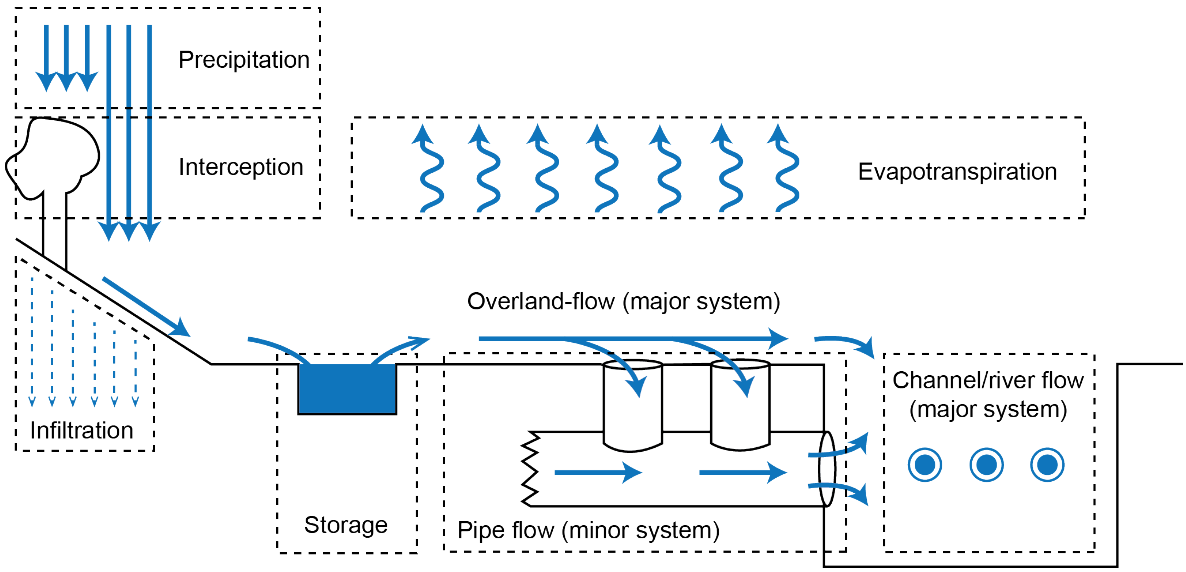

Figure 2.1: An overview of hydrologic processes during urban flooding. Groundwater flow has not been shown in the figure.

"through which water is transferred to the atmosphere from open water and ice surfaces, bare soil and vegetation that make up the earth's surface (American Meteorological Society, 2012).

Infiltration

Infiltration is the process with which precipitation or surface water passes through the soil surface into the lithosphere. Water that exceeds the infiltration capacity produces either overland flow or ponding at the surface (American Meteorological Society, 2012; Seiler & Gat, 2007).

Storage

More specifically depression storage, is the water that is retained in depressions in the surface of the ground. It eventually infiltrates or evaporates (American Meteorological Society, 2012).

Overland-flow

Not all the rainfall is transformed into overland flow. A part is lost due to interception, depression storage, infiltration and evapotranspiration (Butler & Davies, 2000). The *effective* rainfall that is left, or in other words the run-off component that did not infiltrate, becomes overland-flow and moves across the surface to the nearest entry point into the sewerage system.

2.2 Urban flooding

Urban drainage is the process of transporting waste- and stormwater outside the urban area and is directly related to urban flooding. Urban drainage is a relatively young science, having made large strides in development from the 1960's onwards (Lazaro, 1990; M. B. Smith, 2006). This section gives an overview of the principles of urban drainage and the important hydrologic processes that take place during an urban flood.

2.2.1 Dual drainage

An important aspect of urban drainage models is the division of the model into a sewer system and the surface flow above, also called *dual drainage*. According to AMK Associates (2004) urban stormwater drainage systems are composed of two distinct and mostly separate components, namely a surface and subsurface storm sewer network. The surface is the "major" system composed of street ditches and various channels designed to handle events of 25-100 year return frequency. The subsurface sewer network is the "minor" component, designed to carry the runoff from a storm of 2-10 years return frequency. The systems are linked curb inlets and manholes. This consideration of distinct surface flow and its interaction with sewer flow is denoted as "dual drainage modelling", see figure 2.2 (Schmitt, Thomas, & Ettrich, 2004).

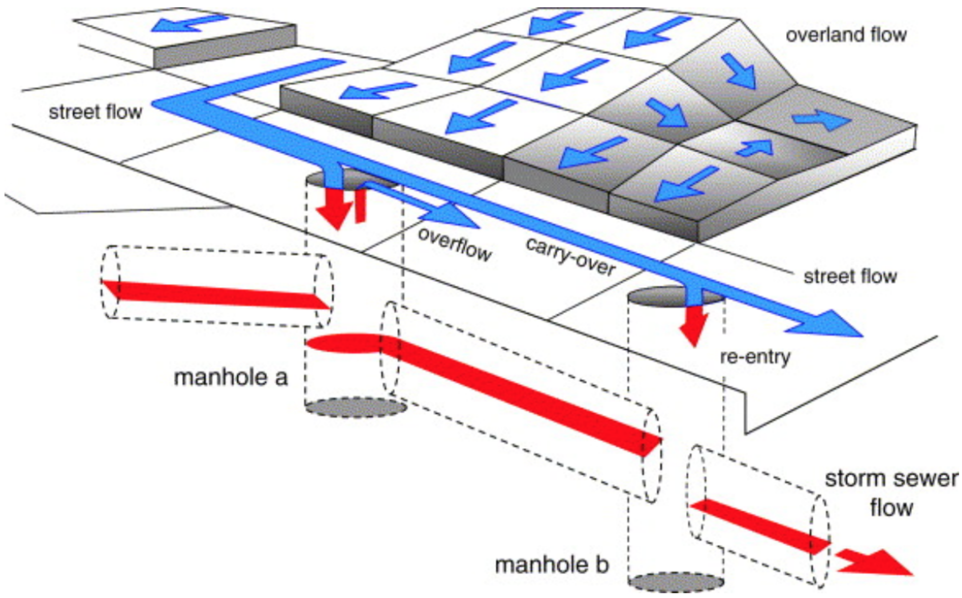

Figure 2.2: Idealised surface (blue) and storm sewer (red) flow components in dual drainage systems (M. Smith, 1993).

Minor drainage system

The minor system in dual drainage consists of conduits or pipes that intercept and receive water from houses, parks and street and conduct them to the major systems such as channels or rivers (AMK Associates, 2004; Mascarenhas et al., 2005). The sewerage system falls into this category.

Major drainage system

The major system is defined as the surface (streets, parks) and all pre-existing river channels and manmade channels. The rivers and channels are meant to receive waters from the minor system and overland flow. All surface flow falls into this category.

2.2.2 Processes

Channel and river flow

When in an urban area, channels and rivers are part of the major drainage system. Water from the minor system and overland-flow flows into the channels and rivers, after which the channel or river discharges it away from the city. During an extreme rainfall event the channels or rivers can overflow, inundating the neighbourhood. The water can follow other paths as well and flood lower areas (Mascarenhas et al., 2005).

Channel flow is often modelled in one dimension using the Saint-Venant equations (Mascarenhas et al., 2005). These equations have a number of assumptions (Mascarenhas et al., 2005):

- The flow is one-dimensional (velocity is considered uniform over the cross-section).
- The centrifugal effect due to the channel curvature is negligible.
- The pressure within the cross section is hydrostatic and vertical accelerations are ignored. The fluid density is constant and the water surface is horizontal in the transverse direction.
- The effect of boundary friction and turbulence can be simulated with a resistance force deduced for special flow conditions.

There are two governing Saint-Venant equations: the continuity equation (2.1) and the momentum equation (2.2) (Julien, 2002; Mascarenhas et al., 2005; Mujumdar, 2001).

$$\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} + i_b P - iW - q = 0 \tag{2.1}$$

In the continuity equation, i_b is the rate of infiltration through the wetted perimeter P, i is the rainfall intensity through the river width W, A is the cross-sectional area and q is the unit discharge of lateral flow. This equation is often simplified to the form of $\frac{\delta Q}{\delta x} + \frac{\delta A}{\delta t} = 0$ by assuming an impervious channel, no rainfall and no lateral inflow (Julien, 2002).

$$\underbrace{\frac{\delta Q}{\delta t}}_{\text{Local acceleration terms}} + \underbrace{\frac{\delta}{\delta x}\frac{Q^2}{A}}_{\text{Convective acceleration term}} + \underbrace{gA\frac{\delta h}{\delta x}}_{\text{Pressure force term}} - \underbrace{gAS_0}_{\text{Gravity force term}} + \underbrace{gAS_f}_{\text{Friction force term}} = 0 \tag{2.2}$$

In the momentum equation, h is the water height from the bottom of the river cross-section A. S_0 is the bed slope and S_f is the friction slope. In this particular form the momentum equation does not account for lateral inflow. Adding the necessary term, $\frac{q \cdot Q}{A^2}$, to the left hand side would fix that (Mascarenhas et al., 2005).

The momentum equation as seen in equation 2.2, also referred to as the dynamic-wave approximation of the Saint-Venant equation (Julien, 2002), is often modified for a more adequate application to practical engineering problems. Depending on the accuracy desired terms of the momentum equation are eliminated (Mujumdar, 2001). The mathematical aspect is simplified by eliminating parts of the equation, but these manipulations can lead to unrealistic flow representation when applied incorrectly (Mascarenhas et al., 2005). It is therefore important to understand under which conditions terms may be eliminated.

In many applications, when the velocities are slow and their variation in time are slow (approximating steady non-uniform flow), the local acceleration term is very small and can be neglected (Julien, 2002). The result is the the quasi-steady dynamic wave approximation. One of the applications where this is the case is a flood wave in a river (Mehaute, 1976).

Eliminating the convective acceleration term is acceptable when the flow is subcritical (Julien, 2002), leaving the diffusive wave approximation $S_f = S_0 - \frac{\delta h}{\delta x}$. The kinematic wave approximation is obtained when the pressure force term is also eliminated. This is acceptable when $\frac{\delta h}{\delta x} << S_0$. This condition is met with surface runoff, where the waterbody is sufficiently flat and the surface area large. Kinematic flow will be detailed more in the next section, where it is applicable.

Overland flow

Modelling overland-flow in an urban context is not a straightforward task. The urban landscape has features that interact with the flow in diverse ways. A number of examples are given in Mascarenhas et al. (2005): walls can act as weirs, streets as channels and parks as temporary reservoirs. Overland flow can be described by the dynamic-wave approximation, but it is adequate enough to assume that acceleration terms are negligible as flow over inundated urban flood plains is assumed to be slow and shallow (Seyoum et al., 2012). If the elevation in the flow direction is steep enough and the water depth shallow enough, the kinematic-wave theory may even be used (Miller, 1984).

The assumptions made in kinematic-wave theory can be summarised to the fact that Q is assumed to be a function of h only and that the other terms are negligible, so the equation becomes $S_f = S_0$. "Thus, the bed slope, S_0, is assumed to be large enough and the water wave long and flat enough so that the change in depth and velocity with respect to distance and the change in velocity with respect to time are negligible when subtracted from S_0" (Miller, 1984). These assumptions work for certain types of surface runoff, where a flat layer of water runs over a large area and the surface angle is steep. Mascarenhas et al. (2005) uses it for steep areas where water flows in one direction only and is not retained.

When a simulation in two dimensions is needed, the Navier-stokes equations can be used, averaging them over the depth (Seyoum et al., 2012). The Saint-Venant equations are derived from the more general purpose Navier-Stokes equations. The most important difference between these two sets is the complexity.

Surface and sewer link

The interaction between the surface flow and the sewerage flow is an important aspect of the dual drainage theory. When overland flow encounters an inlet or a manhole, the discharge that enters can be described in different ways, depending on the properties of the flow and the capacity of the entrance. When the velocity is high enough a part of the flow will “overshoot” the entrance, even if the capacity is sufficient. This limits the discharge that can enter. If the velocity is low enough and the water depth high enough, the capacity of the entrance can be fully used. Both reactions are different and are modelled as such. When simulating the discharge that enters a manhole, Mascarenhas et al. (2005) uses equations for weir flow when the water depth is low. Once the water depth reaches a threshold the discharge is described using a formula for orifice flow.

Water can also flow back through manholes and inlets onto the streets. This is the case when the capacity of the sewerage network has been exceeded. Water will be pushed upwards under pressure and overland flow cannot enter the sewerage system anymore.

Pipe flow

Flow in storm sewer pipes is characterised as either under pressure or free surface flow. When not operating at full capacity, storm sewers maintain a free surface and can be described in the same way as channels (Mascarenhas et al., 2005). This means that the Saint-Venant equations can be applied. Mascarenhas et al. (2005) even goes as far as simplifying pipe flow to free surface flow only, not considering pressurised flow. The applicability of the approach is demonstrated in multiple examples.

Which form of the Saint-Venant equations is used depends on the hydraulic effects that are desirable. Seyoum et al. (2012) recommends the dynamic-wave approximation, because of the importance of backwater effects and surcharge from manholes, while (Mascarenhas et al., 2005) ignores both phenomena and achieves acceptable results. The choice depends on whether surcharge, backwater effects and quickly changing water levels are significant to the outcome.

2.3 Conceptual model

The creation of a conceptual model is one of the steps in the hydrologic modelling methodology defined by Refsgaard (1996). He gives an overview of the whole modelling process (appendix A), but does not delve deeper into the definition or construction of a conceptual model. It appears that the construction of a conceptual model is the least understood stage in the modelling process (Law, 1991) and that there is discussion on what it exactly entails (Robinson, 2006). Robinson (2006) makes an attempt at unifying the different opinions. This section uses these findings to give a definition of the conceptual model, detail its contents and requirements and explore methods to validate and present it.

2.3.1 Definition

"Conceptual modelling is the abstraction of a model from a real or proposed system. This process of abstraction involves some level of simplification of reality..." (Robinson, 2006). Robinson (2006) summarises the key facets of conceptual modelling as follows: (a) the conceptual model is about moving from a problem situation, through model requirements to a definition of what is going to be modelled and how, (b) conceptual modelling is iterative, (c) the conceptual model is a simplified representation of the real system, (d) the conceptual model is independent of the model code or software and (e) the perspective of the client and the modeller are both important.

2.3.2 Contents

A conceptual model should include a description of the objectives, inputs, outputs, content, assumptions and simplifications in the model (Robinson, 2004). Pace (2000) adds algorithms, characteristics, relationships and data to this list.

Balancing According to Robinson (2006) a balance must be found in simplifying the conceptual model. While it is generally agreed that creating the simplest model possible is advantageous, there is are dangers in oversimplifying. A simple model can be difficult to embellish, hard to understand and often requires extensive assumptions.

2.3.3 Validation

A conceptual model is validated before moving onto the modelling steps to verify whether the logic and decisions made are sound. It involves "checking that the conceptual model is sufficiently accurate for its intended purpose" (Robinson, 2006). It is impossible to compare outputs to the real world, so other methods must be utilised. What is possible is comparing the choices with existing literature and having an expert validate the logic and simplifications. Moreover, expert validation is important due to the fact that a correct structure, logic and simplifications alone do not guarantee that the purpose of the model will be achieved. Thus validation of the conceptual model by an experienced professional is required to test the validity at this stage.

A comprehensive guide on conceptual model validation is given by Liu et al. (2011). It notes three important criteria for validity: (a) the conceptual model's structure, logic, mathematical and causal relations, and the processes need to be reasonably valid; (b) the conceptual model must be internally complete, consistent and correct; (c) the theories and assumptions must be correct.

2.4 Summary

An overview has been given of the most important hydrologic processes in urban flooding. Concepts in urban drainage have been explored and a definition with contents has been given for the conceptual model. Finally a method of validating the conceptual model has been examined.

In the following chapter a study of the area will be given, including the geography, climate, soil contents and surface characteristics. A description of the pluvial flooding event will also be given.

Chapter 3

Study Area

Ciudad del Plata is a city on the west shore of the Rio Santa Lucia and on the coast of the Rio de Plata in Uruguay (figure 3.1).

Figure 3.1: Ciudad del Plata, Rio de la Plata and the Rio Santa Lucia (map data ©2015 Google).

Ciudad del Plata is is built up of multiple districts. Figure 3.2 shows a map of the city. The Delta del Tigre district is located in the east, close to the location where the Rio Santa Lucia flows into the Rio de la Plata. A close up of the district can be seen in figure 3.3. It is a residential area that is protected by a dyke against flooding from the Rio Santa Lucia. The dyke surrounds most of the district (figure 3.4).

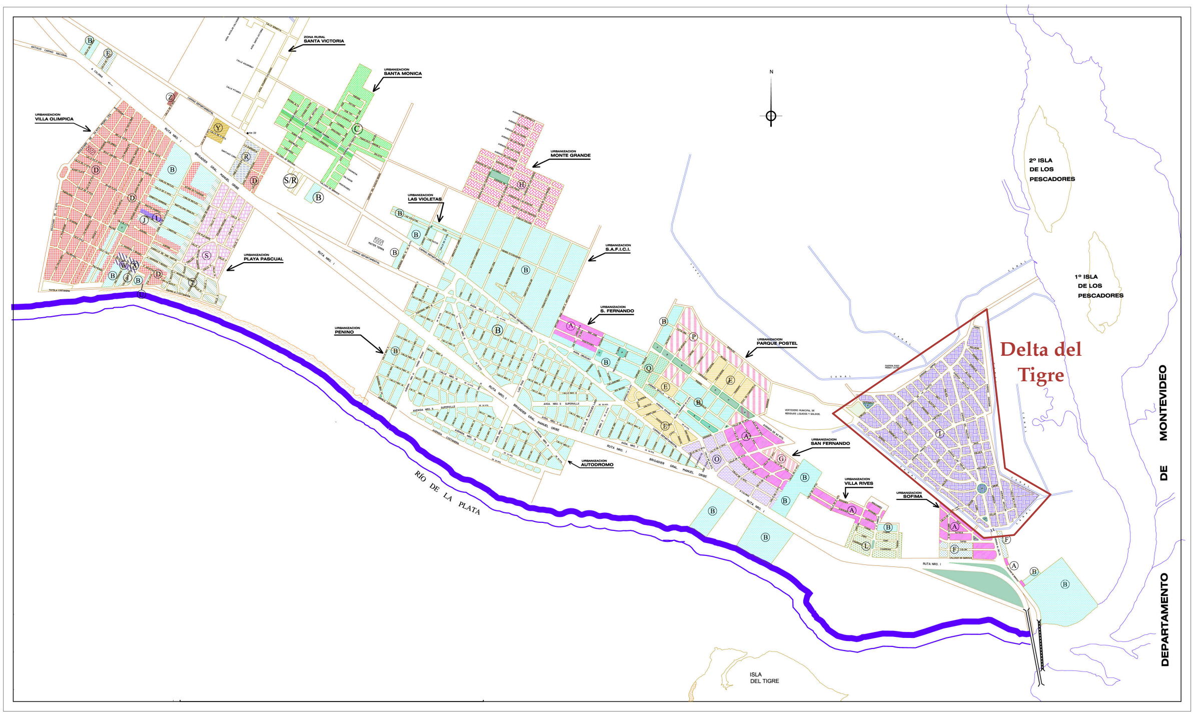

Figure 3.2: An overview of Ciudad del Plata, with the dyke in the south is represented by a blue line. The Delta del Tigre is delineated with a red line in the east. Retrieved from www.ciudaddelplata.org.

Figure 3.3: A map of the Delta del Tigre. Source: DINAGUA.

3.1 Geography

The direct environment of the Delta del Tigre like most of Uruguay, is best described as rolling plateaus. An important characteristic of this environment is the absence of mountains, the hills in Uruguay rarely exceed an elevation of 200 metres. As a result the city is vulnerable to high wind and sudden shifts in wind direction (Hudson & Meditz, 1990).

The elevation of the Delta del Tigre is mostly flat, with the few elevated areas illustrated in figure 3.4. The highest point is located in the west and it encloses the Delta del Tigre together with the dyke, making the district a low point surrounded by elevated features.

Figure 3.4: A map of the Delta del Tigre with yellow height lines. The dots are measurement points on the roads and the red line surrounding the district represents the dyke. Based on material provided by DINAGUA.

3.2 Climate

The climate in Uruguay is uniform nationwide and the whole country is located in the temperate zone. According to the Köppen climate classification the country has a humid subtropical climate. The criteria for this classification are a temperate zone, the absence of a dry season and a hot summer with temperatures exceeding twenty-two degrees centigrade (Peel, Finlayson, & McMahon, 2007). The seasonal variations are pronounced, but extremes are rare. There is an abundance of water in the country and high humidity and fog are common. Rainfall is evenly distributed throughout the year. Montevideo, located 20 kilometres away from the Delta del Tigre, averages 950 millimetres of rainfall annually (Hudson & Meditz, 1990).

3.3 Soil

The composition of the soil in Ciudad del Plata has not been mapped yet. It can however be constructed from the description of the flooding event by DINAGUA (van Overeem & Steenbergen, 2015) and the experiences of the DRR-team (van Overeem & Steenbergen, 2015). According to DINAGUA precipitation does not infiltrate, but immediately ponds or becomes surface runoff. The DRR-team describes the soil in Ciudad del Plata as mostly clay-like with loam in some areas. It can be assumed that the whole area of Ciudad del Plata, except for the sandy beaches, consists of impermeable soil (van Overeem & Steenbergen, 2015).

The dyke on the shore of the Rio de la Plata and the dyke surrounding the Delta del Tigre consist entirely of very silty clay or loam.

3.4 Surface characteristics

A large portion of the surface in the district is made up of buildings and roads. A significant portion of the roads is not asphalted but still impermeable due to the soil. Sidewalks and curbs are absent and there are few other features to keep the water on the roads. There is no stormwater drainage system, so rainfall that falls on buildings is not intercepted. Neither is water stored on roofs as most of them are pitched.

Surface that is not built on or covered by a road is covered in grass. Trees are present and surround most houses. The district is best described as moderately green, with but a few small sections where no grass or trees grow. The dyke on the other hand and its immediate surrounding area, including the channels, is overgrown with tall grass.

3.5 Urban drainage

Precipitation that falls onto the surface runs off to channels on both sides of the road. They act as the stormwater drainage system in the quarter that guides surface runoff to the outer channels next to the dyke (these small channels are referred to as drainage channels from now on). When a drainage channel has to cross a road it runs through a culvert underneath.

On the inside of the dyke in the Delta del Tigre another channel is located (referred to as the main channel). In the main channel the water level is low, about 5 to 10 centimetres (van Overeem & Steenbergen, 2015). Precipitation in the Delta del Tigre flows into the inner channel either through overland flow or the drainage channels, and is then discharged through culverts in the dyke into a channel outside the district. Non-return valves are located at the end of the culverts (figure 3.5). These allow stormwater to be discharged from the channels inside Delta del Tigre to outside the dyke, but prevent the reverse from happening.

Figure 3.5: A photo of the non-return valves, taken from the side of the Rio Santa Lucia. Source: DINAGUA

3.6 Flooding event

A number of things happen once a rainfall event starts. This section describes the processes and the sequence of events that occur. An illustration of the whole process and the failure mechanisms can be seen in appendix B.

Depending on where the precipitation lands different events start, some of which are interconnected. Part of the precipitation will be intercepted by shrubs, grass and greenery in general. This water will leave the urban flood event by evapotranspiration. The rest of the precipitation will fall to the surface, where in this particular case it will not infiltrate due to an impermeable surface. The water will immediately run off and become overland flow. Overland flow can interact with the environment in a number of ways.

For one, it can become depression storage. In certain locations water can get stuck and stay there until it evaporates (including buildings it enters). Precipitation that falls into a depression storage will stay there as well. The capacity of the depression storage can be exceeded, in which case the storage will overflow. Overland flow can also erode the soil, as is the case in certain locations in Ciudad del Plata.

Eventually the overland flow will flow into drainage channels or the main channel at the circumference of the Delta del Tigre. At the beginning of the extreme rainfall event the drainage channels are able to cope with the flow and guide it, through the channel and culverts under roads, to the main channel. When the channel flow becomes large enough to either exceed the capacity of the channel or the capacity of the culverts, local inundations will occur. When the main channel overflows, the drainage channels will overflow as well and inundation will occur not only next to the main channel, but also around the drainage channels.

Both the drainage channels and the main channel also receive water from precipitation. During the course of the rainfall event the discharge in the channel increases and the water level rises rapidly according to locals (van Overeem & Steenbergen, 2015). More accurate descriptions or measurements are not available.

A failure mechanism known to occur is the blocking of the non-return valves at the end of the culverts in the dyke. When the water level outside the dyke rises the non-return valves close and block the water flow through the culverts. Such a situation occurs when the Rio Santa Lucia goes beyond its banks and floods the area east of the Delta del Tigre, but more often occurs even before that due to the outside channels filling up with rainwater. The valves prevent the stormwater inside Delta del Tigre from exiting through the culverts.

3.7 Summary

The study area has been analysed. It became apparent that the geography and the dyke keeps the water from leaving the district freely, while the soil keeps the water from infiltrating. The flooding event has been described and failure mechanisms have been identified.

In the next chapter the conceptual model will be described. As the conceptual model is a blueprint for the model, the purpose of the model is first decided after which the requirements will be given. After an analysis of the available and necessary data the conceptual model design is described, including assumptions and boundary conditions.

Chapter 4

Conceptual model

This section covers the design of the conceptual model and begins with the purpose and requirements. An ideal and an available dataset are given, from which limits to the model become clear. With these limits in mind, a conceptual model structure is presented. The other sections detail the modelling of the hydrologic processes, their simplifications and the assumptions that were made. Constraints and boundary conditions are presented in the last section.

4.1 Model purpose

The model, that the conceptual model serves as a blueprint for, has a purpose that needs to be taken into account when creating the conceptual model. The final model must improve the understanding of hydrologic processes during urban flooding events in Delta del Tigre. To that end the hydrologic events must be simulated adequately. It is not the purpose of the model to give the most accurate simulation of every single hydrologic process during the flooding. Instead it must correctly simulate the general behaviour of the processes and their interaction. These interactions are important when trying to understand the behaviour of the whole system during an urban flooding event. Thus the conceptual model must be created with this purpose in mind.

It must be noted that the validation of the purpose is only partly possible as the conceptual model provides no output. This validation will be carried out in chapter 5 by means of validation by an expert.

4.2 Requirements

To fulfil the described purpose, the model must meet a number of requirements. For the Delta del Tigre, based on the area study in chapter 3, a number of interactions between hydrologic processes are considered requirements if the model is to simulate the situation correctly.

- The model must give the inundation depths in Delta del Tigre for the whole duration of the rainfall event as output.

- The model must simulate:

– the influence of the dyke, culverts and gates on the flooding process.
– The open water drainage channels.
– The lateral inflow into channels from overland flow.

4.3 Data

The disparity between required and available data is used in the section to highlight limitations that the currently available data has on the model.

4.3.1 Required

The required data set is described in table 4.1:

Table 4.1: Required data with preferred, ideal criteria

Description	Ideal criteria
General map	Includes dimensions of the area.
Infrastructure	Includes the dimensions of channels, culverts, the dyke, roads and houses.
Elevation map	Covers the whole area of the Delta del Tigre with measuring points no further from each other than 5 metres.
Hyetograph for extreme rainfall event	Rainfall measured every minute.
Hydrograph	During the same period as the rainfall event, for the culverts in the dyke.
Channel data	Initial channel depth estimate and friction values. If not already determined from the elevation: accurate slope measurements.
Inundation depths	Inundation depths for districts for the same period as the rainfall event.

4.3.2 Available

The available data is scarce. Maps describing the landscape and infrastructure are available and contain the necessary information. GIS data files that contain dimensions of sectors in Delta del Tigre have been provided by DINAGUA.

4.3.3 Limitations

The hydrologic processes will have to be simplified to not create a level of perceived accuracy that exceeds the maximum achievable with the available data. The limited elevation data has the greatest impact on the shape of the model. As described in table 4.2, the elevation is only available for the roads and a gap exists where no measurements have been taken. Detailed simulations are unfeasible due to the large distance between every measurement point and the fact that areas between roads have not been

Table 4.2: Available data

Description	Details
General map	Contains dimensions of areas and lengths of the road.
Elevation map	Covers most of the map, but skips a significant part in the east. Measurement points are about 20 to 25 metres apart and are located only on roads.
Dyke elevation	The dimensions of the dyke are measured every 90 metres.
Hyetograph	Rainfall measurements are available for Montevideo and can be used for Delta del Tigre.

measured. For example, the suggested data resolution for two dimensional overland flow simulation in urban areas is no higher than 5 by 5 meters (Leandro et al., 2009). Above that the averaging will create an inaccurate and possibly incorrect representation of the area.

4.4 Choice of model

Due to the limitations imposed by the data a cell-based structure has been chosen for the model. In a cell based model, the study area is divided into "cells" that group together areas in which the major properties of geometry, hydraulic behaviour, land and topography are almost uniform (Mascarenhas et al., 2005). In such a fashion, parks and open spaces close to each other are grouped into a single cell. The flow between cells is simulated in one dimension and the flow path is defined beforehand.

A cell-based model is flexible in the sense that it can represent a large diversity of links between cells. These cells and links can be used in different ways to ensure that the hydrologic behaviour represents what happens in reality. This approach can make use of the dual-drainage concept by using links to connect the cells to the drainage system. Furthermore, the model naturally averages areas, making it useful even when detailed data is not available.

While the water between cells is not bound to a direction (it can flow from a to b abd from b to a), it is bound to to a single flow path. The definition of flow paths is a critical step in creating the model. Thus the flow paths must be defined based on observations and measurements of surface height.

4.5 Assumptions

A large number of assumptions have been made, not only to adapt to the low availability of data, but also to keep the model only as complex as is warranted. A full list of the assumptions and a detailed argumentation on them can be found in appendix C. This section lists and arguments the most important assumptions that have the biggest impact on the conceptual model.

Cell-based model Usage of the cell-based model requires a number of assumptions. The most important ones relate to the fact that a cell homogenises a section of the study area. Thus it is assumed that cells can represent nature in homogenised sections and that every property inside is the same, including the water level. The flow between cells is assumed to occur without the influence of inertia terms. This allows for the discharge to be modelled as a function of the difference in water level height between two cells. The cells are connected through links that simulate the flow using hydrologic processes such as channel flow and weir flow. Using different types of links allows for the simulation of different kinds of flows.

The inertia terms, consisting of the convective term and the local acceleration term, are not considered, because the assumptions that have been made to adapt to the available data do not warrant the detail that the dynamic-wave equation with inertia terms would give. The uncertainty in the assumptions and data is too large for that. While not preferable, the disregarding of inertia terms in river and channel flow is acceptable (Julien, 2002; Mascarenhas et al., 2005; Miller, 1984).

Dual-drainage Assumptions have been made on the basis of dual-drainage modelling theory. Flow in the study area is assumed to occur in two layers: the surface layer and the drainage layer, mirroring the *minor* and *major* division that is characteristic for dual-drainage. The drainage layer includes only the drainage channels and their culverts (their function is to intercept water and conduct it to major flow systems), while the surface layer contains the surface and main channels surrounding the district. This division has also been made to simplify the cells in the model, as demonstrated in figures 4.1 and 4.2.

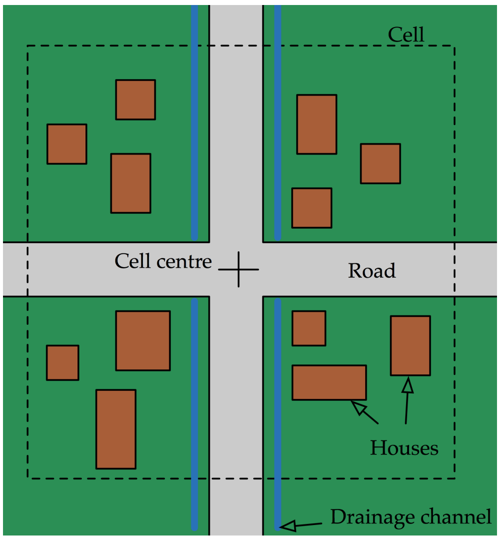

Figure 4.1: Proposed cell layout.

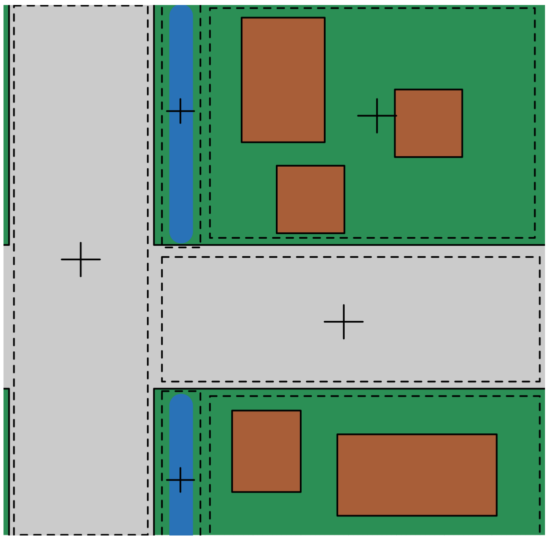

Figure 4.2: Alternate layout for single layer (non-dual drainage) approach.

The interaction between the layers happens through links that simulate weir flow, using equations that are similar to tresholds. The interaction is visualised in figure 4.3. The assumption that weir flow equations approximate the flow between the surface and drainage channels is based on the similar use in Mascarenhas et al. (2005), where weir flow equations are used to approximate the flow into channels in an urban area. Using channel flow would be physically incorrect as the difference in water levels between the surface and the channel is large due to the shape of the channels.

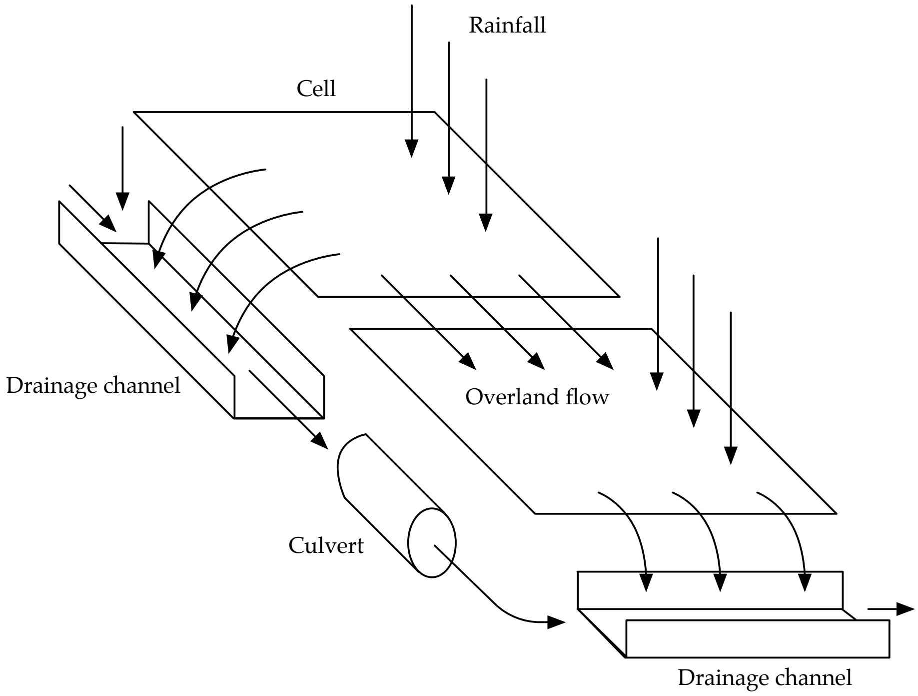

Figure 4.3: Overview of the interaction between plain cells and the drainage layer.

The difference between drainage channels and main channels needs some more clarification. Due to their functions they have been put into different layers, but the interaction between surface cells and channel cells is in both cases the same. Weir flow is in both cases assumed as the approximation of the flow. Figure 4.4 gives an illustration of cells and their interactions.

Negligible processes Important assumptions have been made regarding infiltration, evapotranspiration and interception. All three processes are assumed negligible. Due to the composition of the soil infiltration is assumed to not occur. Interception only occurs at the beginning of the event, and is insignificant when looking at the intensity and length of the rainfall.

4.6 Model design

This section covers the actual design of the model and includes the elements (cells and links) that make up the model, their visualisation and their mathematical description. Model parameters are derived from the design and mathematical representation. The section ends with the boundary conditions and constraints.

4.6.1 Cells and links

To create the model according to the assumptions, the following cells have been defined:

Plain cells

These are homogenous areas on the surface that also act as reservoirs to simulate inundation. Plain cells can be used to represent single features in an area, such as a park or a house, but can also be applied on areas that are assumed homogenous, such as a housing district. The grouped features need to present similar characteristics that justify the grouping into a cell.

Channel cells
These cells represent channel reaches. Both the main channels and drainage channels are represented by these cells. When representing drainage channels, the cell takes the shape of *one channel* with the same height and combined width of all the drainage channels in the plain cell. Thus a single channel cell represents all the drainage channels that are located in the plain cell.

Next to the cells, a number of links have been defined to simulate the different flows between cells:

Channel link (diffusive-wave)
This link represents the flow between surface cells.

Culvert link
This link is used for the flow in drainage channels when a culvert is present and for the main channels when the flow passes through the dyke. The culvert is simulated by applying a head loss to the diffusive-wave equation.

Weir link (threshold link)
This link is used to approximate the transition of flow from plain cells to drainage channels, where a part of the water flows into channels and another part becomes overland flow.

Figure 4.4 shows how the cells and links are connected with each other.

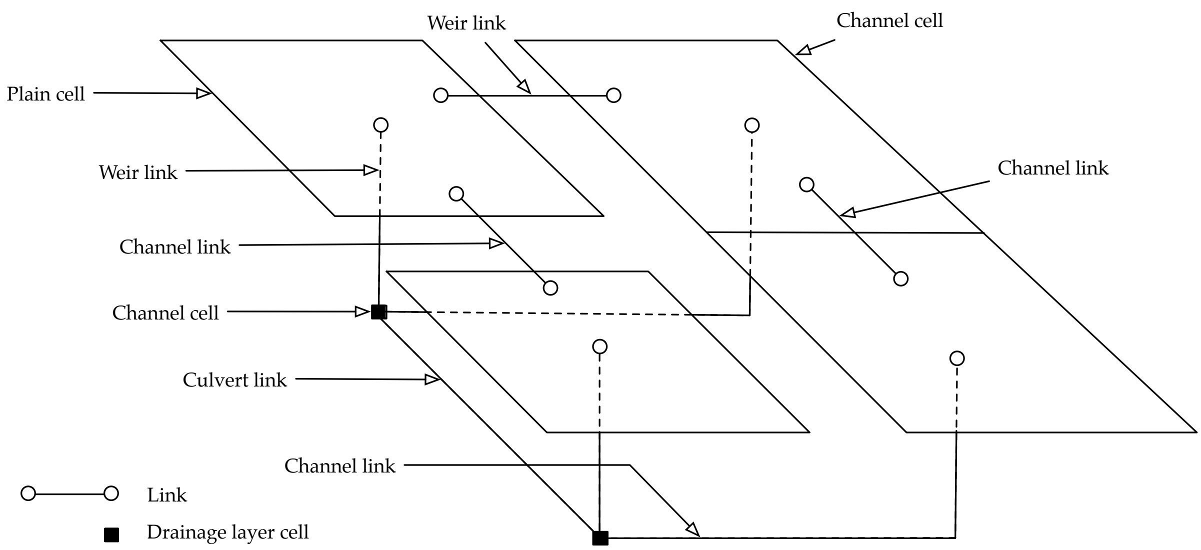

Figure 4.4: An overview of the cells and their links.

4.6.2 Structure of hydrologic processes

The hydrologic processes (links) and infrastructure (cells) are all interconnected. This results in a complex network of cells and links. Figure 4.5 visualises in a simple manner how the hydrologic processes are involved in the model.

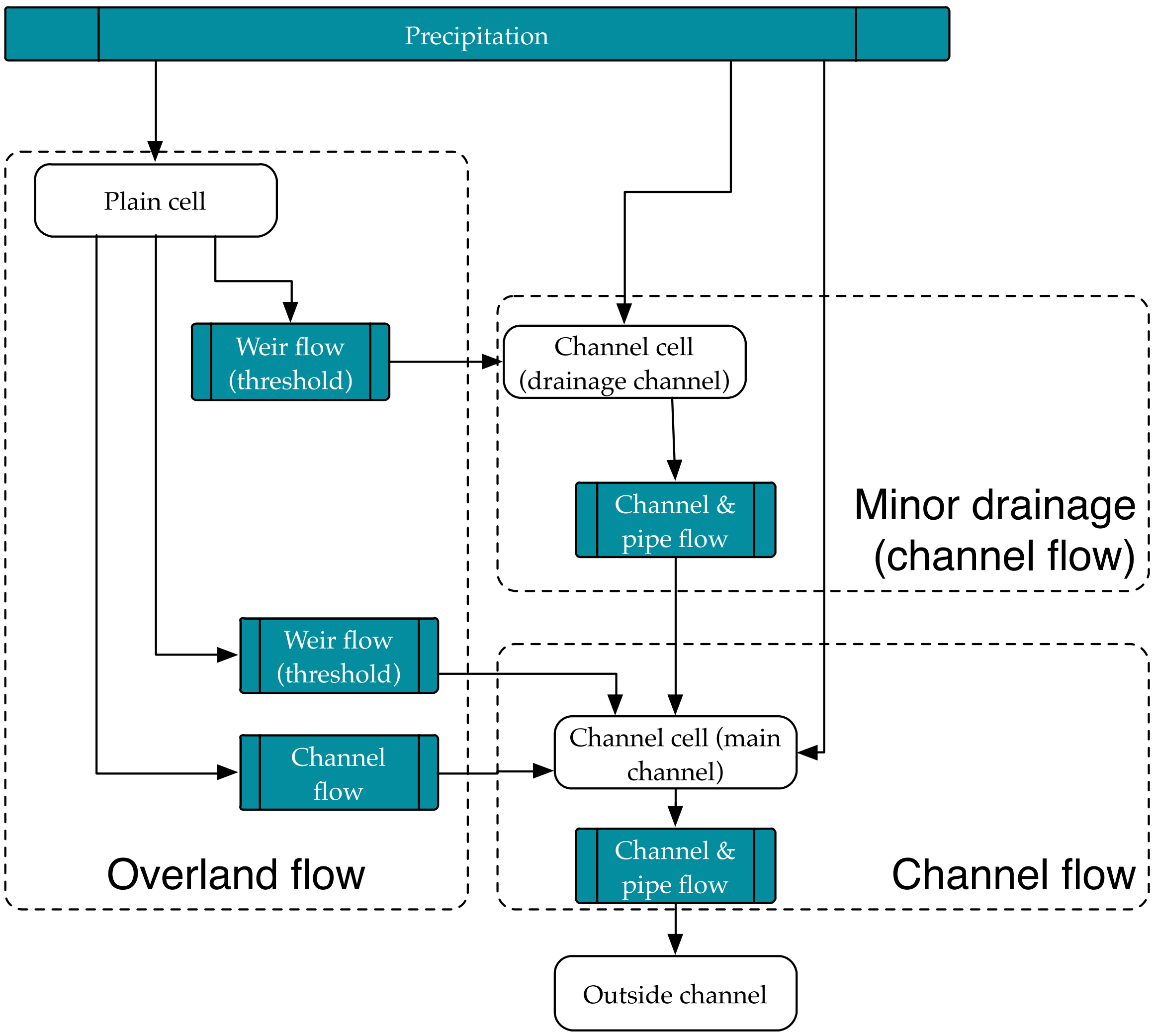

Figure 4.5: Visualisation of model structure, where green cells are the hydrologic processes and white cells the elements in the study area.

The plain cells, together with the weir- and channel flow links are the overland flow. The network of plain cells and channel flow links make up the surface runoff, where water flows between the plain cells and causes the inundation. The weir flow links that act as thresholds represent the water flow into the main channels and the minor drainage system. The minor drainage system is a network of channel cells, representing the (small) drainage channels in the area, and the channel (channel flow) and culvert links (pipe-flow) that connect them. Both the overland flow and the minor drainage system connect to the main channels. These guide the water outside the study area through the culverts in the dyke.

4.6.3 Description and mathematical representation

Cell balance

The water mass balance applies to cells. The integral continuity equation is as follows (Mascarenhas et al., 2005):

$$A_{S,i}\frac{dZ_i}{dt} = P_i + \sum_k Q_{i,k} \tag{4.1}$$

where $A_{S,i}$ is the water surface area of the cell, Z the water elevation in the cell, P_i the rainfall flow over the cell and $Q_{i,k}$ the exchange between adjacent cells. The flow is positive when water flows into the cell, thus in the flow direction from cell "k" to "i".

The (possible) inflows $Q_{i \to k}$ for channel cells are: (a) the overland flow from adjacent plain cells, (b) the lateral flow from drainage channels and the flow from the previous or next channel cell, depending on the flow direction.

The (possible) outflows $Q_{i \leftarrow k}$ are: (a) the flow to the next or previous channel cell, depending on the flow direction and (b) the flow to the adjacent plain cell as a result of the channel overflowing.

Channel flow

The equation for channel flow is used for both channel flow as well as the one-dimensional overland flow. When simulating the flow between drainage channel cells it represents the combined flow of all the drainage channels. By adjusting a coefficient the equation is made to mimic the complex flow properties of the flow between cells. The coefficients have to be calibrated for each link and each water level in a link. The channel flow is described by the following equation, derived from the diffusive-wave equation:

$$Q_{i,k} = \phi_R \sqrt{|Z_k - Z_i|}\frac{Z_k - Z_i}{|Z_k - Z_i|} \tag{4.2}$$

where $Q_{i,k}$ is the discharge from cell "i" to cell "k", $Z_k - Z_i$ the difference in water level between the cells and ϕ_R the river flow coefficient. The coefficient is adjusted by trial and error during the modelling process to correctly simulate the flow. The initial values are calculated beforehand for different water levels using:

$$\phi_R = \frac{A_{i,k}R_{i,k}^{2/3}}{n\Delta x^{1/2}} \tag{4.3}$$

where $A_{i,k}$ is the wetted area, $R_{i,k}$ the hydraulic radius, Δx the distance between two cell centres and n the Manning coefficient. Since the water level between the cells is different an estimate must be made for the water level in the link:

$$Z_p = \alpha Z_i + (1 - \alpha)Z_k \tag{4.4}$$

where Z_p is the weighted elevation and α is the weighting factor between 0 and 1. Setting α to $1/2$ will yield the average water level between the two cells.

Weir flow – treshold

Weir flow is used to simulate the discharge from overland flow into the drainage channels. Due to the cell-structure of the model and the assumptions made in regard to flow between cells and layers, the channel flow equation was physically not preferred to simulate the discharge between layers. As can be seen in equation 4.2, the river flow coefficient ϕ_R is used to calibrate the flow properties for channel flow. This coefficient is based on the wetted area, the hydraulic radius, the manning coefficient and the distance between cell centres.

The coefficient and its parameters are not suited for the discharge to drainage channels. There are multiple drainage channels of varying length per cell. The coefficient and its parameters do not physically account for this, even if the discharge can possibly be simulated correctly with trial and error.

The weir flow equation has a better representation of the flow between plain cells and drainage channels. It prevents the water in the cell from completely flowing into the channels at the start of the event, simulating the initial buildup before the flow becomes significant. A single weir link is used to represent the combined flow into all the drainage channels in a cell. The equation is used in Mascarenhas et al. (2005) to simulate water flow into manholes and the flow over curbs. The equation for free flow, when the drainage channel has not yet overflow, is as follows:

$$Q_{i,k} = \begin{cases} \mu_1 b\sqrt{2g}(Z_i - Z_c)^{3/2} & Z_i > Z_k \\ \mu_1 b\sqrt{2g}(Z_k - Z_c)^{3/2} & Z_i < Z_k \end{cases} \tag{4.5}$$

Where b is the effective spill width of the weir, μ_1 is the discharge constant, g is the gravitational constant and Z_c is the elevation of the spillway crest. Z is the water level of either cell "i" when the flow direction is towards the channel, or the water level of cell k, when the flow direction is towards the plain cell. The effective spill width b accounts for the length of the drainage channels in a cell. The discharge constant then has to be calibrated for the links.

Once the water depth in the drainage channels exceeds the channel height, the weir becomes "submerged". At this point the following equation applies for the flow:

$$Q_{i,k} = \begin{cases} \mu_2 b\sqrt{2g}(Z_k - Z_c)\sqrt{Z_i - Z_k} & Z_i > Z_k \\ \mu_2 b\sqrt{2g}(Z_i - Z_c)\sqrt{Z_k - Z_i} & Z_i < Z_k \end{cases} \tag{4.6}$$

where μ_2 is the discharge coefficient.

Culvert head loss

When a drainage channel passes a road, the flow is guided through a culvert. Not only does a culvert have a maximum discharge, it it also a source for head losses due to a quick constriction in the wetted area. The presence of culverts is important as the flow is constricted, thus influencing the possibility of a flood.

The head loss for a single culvert can be expressed by the following equation:

$$S_l = \frac{K(v_b^2)}{2g} \tag{4.7}$$

where S_l is the local head loss, K the head loss coefficient, g the gravity acceleration and v_b the velocity in the culvert.

All the drainage channels in a plain cell are represented by a single link, but the same cannot be done for the culverts. Trying to simulate all the small culverts in a cell by a single large one will result in incorrect behaviour of the flow. A solution is to calculate the head loss for a single culvert, in a single drainage channel, and then multiply that head loss by the amount of culverts in a plain cell.

This link is used for the culverts in the dyke as well, until the gates close, after which no flow occurs through those links.

4.6.4 Model parameters

Table 4.3 displays the model parameters that will have to be calibrated in further steps. This calibration will have to be done for every link, as all the parameters influence the flow in one particular link. The discharge coefficient will also have to be calibrated for every (weighted) water level in the link.

Table 4.3: Model parameters

Parameter	Symbol	Unit
Discharge constant (channels)	$\phi_{R,i}$	-
Weir coefficient	$\mu_{d,i}$	-

4.7 Boundary conditions and constraints

The identification of boundary conditions and constraints is part of the conceptual model. A boundary condition is a specific type of constraint at the boundary of the domain in the system. Mathematically there is no difference between boundaries or constraints.

The boundary conditions are as follows:

- The flow between cells and the dyke is zero.
- The infiltration, evapotranspiration and interception in cells is zero.
- The flow between cells and the border of Delta del Tigre in the North-West (higher elevation that represents the boundary of Delta del Tigre) is zero. Thus water does not leave the premises of Delta del Tigre by other ways than the culverts in the dyke.
- The discharge through the culverts in the dykes is locked to the discharge data for them (in other words the discharge through a culvert is a certain tabulated value that is not modelled).

The only constraint is:

- Water flows only along a predefined path.

4.8 Summary

This chapter has given a description of the conceptual model, from the purpose to the boundary conditions. A choice was made for a cell-based model divided into two layers based on the dual-drainage methodology. Cells and links have been defined that are applicable to Delta del Tigre and equations were given.

The next chapter will discuss the conceptual model that was presented here.

Chapter 5

Validation

The validation of the conceptual model is done according to the outlines given by Liu et al. (2011) in section 2.3.3: first the conceptual model's structure, logic, mathematical and causal relations, and processes are checked for validity. This is done by reasoning the usage with the help of existing literature and comparing the decisions made with other works. Second the conceptual model is validated to be internally complete, consistent and correct. This is done by comparing the contents with what has been put forward by Robinson (2004) and Pace (2000) and by searching for contradictions in the model. Finally the theories and assumptions are validated by using existing literature. The opinion of an expert is used as an extra and final validation of the conceptual model. The criteria are covered in three sections, while the fourth section is on the expert validation that has been carried out.

5.1 Structure

The model's structure, logic, mathematical and causal relations and the processes need to be reasonably valid.

Cell structure and logic ✓ The model's structure, described as cell-based, is similar to what commercial modelling packages use for one-dimensional simulation, where the model is described by "nodes" and "links" (for an example, see the SOBEK Suite by Deltares). The division of the model into a two layers has a theoretical basis in dual-drainage, but an important difference must be noted. Dual drainage divides subsurface pipe flow from surface flow, a much clearer division than what is done in the conceptual model in this thesis. The drainage channels are actually part of surface flow, but have been simplified to another layer, limiting the interaction between the drainage channels and the surface. Due to the similar function of the drainage channels and pipe-based subsurface stormwater drainage (conducting flow to major systems) this simplification is seen as reasonably valid.

Relations ✓ The mathematical and causal relations between cells are based on physical phenomena. They have been simplified to account for the more complex flow interaction by means of parameters. The initial values for the parameters are based on the properties of the flow container, making for a valid representation of the flow.

A point of discussion is the simplification of two dimensional overland flow to one dimensional equations. This decision has a theoretical basis and is deemed acceptable, but it puts great importance on a good analysis of the paths that water flows in, as a wrong definition of flow direction will result in large inaccuracies.

Processes ✓ The description of the processes during urban flooding has been based on observations by DINAGUA and the descriptions of the situation in the DRR-team report. While not all the processes have been included (notably the reservoir behaviour of flooded houses has been left out), the important processes with the most influence on the urban flood have been accounted for.

5.2 Content

The conceptual model must be internally complete and consistent.

Completion ✓ The conceptual model accounts for all the described processes and describes all aspects of the conceptual model including: objectives, inputs, outputs, assumptions and simplifications. The algorithms that describe the flow, the characteristics of the flow and the relationships between cells have also been given. The required and available data sets have also been detailed.

Consistency ✓ The model does not contradict itself, nor does it deviate from the assumptions made. All relations are based on known hydraulic laws and conform to the mass and momentum conservation principles.

5.3 Assumptions

The theory and assumptions used in the conceptual model must be correct.

Theory ✓ The theory used is based on a multitude of authors and works, predominantly Mascarenhas et al. (2005) and Julien (2002). No changes that would violate basic principles have been implemented.

Assumptions $\sim$ Every single assumption made is based on either basic principles, experience of professionals, or research done by other authors. In that sense they are reasonably valid. What must be mentioned is the accuracy of the model as a result of the assumptions. Many of them are necessary to get a physically realistic representations of flow in the system with the available data, but with every assumption a new margin of error is gained. The accumulation of those errors is a risk that will have to be validated in the final model. As can be seen in figure A.1 in the appendices, the hydrologic methodology is an iterative process where the conceptual model might need adjustments after the final stage has been completed. Due to this uncertainty it is not warranted to say that the validation of the assumptions is final and correct. An analysis at this point in time does not show any inconsistencies or errors.

5.4 Expert validation

For the validation of the conceptual model an expert in the field was necessary, as there is no possibility of comparing outputs to real world data, meaning that there is a reliance on experience to judge the validity. This particular model has gone through the necessary validation by experts of the DRR-team before being presented. The validation of the structure, content and assumptions presented in this chapter has also been approved.

5.5 Summary

The conceptual model has been validated by judging three criteria: the validity of the structure, content and assumptions. The conceptual model and the validation itself have also been judged by experts. While it is impossible to provide a definitive validation as there are no outputs to compare, a preliminary validation has been completed.

The next chapter is the discussion of the conceptual model. The ability to construct the model with existing software packages and the flexibility of the conceptual model will be discussed.

Chapter 6

Discussion

This chapter first discusses the process by which the conceptual model was created. Second the usage of the model is discussed, including the flexibility and ability to use existing software packages to construct it. Finally the findings and results are discussed.

6.1 The process

The process with which the conceptual model came to be was complicated in a number of ways. First of all it was impossible to do first hand observations of the study area and floods. There was a reliance on the observations the DRR-team gathered, some of which also were not first hand. The validity and usefulness of the results stand on the validity of these observations. It would be useful for future research to consider carrying out and documenting observations.

The second complication was in the form of communication. Due to a difference in time zones it was difficult to directly contact the people involved from Ciudad del Plata, making for a slower and more difficult exchange of information. A trip to the study area would have facilitated a quicker exchange and would have given the opportunity to observe the area. Such a trip is recommended when further research is carried out.

6.2 Use of conceptual model

The conceptual model is flexible enough to adapt to most changes in the assumptions and boundary conditions. It is also applicable in different areas under different circumstances. This is due to the cell- and link-based nature of the model. Depending on the necessary simulation, different cells and links can be defined. A cell can be made to simulate infiltration, interception and evapotranspiration by adding the necessary links to the cell. The cell itself can be changed in size to adjust the accuracy of the model, and other cell types can be defined for different situations. An example of a possible cell type is one for hilly areas with pure runoff. These cells do not inundate due to the steepness of the surface and only transfer rainfall to plain cells.

It is possible to test designs with this model, as the cells and links can be adapted to simulate different solutions to flooding problems. Infiltration areas can be simulated with extra links and retention areas can be simulated with an extra cell-type. The flexibility for adapting the model to different regions, and testing solutions to flooding problems is present But the model has one aspect that is inflexible, and that is the predefined flow paths. Due to the one dimensional nature of the conceptual model it is impossible to study the dynamic propagation of a flood wave in a flat environment.

It is feasible to use existing software packages to construct the model. The conceptual model has great similarities to the "node" and "reach" approach used in SOBEK, a software modelling package by Deltares. It should be noted that while very similar, SOBEK does not by default have all the links and cells that can be conceived using the conceptual model, but these can be constructed and added by the modeller to the package. In general, 1D modelling packages will allow the creation of a network of nodes and links, similar to the approach proposed in this thesis. Notable examples apart from SOBEK are SWMM and MIKE Flood. Default hydrologic behaviours are easily simulated with the existing packages, but the conceptual model has a notable capability that requires custom nodes which may not be available. It is possible to simulate complex hydrologic reservoirs by linking volumes in cells to certain discharges in an empirical way, thus simulating for example the retention of water in buildings.

6.3 Results

The creation of a conceptual model has led to a number of findings. It allowed to determine the significant hydrologic processes for an urban flood event in Ciudad del Plata and to establish their relations. But the understanding of these processes and their relations has room for improvement. With more accurate observations on the flow paths and inundated sections in the district the dynamics of the flood can be better understood. A better analysis of the soil would allow for a more accurate estimation of the infiltration.

The findings in general represent the knowledge of the flood we have with the limitations of data that are currently present. The creation of the conceptual model allowed the identification of these limitations and the derivation of the data that is needed for a model. It is expected that with the gathering of data our understanding of flood dynamics will improve, but it is unlikely that the identified processes and their relations will change in shape so much that most assumptions and recommendations become invalid. Many assumptions and decisions have been made with the help of existing literature and are applicable to many situations, not just Ciudad del Plata. The general applicability of the model and the assumptions is a boon for its usage, since it is expected that it will be used in situations with different levels of quality of data.

Chapter 7

Recommendations

Below the most important findings and recommendations for DINAGUA are detailed.

Observations

It is important to observe and document the flood behaviour more. Things to observe would be how quickly the drainage channels fill, at what moment in time the capacity of the main channel is exceeded, where the water is held up, how deep the inundations are, in what areas they occur and along which paths the rainwater flows after hitting the ground. This general behaviour of the flood needs to be documented, as it is usable for the validation, allowing for a comparison between model behaviour and the documented flood behaviour.

A possible method of observing would be using satellite images, but since the floods occur during heavy rainfall clouds can block the visibility. Other possibilities include arial observations from airplanes and observations from the ground using people. If the choice is made for arial or satellite observations it might be possible to combine the observations with the improvement of elevation data. In such a case a spatial resolution of at most 5 by 5 metres is recommended. For the best observation of the flood dynamics a temporal resolution in the tens of minutes is recommended (Liu et al., 2011).

Data

The model needs more data than is currently available. Data should be gathered on discharge for culverts in the dyke, channel flow estimates and inundation depths. The location of the drainage channels should be mapped. It is also necessary to gather data on the roughness of the surface and the greenery, so that an important parameter for the flow, the roughness coefficient, can be estimated. This can be done by describing the study area in regions of a particular roughness coefficient. Thus the area is divided into regions of possibly heavy overgrowth, small vegetation, dense grass, asphalt and others. Having either pictures or aerial coverage would allow to estimate the necessary roughness coefficient. A useful guide for the estimation of roughness coefficients in flood plains by means of photographic footage is presented by George J. Arcement and Schneider (1989).

The elevation measurements are not accurate enough. The eastern part of the district has not been mapped and of the section that has been, only the roads have been measured. Not only are measurements for the whole district necessary, they are also needed for the area between the roads. Furthermore, the distance between measurement points is currently around 30 metres, while a distance of five is recommended for urban flood simulations (Leandro et al., 2009). Such measurements are best done with either a satellite or an airplane and it is recommended to follow the advice given in Leandro et al. (2009) and aim for a resolution lower than or equal to 5 by 5 metres.

It should be made sure that the data for the rainfall event, the discharge through the culvert and the inundation depths in the study area are for a single flood event. The time scale of the measurements should be in the tens of minutes, not more (Liu et al., 2011). While the discharge in culverts can be measured with local instruments, the inundation depths require arial or satellite footage.

Model structure
A cell-based model is recommended due to its flexibility and usability with data sets of different accuracy levels, including less accurate ones. The model can evolve together with the data as it becomes more complete and accurate.

Dual-drainage
It is recommended to apply the dual-drainage principle and divide the model into two layers with the drainage channels in a separate layer from the surface flow. This simplifies the model in a manner that mimics the dual-drainage principles of separating minor flow from major flow.

Negligible terms
For the flow simulation between cells, it is recommended to disregard the inertia terms as the accuracy is not warranted and increases the complexity of the model.

For the infiltration, evapotranspiration and interception it is recommended to assume them as not occurring, as they are insignificant processes for the duration of the flood.

Threshold
It is recommended to use the weir flow equation, which acts as a threshold, to simulate the surface flow into channels. This prevents the water in the cell from completely flowing into the channels at the start of the event, simulating the initial buildup before the flow becomes significant.

Boundary conditions
It is recommended to use the surrounding dyke and higher elevation in the west as the boundaries of the system. For an urban flood event these separate the flow in the Delta del Tigre, the only connection to the outside being the culverts in the dyke. This allows for the use of the discharge in the culverts as boundary conditions for the system. These are convenient since measuring them is simple.

Chapter 8

Conclusions

The thesis was set out to aid DINAGUA in the creation of a national water plan by creating a list of recommendations for urban flood modelling in Delta del Tigre. To this end a conceptual model was created. The process was challenged by a lack of accurate data. Modern developments in flood modelling were applied to a situation where data is scarce. By combining cell-based modelling with dual-drainage principles a physically valid conceptual model was created.

This chapter starts with concluding remarks on the process, then moves onto the limitations of the thesis. The findings are summarised and the chapter ends with opportunities for further research.

8.1 The process

The process of creating the conceptual model was complicated by the distance to the study area, difficulty in communication with institutes in Uruguay and lack of accurate information on the geographic features, infrastructure, weather conditions and descriptions of the flood processes. The information and data that was available was limited. It was only weeks into the process of writing this thesis that the last parts of the necessary information were received. This can be attributed to the different time zones, that forced the communication to occur through mail messages. It can also be attributed to the little amount of time that was available to important parties to dedicate to this research. These difficulties did not have a major impact on the result, as the literature research took longer than expected, filling the gap that resulted from the delay in receiving data.

There was a setback in the aspect of planning. It was assumed that the literature research performed in the preliminary report dedicated to this thesis would be enough to start. This proved to be false, as during the course of creating the conceptual model it became apparent to the author that more knowledge on hydrologic models was necessary. Thus more time was spent on the reading of flood theory.

8.2 Limitations

The thesis has a number of limitations, the first of which is concerned with the methodology itself. To give recommendations a conceptual model was constructed. The validation of a conceptual model is a difficult task and impossible to carry out definitively before having created the final model itself. This is due to the fact that a conceptual model does not produce any output that could be compared with real world data. Thus, while a validation has been carried out, including a check by a professional engineer, it is not definitive. This means that the conceptual model might have to be adjusted after it has been used to create the final model, therefore possibly changing a number of the recommendations. The largest uncertainty can be attributed to the recommendation on the model shape, such as the number of necessary dimensions for flow modelling and the negligible terms in equations.

Another limitation must be mentioned, which is the author. As this is a Bachelor's thesis, the knowledge and experience available to the author is limited. These limitations were mitigated by relying on existing literature and by consulting with supervisors. The format of a Bachelor's thesis also imposed a maximum amount of time that could be allotted to the thesis. This resulted in a narrower scope, limiting the study area to the Delta del Tigre and the format of the methodology to that of a conceptual model instead of a full model.

These limitations can be overcome in future research. By not limiting the scope to that of a conceptual model, it is possible to finish a single iteration of the hydrologic methodology. This will allow for a definitive validation. It is therefore also recommended to not limit the time span to that of a Bachelor's thesis, as ten weeks will prove to be too little time.

8.3 Findings

From the conceptual model a number of recommendations were derived. First were the recommendations relating to the data. The documented observations on flood dynamics and the resulting inundations were found insufficient and the available data, such as the one on elevation, was not as complete and accurate as necessary. It was recommended to improve both the observations and the measurements, and directives for doing so were given.

Further recommendations were concerned with the structure of the model and the simulation of the water flows. A cell-based, one-dimensional model structure was recommended due to applicability in situations with less accurate data sets and its flexibility. The dual-drainage principle was found to be applicable and useful for the study area. Moving the drainage channels into another layer simplifies the cell network, lowering the complexity of the model.

During the creation of the conceptual model it became apparent that the available data and consequent model accuracy does not warrant the inclusion of a number of smaller terms in the equation for simulating the flow between cells. It was therefore recommended to not include the two smallest terms in the Saint-Venant equation, a recommendation that can stay valid even for more accurate models due to the relatively small size of these terms when compared to the other ones in the equation. It was also recommended to assume a number of hydrologic processes as non-existent, namely the precipitation, evapotranspiration and infiltration. These processes are insignificant during the course of the flooding events in Delta del Tigre.

Another recommendation related to the simulation of water flow between cells was the use of the weir-flow equation as a "threshold" between plain cells and channel cells to better simulate the behaviour of a cell and its interaction with channels. A convenient system boundary at the dykes was recommended, since the discharge through the dyke culverts can then be used as a boundary condition.

8.4 Further research

A number of future research opportunities can be found in this thesis. The directives that were given for the improvement in data can be used to conceive and carry out a plan. There is also the possibility of narrowing down the requirements for the data, such as the exact resolution of data necessary to accurately simulate the flood dynamics. An investigation can be launched into the effect of cell size on the simulation accuracy, or at how well the model behaves at very small cell sizes.

An obvious opportunity and the next step, is to construct the model, calibrate and validate it. This will also allow for a conclusive validation of the conceptual model.

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APPENDICES

Appendix A

Hydrologic methodology

Refsgaard (1996) provides a comprehensive overview of the hydrologic methodology and gives a number of useful definitions, see figure A.1.

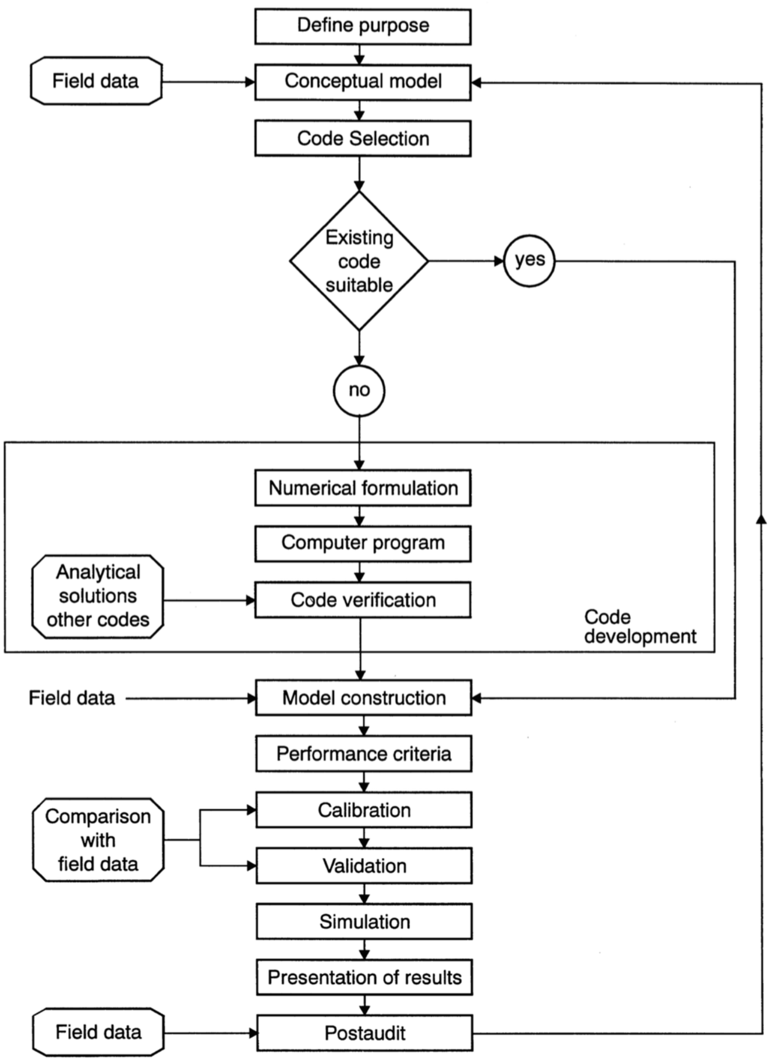

Figure A.1: An overview of the different steps involved in hydrologic modelling (Refsgaard, 1996).

Appendix B

Failure mechanisms for flooding in Delta del Tigre

This appendix serves as an illustration of the hydrologic processes that occur during a flooding event in Delta del Tigre. Figure B.1 lists the symbols that are used in the illustrations. Figure B.2 gives an overview of the hydrologic processes during a rainfall event, while figures B.3 and B.4 show two prominent failure mechanisms for the flood.

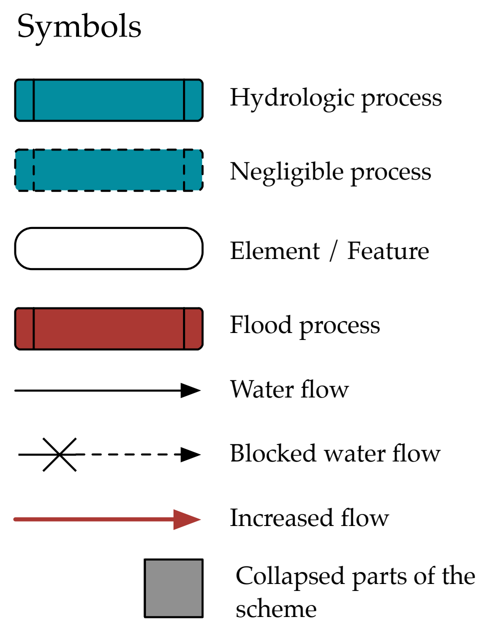

Figure B.1: Symbols used in illustrations

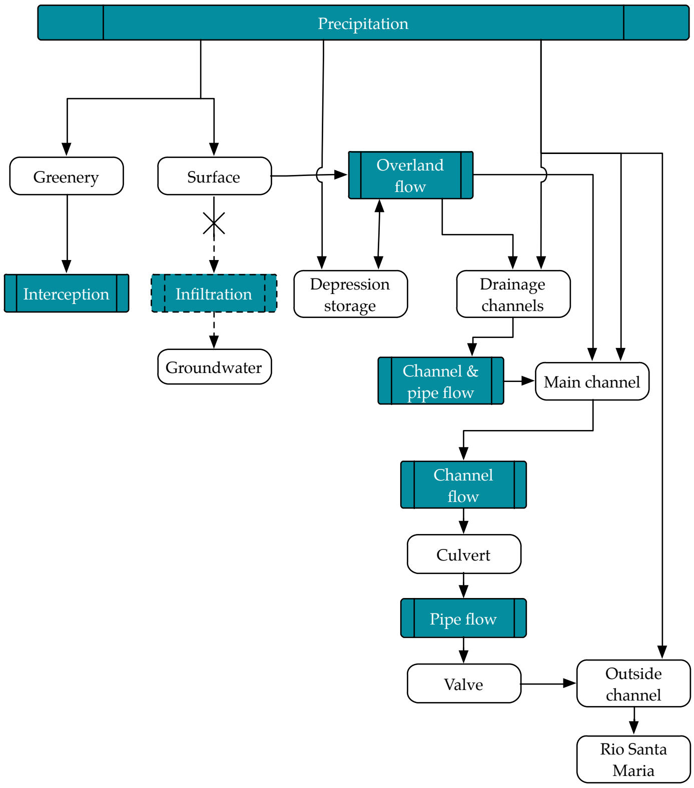

Figure B.2: Overview of hydrologic processes in Delta del Tigre during a rainfall event. Evapotranspiration has been left out for clarity.

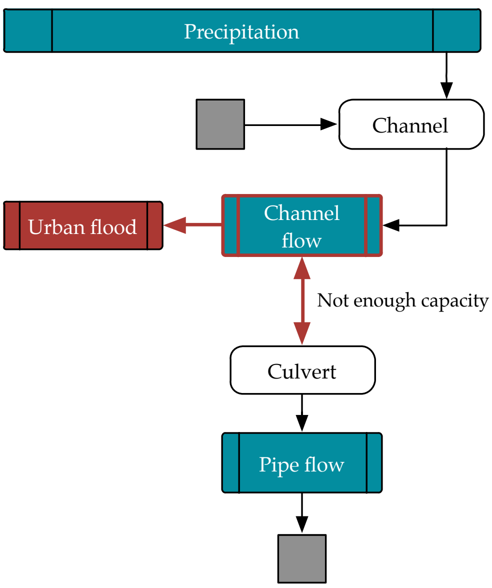

Figure B.3: Drainage system failure due to low capacity of the culvert

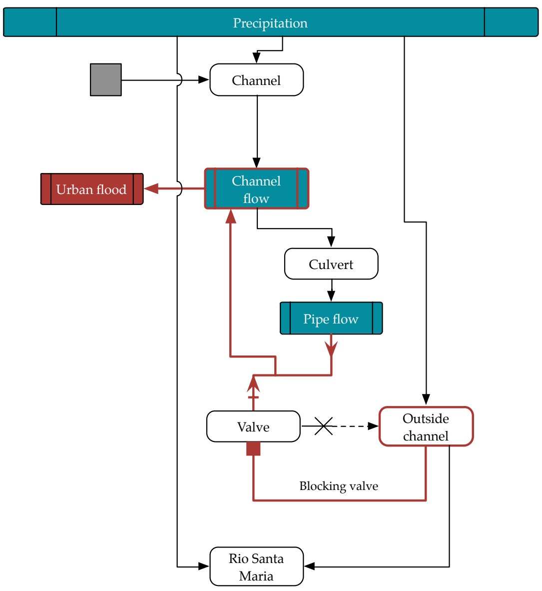

Figure B.4: Drainage system failure due to the non-return valves not functioning

Appendix C

List of assumptions

This appendix lists the assumptions of the model. An explanation is given where the reasoning needs clarification. The basic assumptions for the use of a cell-based model structure are as follows (Mascarenhas et al., 2005):

1. Nature can be represented by cells that interact with each other.
2. The water surface in a cell is horizontal.
3. The water volume inside a cell is directly related to the water level at its centre.
4. The basic principles of mass and momentum conservation govern the flood movement.
5. The flow between cells can be calculated from known hydraulic laws.
6. Flow equations are taken in their one-dimensional form.
7. The inertia terms in flow between cells are not considered. The discharge can then be defined as a function of only the water level Z_i inside the cells: $Q_{i,k} = Q(Z_i, Z_k)$.

A number of other assumptions has been made with respect to the open channel stormwater drainage in Delta del Tigre:

8. The flow is assumed to occur in two decoupled layers: the surface layer with overland flow and the "drainage layer" with channel flow. The main channel is placed in the surface layer while the drainage channels are placed in the drainage layer.
9. A drainage channel cell represents all the drainage channels that are located in a plain cell.
10. The flow into channels is described through a weir flow equation.
11. Excess water from channels is returned to the surface flow.
12. The channel profile is the same over the length of the channel, with the exception of culverts in the channel.
13. The inertia terms for flow in channels are not considered.

14. A culvert in a drainage channel can be simulated by applying an equation for head loss to the channel flow.
15. The Manning's roughness coefficient between two cell centres can be determined by performing a weighting for the vegetation type where the flow occurs. The coefficient is the same over the length of the flow.

Further assumptions are:

16. Infiltration, evapotranspiration and interception are negligible.
17. The dyke is schematised as a wall through which no flow occurs, except through culverts (lateral in- or outflow on cell borders next to the dyke is zero).
18. Rainfall has the same intensity over the whole study area.
19. Rainfall that falls on buildings becomes overland flow.
20. The geometric shape of cells is a square.

C.1 Argumentation

7 - inertia terms for overland flow

The inertia terms for overland flow are not considered for two reasons: (a) it simplifies the equations and subsequent matrix that has to be solved and (b) inertia terms are small for overland-flow and can be assumed insignificant. The overland flow is therefore represented by the diffusive-wave approximation. The kinematic-wave approximation has not been used as it is more suited for areas with varying elevation, such as surface runoff from hills to rivers (section 2.2.2).

8 - layers

The decoupling of the system into layers mirrors the dual-drainage system described in section 2.2.1. Instead of separating the surface and subsurface flows, the overland flow is separated from the flow in drainage channels. With this assumption drainage channels are considered part of the minor drainage system (section 2.1). This allows for coarser cells, because otherwise the drainage channels would split large cells into many small ones (compare the proposed cell layout in figure 4.1 with figure 4.2). Smaller cells result in a more accurate model, but are more complex to model and require more data than is available. Elevation measurements in particular are not plentiful enough to warrant such a detailed model.

The main channel is not considered a part of the drainage layer, but rather is part of the surface layer (major drainage system). This division into minor and major drainage systems mimics the function of the channels. The drainage channels are meant to convey water from the streets and parks to the major drainage system, which is the main channel.

An overview of water flows between cells and layers can be seen in figure 4.3. Part of the precipitation that falls on the soil flows from the surface layer into the drainage channels. Another part becomes overland flow and flows to the neighbouring cell. The water that stays in the cell is the inundation of that area. When the drainage layer overflows the excess water is returned to the surface cell, this has not been depicted in the figure, just as evapotranspiration.

10 - weir flow

To correctly model the overland flow into channels the weir flow equation was chosen. It approximates the real-world behaviour where a part of the overland flow flows to another cell and a part flows into the channels. The big jump in water levels between surface cells and channel cells would, at least in the initial stages of the simulation, lead to error when using other hydraulic representations such as channel flow. A similar choice for the weir flow approximation was made in Mascarenhas et al. (2005) to simulate the flow into manholes and the discharge of overland flow over curbs into rivers.

12 - channel profile

The profile for the channels in Delta del Tigre can be assumed the same over its whole length as the change in profile dimensions is insignificant. The transition from channels to culverts, where the profile changes significantly, is handled by a transition link that accounts for abrupt enlargements or constrictions.

13 - culverts

It is assumed that the most important aspect of the culvert for the model, the abrupt constriction of the flow, can be adequately modelled as a local head loss in the channel. Mascarenhas et al. (2005) uses a similar approach for underground galleries that abruptly constrict or enlarge.

15 - inertia terms

The inertia terms, consisting of the convective term and the local acceleration term, are not considered for the flow in channels, because the assumptions that have been made to adapt to the available data do not warrant the detail that the dynamic-wave equation with inertia terms would give. The uncertainty in the assumptions and data is too large for that. While not preferable, the disregarding of inertia terms in river and channel flow is acceptable (Julien, 2002; Mascarenhas et al., 2005; Miller, 1984).

16 - negligible processes

Due to the composition of the soil in Delta del Tigre the infiltration is negligible. The loss to runoff as a consequence of interception only occurs at the beginning of the storm. This loss is also insignificant when looking at the intensity and length of the rainfall event. Evapotranspiration in general is not significant for urban runoff during a rainfall event.

18 - spatial variability of rainfall

Urban catchments are sensitive to spatial differences in rainfall intensity, even more so when impermeable surfaces are investigated (Pechlivanidis, McIntyre, & Wheather, 2008). However, the variability caused by the rain gradient, when a rainfall event covers the whole area, is insignificant (Tokay, 2012). Considering the scale of the study area (small) and the intensity and scale of rainfall events in Uruguay (large), it can be assumed that the only spatial variability is caused by the rain gradient, and thus it can be assumed that rainfall intensity is the same over the whole area.

19 - roofs

Water that falls on a building is assumed to immediately turn to overland flow. This is because nearly all roofs are pitched and a stormwater interception system is absent from buildings. This also means that storage on roofs is assumed negligible.

20 - cell geometry

The layout of the roads and districts in Delta del Tigre is regular enough to forego the use of the more computationally intensive and mathematically difficult prismatic cells (Mascarenhas et al., 2005) and use square cells.