Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

TESINA

Títol

Modelling Runoff Interception in 1D-2D Dual Drainage Models

Autor/a

Jose Manuel Torcal Trasobares

Tutor/a

Manuel Gómez Valentín - Beniamino Russo

Departament

Enginyeria Hidràulica, Marítima i Ambiental

Intensificació

Enginyeria Hidràulica

Documento

Memoria

Data

Junio de 2014

Modelling runoff interception in 1D-2D dual drainage models

Jose Manuel Torcal

TU Delft – UPC Barcelona Tech

Academic year: 2012-2013

Delft University of Technology

Escola de Camins
Escola Tècnica Superior d'Enginyeria de Camins, Canals i Ports
UPC BARCELONATECH

Master Thesis (Tesina Final de Carrera)

Modelling runoff interception in 1D-2D dual drainage models

Jose Manuel Torcal Trasobares June 2014

Ingeniería de Caminos, Canales y Puertos ETSECCPB (UPC) & Exchange Student at TU Delft

Supervision:

Prof. Dr. Ir. Clemens	Delft University of Technology
Ir. Spekkers	Delft University of Technology
Prof. Dr. Gómez	Universitat Politècnica de Catalunya
Prof. Dr. Russo	Escuela Universitaria Politécnica de La Almunia

PREFACE

This thesis is the result of the graduation research for the degree of Ingeniería de Caminos, Canales y Puertos, done during an exchange programme at the faculty Civil Engineering and Geosciences of Delft University of Technology.

I would like to thank all those people who have supported me accomplishing this study. First I would like to thank my supervisors in Delft: Francois Clemens and Matthieu Spekkers. They have led me during my first steps in the field of Research and they are a good example of efficiency and understanding.

I would like to thank my supervisors in Barcelona: Manuel Gómez and Beniamino Russo for their comments, support providing data and flexibility when dealing with international bureaucracy, even when being on holidays.

Thanks also to the engineers that help me to fight against the Nile's crocodile: Ir. Johan Post and Prof. Dr. Ir. Olivier Hoes from TU Delft, Ir. Geert Prinsen and Ir. Edward Melger from Deltares. The model would have not worked without their help.

Y por último, aunque no por ello menos importante, gracias a mi familia. Gracias a mis padres por enseñarme los valores de trabajo, respeto y coherencia. Hay cosas que sólo se aprenden en casa, y ellos lo ejemplifican cada día. Gracias a mi hermana por ser fuente inagotable de cariño, ten paciencia porque espero poder hacer más viajes de esos que te ponen nerviosa. Y gracias al resto también, a los que no están aquí pero están entre nosotros, y a los que no estando entre nosotros dejaron su huella en mí.

The content of the thesis is the sole responsibility of the author.

Jose Manuel Torcal Trasobares, June 2014

EXECUTIVE SUMMARY

Flooding in urban areas is the one of the main natural hazard for the largest cities worldwide. This circumstance combined with an increasing urbanization and the uncertainty of the effect of climate change has led to a more extensive use of urban flood models. Between the multiple available options, this research focuses in the so-called 1D-2D dual drainage models. This approach describes the flow in the sewer system as one-dimensional and the flow in streets as two-dimensional. The interaction between streets and sewer pipes is also considered and here it is where the “dual” part comes. Zooming in this interaction, this thesis deals with the process of intercepting the water that flows in the street during a rain event and conveying it to the sewer system. This process is done by drain inlets, which are holes located in the streets, covered by metal grates, which drain the surface flow.

The aim of this thesis is to *study to what extent a “1D-2D” dual drainage model can reproduce the process of runoff interception by drain inlets*. In order to study this process, two research questions are studied:

1. *How can the runoff interception by drain inlets be modelled using commercial software packages?*
2. *What level of detail in roughness and topography is it desirable to mimic the runoff interception process in a 1D-2D dual drainage model?*

The two questions are answered using a model in SOBEK, which is an integrated software package with different modules for river, urban or rural water management. In this model the cross section of a street is modelled, spilling different set of discharges and measuring the drain flow intercepted by a drain inlet under different conditions of slopes, roughness and grid size. The range of parameters and the geometry of the model are equal to a laboratory experiment. Hence, the results in SOBEK are compared to the ones obtained in the physical model.

After running the different simulations, a model set up is proposed. The drain inlet itself is modelled as a manhole, working as a connection between surface flow (2D) and sewer system (1D). A Real Time Control module is used to fix a discharge-water depth relationship.

Depending on the topography of the street and the approaching discharges, different adjustments have to be implemented to describe the process properly. In cases of large discharges in areas with low longitudinal slopes and in case of small discharges under almost any combination of slopes, the roughness coefficient has to be increased in order to reproduce sheet flow conditions while using shallow water equations. However, a combination of flat or nearly flat areas and small approaching discharges leads to flow conditions that cannot be described with the configuration proposed. The grid size has to be fine enough to cover the whole area of the drain inlet.

This approach allows the engineer to model a process that will lead to more realistic runoff and interception values, taking into account the hydraulic efficiency of the drain inlets. The proposed strategy needs to be tested in a real case study in order to check their possibilities and limitations.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

1.1. Research motivation

Flooding in urban areas is an important problem all around the world. The 2011 Revision of the World Urbanization Prospects (United Nations, 2012), points out that flooding is the most frequent and greatest hazard for the largest cities, potentially affecting 633 million inhabitants.

According to European Standard EN 752 "flooding" is described as a "condition where wastewater and/or surface water escapes from or cannot enter a drain or sewer system and either remains on the surface or enters buildings". Several trends, such as increasing urbanization and the uncertainty of the effect of climate change, intensify concerns about these events. The population living in urban areas is expected to increase from 3.6 billion in 2011 to 6.3 billion in 2050, which means that 67% of world population will live in urban areas by 2050. Indeed, the future urban population will be increasingly concentrated in large cities of one million or more inhabitants (United Nations, 2012).In Mediterranean countries such as Spain, Italy and France, flash floods are considered one of the main meteorological hazards, as they occur with high frequency and involve fatalities and huge economic damages (Llasat *et al.,* 2010). Flash floods can be defined as "sudden floods arising in small basins as a consequence of heavy local rainfalls" (Llasat *et al*., 2010). In regions such as Catalonia (Spain), 82% of the flood events between 1982 and 2007 were related to flash floods (Llasat *et al*., 2010). Urban areas are prone to flash floods because there is a high percentage of impervious area; so, there is a short time lag between the rainfall occurrence and the peak discharge.

Urban flood models, which are representations of the urban drainage systems, are used to understand the relation between rainfall and flooding in an area, with the aim of estimating future scenarios and minimizing flood risks. They also give engineers insight about the hydrological and hydraulic behaviour of a system. Such model includes a process description and a geometrical description:

- Process description: The part of a model that reproduces physical phenomena in a catchment, e.g. rainfall-runoff transformation, evaporation, hydraulic processes in sewer system.
- Geometrical description: The part of a model that encapsulates dimensions and physical properties of elements within a system, e.g. catchment area, pipe sections, runoff coefficients, topography, sewer network.

Hydraulic and hydrological processes in urban areas are interwoven with geometry and physical properties of the system. Both entities have an influence to the each other, leading to multiple relationships that should be considered in a model (see Figure 1).

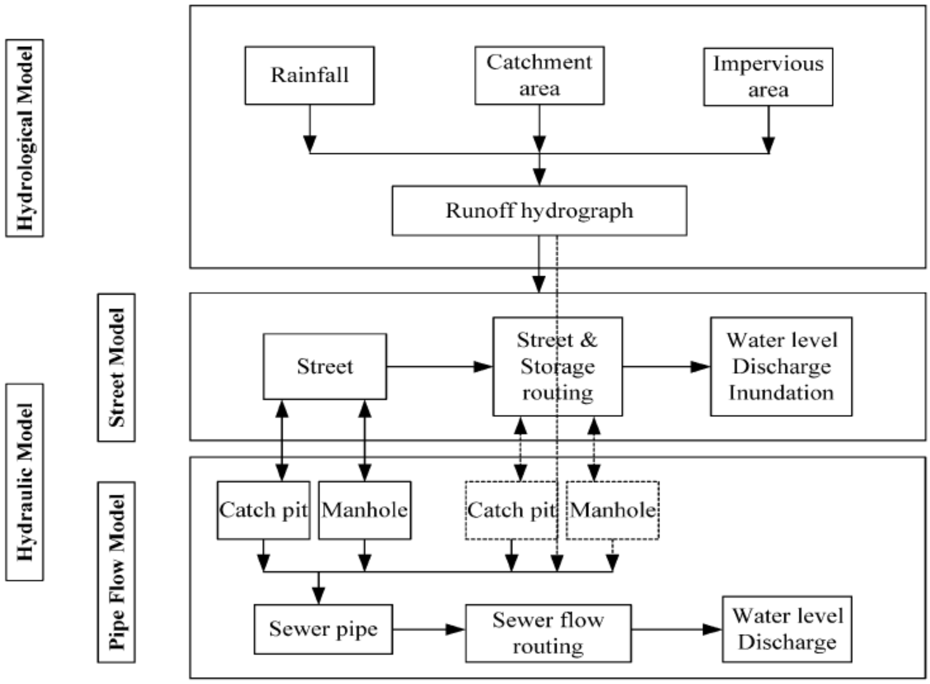

Figure 1. Basic scheme of urban flood model. Taken from O. Mark *et al*., 2004

Multiple reasons have triggered the increase in urban flood modelling, e.g. the development of information and communication technologies and the need for flood management (Vojinovic *et al*., 2009). Within this context the development of the dual drainage concept (Djordjevic *et al*., 1999) has received more attention recently. In the dual drainage approach, the interaction between the surface flow on streets and the flow conveyed in the underground system during a flood event is taken into account. The interactions take place in both directions through manholes and drain inlets, connecting the streets with the sewer network (see Figure 2).

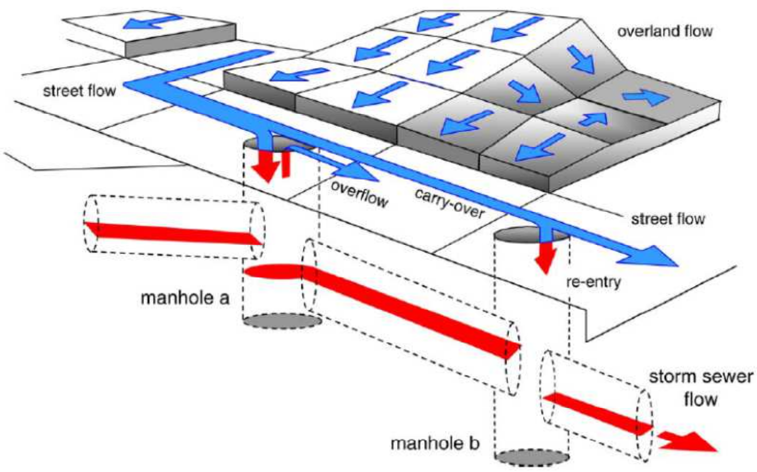

Figure 2. Components and flow interaction in dual drainage approach. Taken from Comment on “Analysis and modelling of flooding in urban drainage systems” (Smith, 2005)

Two different methods can roughly be considered within the dual drainage procedure. On the one hand, the “1D-1D” approach studies both the flow in pipes and the flow in surface pathways and ponds as one-dimensional. On the other hand, the “1D-2D” approach studies the flow in pipes as one-dimensional and the surface flows as two-dimensional. The main characteristics of both methods are summarised in Table 1 (adapted from Vojinovic *et al.*, 2009):

Table 1. Characteristics of 1D-1D and 1D-2D models

Model characteristic	1D-1D	1D-2D
Computational effort	Low	Medium/ Large
Calibration/Validation difficulty	Few data required	Extensive data required
Data processing	Simplified surface geometry (Cross-section definition)	Detailed surface geometry (Digital Elevation Model)
Overland flow simulation	Extrapolating cross-sections	According to terrain features
Results	Mean cross-sectional and unidirectional velocity	Two-dimensional
Price	Less expensive	More expensive

There are some recent developments in favour of the 1D-2D approach. The easy access to public and usually free Digital Elevation Model (DEM) makes it easier to process data to simulate flows in streets using a 2D model. In this case, the flow is directly routed over the surface and the actual flow path depending on terrain features that can be determined by the model itself (Vojinovic *et al.,* 2009). In addition, recent research shows that the simulation of a coupled model can be shorter with an improved hardware configuration. In a case study in the Raval District (Barcelona) (Russo *et al*., 2012) the model run time was reduced from 7 days to 7 minutes. A specific Graphics Processing Unit (GPU) card played an important role in this new configuration (Lamb *et al*., 2009; Smith *et al*., 2013). With this new technique, the use of a “1D-2D” approach can be even considered for real-time flood management.

1.2. State of art

Although drain inlets are important in the dual drainage approach, only little research has been published on their hydraulic behaviour. Manholes, on the other hand, received more attention, especially with multiple experimental campaigns in the last few years: Chanson (2004), Hager *et al.* (2005), Zhao *et al*. (2006) and Camino *et al.* (2011) studied the hydraulics of these elements under different conditions. Conclusions of these works cannot be applied to drain inlets as far as manholes just connect two reaches of a pipeline whereas drain inlets connect the street with the sewer system. The connection between manhole and street has generally maintenance purposes; however, eventually water can flow through this space if sewer system reaches its maximum capacity. In the case of drain inlets, the purpose of these elements is the interception of the runoff of the streets and its conveyance to the sewer system, therefore, the hydraulics of those elements are different.

During non-extreme rain events, the surface rain water directly flow though the drain inlets to the sewer system. This process can be modelled as a broad crested weir. During a storm event, the water flow conveyed in the sewer system could be such that the sewer reaches its capacity, changing from gravity flow to surcharge flow. When the sewer system becomes fully surcharged (Fig.3) and the water flows from pipes to the street, the orifice equation is a better choice than the weir one (Chen *et al.,* 2007). However, weir and orifice formulas are only a rough approximation of the process. One link might represent several drain inlets that may have not the same water level at the same time, which is assumed in the weir and orifice formulas (Mark *et al*., 2004).

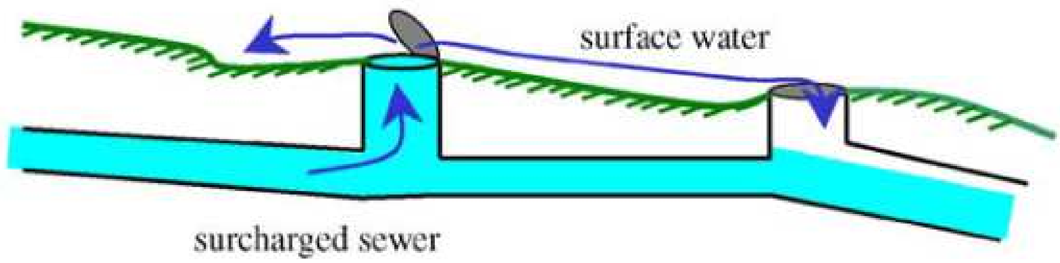

Figure 3. Interaction between surface and sewer system. Taken from Schmitt *et al*., 2004

Gómez and Russo (2010) carried out a series of experimental studies on inlet grates considering a 1:1 scale hydraulic structure. They proposed an equation (see Table 2) to determine the drain inlet efficiency using parameters related to the geometry of these elements. The efficiency of an inlet is defined as the ratio of the discharge intercepted by the inlet to the total discharge approaching the inlet.

Table 2. Equations and parameters related to drain inlets

Element	Equation	Parameters
Rectangular Weir	$Q= C_d L h^{3/2}$	Cd= discharge coefficient L= weir length h= water head
Orifice	$Q= C_d A (2gh)^{1/2}$	Cd= discharge coefficient A= area of orifice g= acceleration of gravity h= water head
Drain inlet efficiency	$E= Q_{int}/ Q_{roadway}$	E= inlet efficiency Q_{int}= intercepted flow by the drain inlet $Q_{roadway}$= total discharge approaching the inlet related to half roadway
Drain inlet efficiency related to a width of roadway x=3 m	$E'= A (k Q_{roadway}/y)^{-B}$	E'= inlet efficiency related to a width of half roadway $Q_{roadway}$= circulating flow associated with the real geometry of the street k= coefficient related to street geometry and flow depth y= flow depth in the street A,B= parameters according to grate geometry
Intercepted flow	$Q_{int}= E' k Q_{roadway}$	$Q_{int=}$ intercepted flow by the drain inlet

Djordjevic *et al*. (2011) compared experimental results between a 1:1 scale drain inlet with a Computational Fluid Dynamics (CFD) model in order to understand the interaction between surface and sewer systems under different flow conditions (inflow and outflow, free and submerged). They obtained similar observed and calculated values of water depths in surface.

Carvalho *et al.* (2011) carried out a numerical research of the inflow into different drain inlets, analyzing the effects of changing the position of the outlet (connection drain inlet-sewer system) on their efficiency.

In another study by Carvalho *et al*. (2011), they developed a numerical model to reproduce different flows occurring in drain inlets. In that case, drain inlet efficiency was evaluated under various flow conditions.

Table 3. Summary of the latest research in runoff interception by drain inlets

Author(s)	Year	Addressed process	Method
Gómez and Russo	2010	Efficiency depending on grate geometry	Physical model scale 1:1
Djordjevic *et al.*	2011	Performance during interaction surface flood-surcharged pipe flow	Physical model and CFD
Carvalho *et al.*	2011	Efficiency depending on outlet location	Numerical model
Carvalho *et al.*	2011	Efficiency depending on flow conditions	Numerical model

However, even considering previous research (see Table 3), some uncertainties still exist about the hydraulic behaviour of drain inlets. Mark *et al*. (2004) pointed out the main ones:

- Even in the situation that one link can represent only one drain inlet, depending on the type of the inlet structure, it may have several openings that may work in different regimes in time.
- During the outflow the pressure force could provoke several phenomena which are complicated to be included in the simulation, e.g. the removal of the manhole cover (Guo, 1989).
- The complexity of the flow nearby the drain inlets makes difficult to model them with the same equations used for the flow in streets and pipes. This happens especially with supercritical flow due to the fact that the boundary conditions set in the model are inherent to subcritical flow.

In addition to that, some commercial software packages used in 1D-2D dual drainage (e.g. SOBEK-Urban, SWMM) connects all runoff of one area (input) directly to a drain inlet selected by the modeller. Therefore, in that case all the runoff is assigned to a drain inlet without considering the processes between runoff and interception by drain inlets. After rainfall-runoff transformation, all the runoff of one area is assigned to one node. Only when the capacity of the sewer system (1D) is reached, water will surcharge on the 2D grid that represents the surface system. At this moment the overland flow processes of this excess water are simulated according to the characteristics of the grid (slope and roughness of streets, obstacles, etc). For instance, in a flat area part of this excess flow can be stored in the cell connected to the drain inlet; therefore, as soon as there is capacity again in the sewer system, this flow will be drained in the same node. In steep areas the flood water can flow downwards, being intercepted by another drain inlet later on. However, the interception process by drain inlets is not simulated in any of the cases.

In other commercial packages (e.g. Infoworks ICM), the rainfall that drops in the 2D domain produces runoff that flows over the 2D grid. This runoff flows according to the topography until it reaches an element of connection between sewer system (1D) and street (2D). Therefore, the interception can be modelled more accurately (Russo *et al*., 2012).

1.3. Research aim and research questions

The aim of the research is:

- *To study to what extent a "1D-2D" dual drainage model can reproduce the process of runoff interception by drain inlets.*

The research questions in this thesis are the following:

1. *How can the runoff interception by drain inlets be modelled using commercial software packages?*
2. *What level of detail in roughness and topography is it desirable to mimic the runoff interception process in a 1D-2D dual drainage model?*

The two questions are answered using a model in SOBEK, which is an integrated software package with different modules for river, urban or rural management.

In SOBEK a cross section of a street is modelled, spilling different set of discharges and measuring the drain flow intercepted by a drain inlet under different conditions of slopes, roughness and grid size. The range of parameters and the geometry of the model are equal to a laboratory experiment carried out by Gómez and Russo (2010). Hence, the results in SOBEK are compared to the ones obtained in the physical model.

1.4. Definitions and key terms

Due to the wide range of shapes and geometries, different names are given to elements which share the same purpose: to drain the surface flow as soon as possible in order to avoid flooding. The following definitions have been used in this research with the aim of homogenizing concepts:

- **Urban drainage system**: A set of elements located above the street and underground whose function is to drain rain water from streets and convey it to the sewer conduit (see Figure 4).
- **Dual drainage**: Engineering approach in which interaction between the surface flow on streets and the flow conveyed in the underground system is considered during a flood event. The interactions take place in both directions through manholes and drain inlets, connecting the roads and streets with the sewer network.

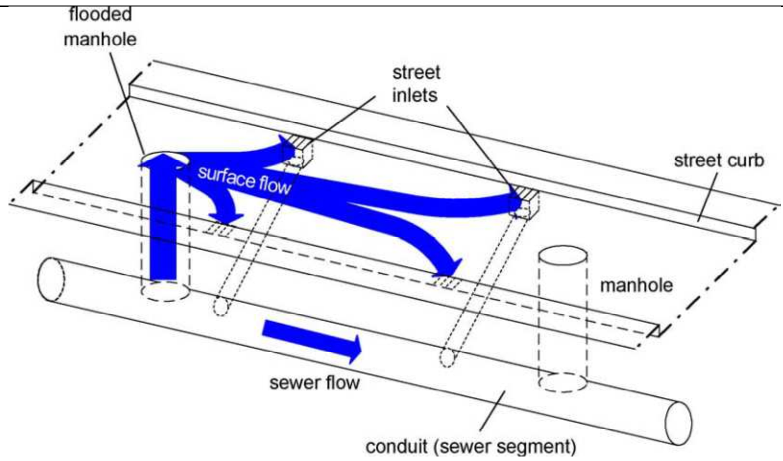

Figure 4. Basic drainage system. Taken from Schmitt *et al*., 2004

- **Surface drainage system**: A group of elements which drain rain water from the street. It is composed by the street itself, drain inlets and connections between drain inlets and sewer conduit.
- **Sewer system**: A group of elements, located underground, which convey water captured by drain inlets to a discharge point. It is composed by a sewer conduit (a pipe that can have different shapes and sizes), manholes and other hydraulic structures (e.g. weirs, valves, etc).

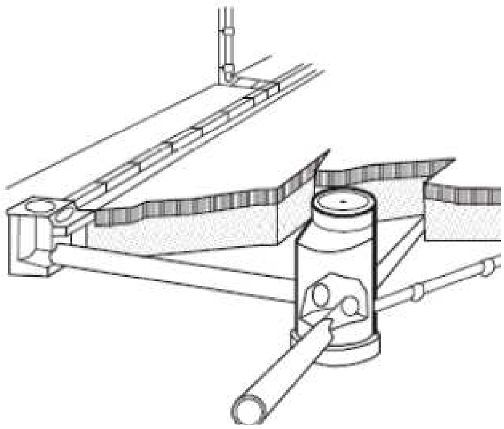

Figure 5. Surface and sewer systems. Adapted from Bourrier, 1997

- **Drain inlet/ gully**: element installed in the street to intercept and drain runoff. It consists in a hole made in the street surface, generally close to the kerb, through which water drains and it is conveyed to the sewer system by a smaller pipe, called connection (see Figure 6).

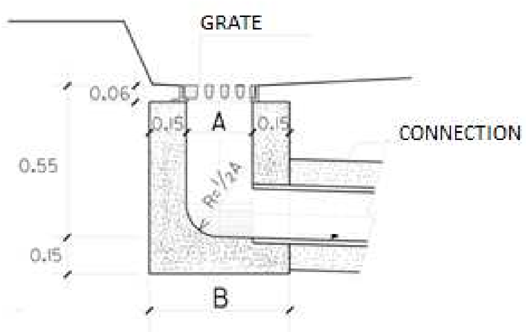

Figure 6. Cross section of a drain inlet.

The hole is covered by a metal grate to avoid that other elements can pass through it. There are multiple different shapes and geometries of grates. These geometries determine a different hydraulic behaviour of the drain inlet (see Fig. 7)

Figure 7. Different grate models. Taken from Gómez and Russo, 2010

- **Interception**: process in which the drain inlet collects and drains (part of) the runoff flowing through it.
- **Manhole**: element installed along the sewer system to allow that an operator can enter the system to supervise and maintain it. The manhole connects street surface and sewer system (see Figure 8). In the street, the manhole orifice has a metal cover to avoid that other elements can enter the system.

Figure 8. Construction of a manhole and connection to the sewer pipe

1.5. Outline of the report

This report is divided into six chapters:

- Chapter II contains an analysis of the theoretical base of the hydraulic of the processes of runoff flow and interception by drain inlets.
- Chapter III contains an explanation of the methods and materials used in this research.
- Chapter IV contains the simulation of a street section with a drain inlet in which different set of parameters, flows and geometries are modelled.
- Chapter V contains the discussion.
- Chapter VI contains conclusions and recommendations.

After the references, there is an Appendix with the results of the different simulations.

2. THEORY

Different software packages use different approximations or solutions of De Saint Venant equations to model flow in the sewer system and overland flow in the streets. The connection between both systems is made through drain inlets.

2.1. Overland flow in streets

Flow in streets can be represented using the 2D shallow water equations of De Saint Venant. These equations describe water motion for which vertical accelerations are small compared to horizontal acceleration, which in general is true for overland flow in the streets. Some software packages (e.g JFLOW, LISFLOOD-FP) use simplifications of the shallow water equations in order to reduce the computational cost (e.g. 2D diffusion wave and kinematic wave). SOBEK solves the full 2D shallow water equations.

The continuity equation for 2D overland flow used by SOBEK is:

$$\frac{\partial \varepsilon}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0$$

Where:

u is the velocity in x-direction (m/s), v is the velocity in the y-direction (m/s), ε is the water level above plane of reference (m), h is the total water depth: $h = \varepsilon + d$ (m) and d is the depth below plane of reference (m).

The momentum equations for 2D overland flow used by SOBEK are derived for the shallow water equations:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \varepsilon}{\partial x} + g\frac{u|V|}{C^2 h} + au|u| = 0$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \varepsilon}{\partial y} + g\frac{v|V|}{C^2 h} + av|v| = 0$$

local acceleration — convective acceleration — pressure force — frictional force

Where:

u is the velocity in x-direction (m/s), v is the velocity in the y-direction (m/s), V is the velocity magnitude : $V = \sqrt{u^2 + v^2}$ (m/s), ε is the water level above plane of reference (m), C is the Chézy coefficient ($m^{1/2}/s$) , h is the total water depth: $h = \varepsilon + d$ (m), d is the depth below plane of reference (m) and a is the wall friction coefficient (1/m).

It is important to note that the friction coefficient (i.e. Chézy or Manning coefficient) is based on a fully developed turbulent flow profile. However, for very thin sheets of water (sheet flow) the flow is rather laminar or transitional. That can happen in mild slope streets during low-intensity rainfall, when the runoff has a very small depth but a large wetted perimeter. Some research has shown that in the case of sheet flow the real friction is larger than the theoretical one; therefore, flow velocities are overestimated (see Myers, 2002).

The Weber number (We) can be used to determine in which cases the flow can be described as a sheet flow. This dimensionless number compares the fluid's inertia to its surface tension using the following expression:

$$We = \frac{\rho v^2 l}{\sigma}$$

in which ρ is the density of the fluid in kg/m^3, v is the fluid velocity in m/s, l is a characteristic length in m (in this case it could be the water depth on the street) and σ is the surface tension of the fluid in N/m.
In fluids with a small Weber number (e.g. below 50), the surface tension of the fluid has an important effect on its movement (Peakall and Warburton, 1996). Hence, the shallow water equations cannot describe the movement properly as far as they do not cover the surface tension effect.

For practical applications, overland flow during flood events could be assimilated to flow through a gutter section. Izzard (1946) proposed a revised form of Manning's equation because the hydraulic radius does not adequately describe the gutter cross section:

$$Q = 0.38 \frac{1}{n} Ix^{5/3} T^{8/3} \sqrt{Iy}$$

in which Q is street hydraulic conveyance capacity, n is Manning´s roughness coefficient of street surface, Ix = street transverse slope, Iy is street longitudinal slope and T is water spread width on the street.

As it is easier to measure water depth (y) in the street rather than flow width, the Izzard expression can be re-written considering y=$Ix\ T$:

$$Q = 0.38 \frac{y^{8/3}}{n\ Ix} \sqrt{Iy}$$

The correction factor 0.38, which has a different value when not using SI units, modifies the Manning equation trying to describe the sheet flow conditions, where the water depth is much smaller than the water width.

2.2. Flow in the sewer system

The water flow in the sewer system can be explained by the De Saint Venant equations. In the case of SOBEK, considering a 1D model, equations of continuity and momentum can be written in this way:

1. Continuity equation:

$$\frac{\partial A_f}{\partial t} + \frac{\partial Q}{\partial x} = q_{lat}$$

Where:

A_f is the wetted area (m^2), q_{lat} is the lateral discharge per unit length (m^2/s), Q is the discharge (m^3/s), t is the time (s) and x is the distance (m).

2. Momentum equation:

$$\underbrace{\frac{\partial Q}{\partial t}}_{\text{inertia}} + \underbrace{\frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right)}_{\text{convection}} + \underbrace{gA_f\frac{\partial h}{\partial x}}_{\text{water level gradient}} + \underbrace{\frac{gQ|Q|}{C^2RA_f}}_{\text{bed friction}} - \underbrace{W_f\frac{\tau_{wi}}{\rho_w}}_{\text{wind friction}} = 0$$

Where:

Q is the discharge (m^3/s), t is the time (s), x is the distance (m), A_f is the wetted area (m^2), g is the gravity acceleration (9.81 m/s^2), h is the water level (m) with respect to the reference level, C is the Chézy coefficient (m$^{1/2}$/s), R is the hydraulic radius (m), W_f is the flow width (m), τ_{wi} is the wind shear stress (N/m^2) and $\rho_w$is the water density (normally, 1000 kg/m^3).

In our case, where the cross sections can be considered closed, the wind friction term is neglected in the momentum equation.

$$\underbrace{\frac{\partial Q}{\partial t}}_{\text{inertia}} + \underbrace{\frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right)}_{\text{convection}} + \underbrace{gA_f\frac{\partial h}{\partial x}}_{\text{water level gradient}} + \underbrace{\frac{gQ|Q|}{C^2RA_f}}_{\text{bed friction}} = 0$$

The fourth term, bed friction, represents the friction between the flow and the channel bed. Therefore, the related force is always in the direction opposite to the water flow. In watercourses, this force together with the gravity force determines the flow conditions.

Any network in SOBEK-Flow-model is composed by reaches connected to each other at connection nodes. In each reach a number of calculation points can be defined. These calculation points represent the spatial numerical grid to be used in the simulation. The De Saint-Venant equations are solved numerically in that grid using the so-called Delft-scheme. It is a staggered grid, which means that water levels are defined at the connection nodes and calculation points, while discharges are defined at the reaches (see Figure 9).

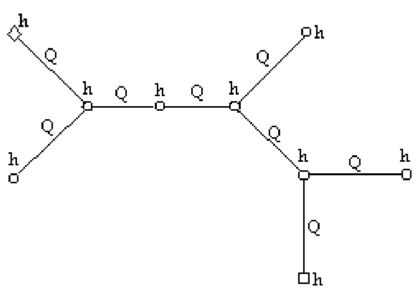

Figure 9. Staggered grid in SOBEK. Taken from SOBEK Online Help.

2.3. Interaction through drain inlets

Drain inlets are essential elements in urban drainage systems. They intercept the runoff on streets and convey it to the sewer system (the interception process). An improper operation (e.g. due to bad location or obstruction) of the drain inlets might lead to urban flooding, even with runoff below design values of the sewer system. This fact is even more important when a dual drainage approach is considered because drain inlets connect surface and sewer system in two directions. Despite that, little research has been published related to its influence in the operation of a dual drainage system.

The discharge intercepted by a drain inlet depends on the geometric definition of the element (e.g. inlet shape, holes area, location of the sink within the drain inlet, grate shape), on the characteristics of the approaching runoff (e.g. velocity and flow) and on the characteristics of the street (e.g. longitudinal and transversal slopes, roughness). In addition to that, the hydraulic efficiency of the inlet decreases due to the presence of silt, leaves and other materials that clog the inlet void area (Gómez *et al*., 2013).

These local conditions have such a big influence that it is not possible to state, for example, that the efficiency of one specific drain inlet is 65%. It should be stated in such a way that the drain inlet efficiency is related to the flow and street conditions, saying for example, the efficiency of the drain inlet is 65% within a range of flows of 0.01-0.3 m^3/s and street slopes smaller than 4%.

Models of drain inlets are subject to a number of uncertainties. For example, one source of uncertainty concerns the geometrical description of different elements, connections, roughness, etc. This uncertainty is difficult to reduce due to the fact that the majority of these elements are located under the street level, making it hard to measure them. Moreover, drain inlets operate under different flow conditions depending on the magnitude of the storm: gravity flow during normal operation (flow drained from street to sewer system) and pressured flow during extreme events (flow escapes the sewer system through drain inlet to the street).

Those uncertainties have to be taken into account when modelling a drain inlet. Even though it might not be possible to overcome them, their influence in the reliability of the results must be analysed. SOBEK allows the interaction between surface flow (Overland Flow module, 2D) and sewer system (Sewer Flow, 1D) through two kinds of manholes, called "reservoir" and "loss":

- Reservoir: Water that exceeds the street level will inundate the "storage area" defined in the 2D grid above the node (Figure 10).
- Loss: Water that exceeds the street level will flow over the 2D grid (Figure 10).

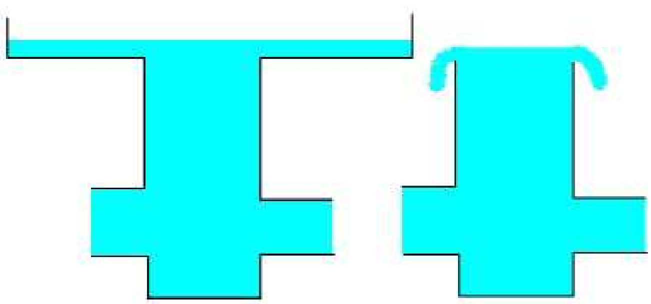

Figure 10. Manholes type reservoir (left) and loss (right). Taken from SOBEK Online Help

3. METHODOLOGY

To have a reference level that allows the validation of the runoff interception model in SOBEK, the same conditions of a 1:1 scale model used in a previous research have been reproduced. The runoff interception is computed in SOBEK modelling the same set of discharges and slopes than in the physical model. The intercepted discharges are compared in both models. Different simulations are run in order to find the sensitive parameters.

3.1. Description of the physical model used by Gómez and Russo

Gómez and Russo (2002) used a physical model in the Laboratory of Hydraulic of *E.T.S de Ingenieros de Caminos* (Civil Engineering) of Technical University of Catalonia (UPC) to determine the drain inlet efficiency of different grates with different ranges of flows and slopes.

The platform has a length of 5.5 m and a width of 3 m, simulating the width of an urban street at a 1:1 scale. This platform is supported by three points of variable height; therefore different slopes can be obtained varying its height, with a maximum longitudinal slope of 10% and a maximum transversal slope of 4%. A drain inlet is located 4 meters from the beginning of the platform, just next to a higher element that represents the kerb of the street. According to the specification from the authors, the Manning roughness coefficient of the platform is considered to be 0.013 $s/m^{1/3}$ but there is not specific research about this value.

Figure 11. UPC Platform and testing area. Taken from Gómez and Russo, 2010.

In the experiment, runoff in a street of longitudinal slope (Iy) and transversal slope (Ix) is simulated. The discharge Q (total discharge approaching the street) flows first from a bucket placed around 15 m above the platform to a tank that dissipates the flow energy and provide a horizontal profile to the surface water level, spreading the flow uniformly at the beginning of the platform, along the whole width. The discharge intercepted by the drain inlet is measured using a limnimeter on a triangular weir. The water depth just upstream the drain inlet is measured on a thin graduated invar scale. In that way, the drain inlet efficiency, E, is recorded for different set of parameters, discharges and grate shapes.

The laboratory tests were performed for eight different longitudinal slopes 0%, 0.5%, 1%, 2%, 4%, 6%, 8%, 10% and five transversal slopes 0%, 1%, 2%, 3%, 4% were tested, considering all the 40 different combinations for every different discharge 20 l/s, 50 l/s, 100 l/s, 150 l/s and 200 l/s.

One of the main outcome of these tests was a potential law expression that relates drain inlet efficiency (E), discharge approaching the inlet (Q), flow depth and geometry of the grate (A, B):

$$E = A\left(\frac{Q}{y}\right)^{-B}$$

The results used for the comparison with SOBEK model correspond to a grate (Figure 12) which coefficient A is 0.3551 and B is 0.8504. With these values, the Q-y relationship will be implemented in the numerical model to compare the discharges obtained in SOBEK with the ones obtained in the platform.

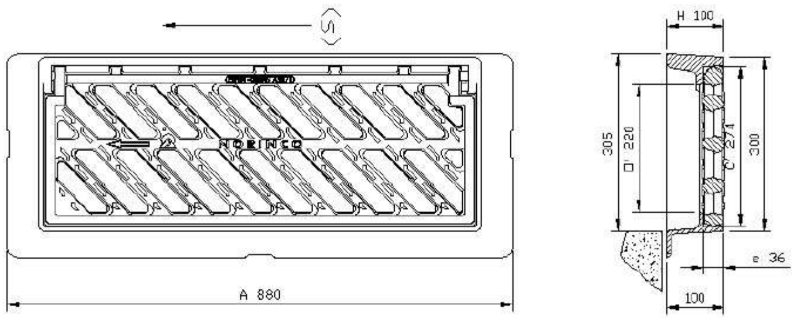

Figure 12. Geometry of the grate used to set the Q-y relationship

3.2. Description of the numerical model with SOBEK

Half of the cross section of a street is represented, from the symmetrical axis of the street to the kerb, to reproduce the experiment of Gómez and Russo in the numerical model. An element emulating a drain inlet has to be installed at the end of this section of street. Different set of discharges are spilled at the top part of the platform, changing longitudinal and transversal slopes, roughness coefficient and grid size. Discharge and water depth in the drain inlet are measured during the different simulations. According to those specifications, the model in SOBEK can be divided in three main parts: street representation (2D grid), discharge spillage and drainage, and drain inlet representation (connection between 1D and 2D).

3.2.1. Street representation

Streets in an urban drainage model, or the laboratory platform in the case of this thesis, are represented using a 2D Grid in SOBEK. The bottom levels of the different cells are set according to the desired slopes.

Two columns of higher cells in both sides of the 2D Grid have been used to emulate the kerb, which actually is a boundary that the runoff cannot cross, avoiding that the discharge flows out the domain (see Figure 15).

3.2.2. Discharge spillage and drainage

Discharge spillage is simulated using 2D-Corner nodes linked with 2D-Line Boundary connections. In that line, the discharge is set as a boundary condition and it is spread along the row of cells located just downstream (see Figure 13) to reproduce critical flow conditions. Therefore, depending on the transversal slope different flows are assigned to the cells.

The Froude Number in the platform can be described as:

$$Fr = \frac{Q}{A(y)\sqrt{g * \frac{A(y)}{B(y)}}}$$

Where: Fr is the Froude Number (dimensionless), Q is the discharge (m^3/s), A is the wetted area (m^2), B is the flow width (m) and g is the gravity acceleration (9.81 m/s^2). Due to the trapezoidal cross section of the platform, both A and B depend on the water depth *(y).*

To calculate the discharge that has to be assigned to each cell, the critical flow condition is fixed (Fr=1). Therefore, the unitary discharge can be obtained with the following expression:

$$Q = A(y)^{3/2}\sqrt{\frac{g}{B(y)}}$$

Where the width *(B)* corresponds to the cell width and the wetted area *(A)* can be calculated according to the transversal slope.

There are three different situations within this upstream boundary condition:

1. Case of rectangular wetted area: The platform has a zero transversal slope (Ix=0%) so all the cells have equal discharge spillage (Figure 13, left).
2. Case of triangular wetted area: The transversal slope is larger than zero (Ix>0%) but the discharge is not large enough to cover the whole width of the platform (Figure 13, centre).
3. Case of trapezoidal wetted area: The transversal slope is larger than zero (Ix>0%) and the discharge is large enough to cover the whole width of the platform (Figure 13, right).

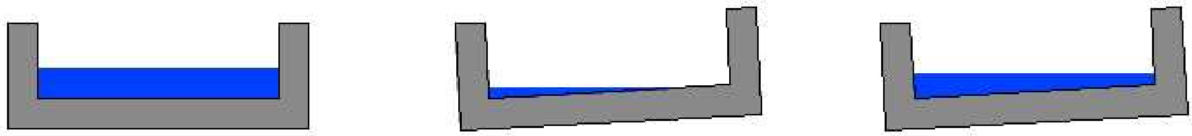

Figure 13. Situations of discharge spillage: rectangular, triangular and trapezoidal wetted area

These three cases are considered when implementing the different model configurations to set up the discharge spillage. In the case of rectangular wetted area, a single 2D- Line Boundary is used to spread the total discharge homogeneously within all the cells (see Figure 14, left). When considering a triangular wetted area, several 2D- Line Boundary are used to cover just the width of the platform that has runoff according to the total discharge and the transversal slopes (see Figure 14, centre). Each of these boundaries has a different flow value. In the case of the trapezoidal wetted area, several 2D-Line Boundary cover the whole width of the platform and spill the flow according to the critical flow formula stated before (see Figure 14, right).

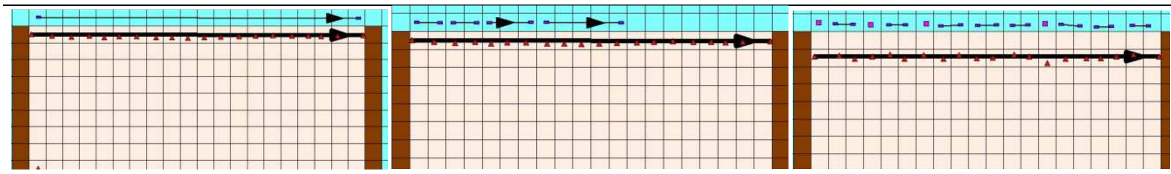

Figure 14. Discharge spillage in the model: rectangular, triangular and trapezoidal wetted area

Two 2D-Corner nodes linked with a 2D-Line Boundary are used in the final part of the platform to assure the drainage of the runoff not intercepted by the drain inlet. In this case, the boundary condition is set as water depth equal to zero. Without this boundary condition, the not intercepted runoff would store at the end of the platform and, eventually, would reach the drain inlet from downstream to upstream, inducing an error in its efficiency.

3.2.3. Drain inlet representation

SOBEK is not able to compute the processes inside the drain inlet (e.g. eddies and turbulences). It works at a different scale, solving the continuity and momentum equations in the different nodes. There is no such an element in which you can set a discharge to the sewer system according to the water levels measured in the 2D grid. Therefore, it is not possible to reproduce a drain inlet using any of the nodes of the Urban module (weir, manhole, etc).

Different combination of elements were tried in order to emulate a drain inlet. The following part describes a configuration that did not work out, but it is nevertheless worth to mention here to support future research. The configuration was the following one:

- A 2D boundary condition composed by 2D-Corner nodes, located on the grid, emulating the grate of the drain inlet. That boundary condition has the same length of the drain inlet and intercepts the runoff flowing through the cells where it is located.
- A 1D2D connection node, which is the element that allows transferring the intercepted flow by the 2D boundary condition to the sewer system. That element is just a connection and no hydraulic conditions can be set on it.
- A channel of small length but large cross section, in which water can flow without any restriction. A measure station is located on it, with the aim of registering water levels. Due to the geometric conditions of this channel, it can be assumed that the water levels on it are just the same than in the 2D boundary condition.
- A pumping station, which only has the objective of fixing a Q-y relationship in the flow. Therefore, the pumping station is permanently switched on, and the discharges are according to the water levels observed in the measure station described in the previous point.

This configuration failed because of several reasons:

- Too synthetic set up: such a complex combination of elements makes it too difficult to use it when applying a model of common engineering practice.
- Too long computational time: in average, the computational time was six times longer when using this configuration.
- Model reliability: using too many elements makes difficult to check if the model reproduces the runoff interception properly.

These problems were overcome and the final model set up was implemented:

- A manhole just located in the grid cell where the drain inlet would be installed. If the cell is smaller than the grate size, several cells are used to cover the whole inlet area. Manholes are connected by a flow-pipe.
- A Flow-pipe that conveys the flow intercepted by the manhole(s) out of the system. This pipe connects the 2D grid with the sewer network.
- A Flow- External Pump Station between the flow-pipe and the sewer system. In this pump station, a discharge- water depth (Q-y) relationship can be set using the Real Time Control (RTC) module of SOBEK. Therefore, the discharge conveyed by the pipe will be fixed according to the water depth measured at the bottom of the manhole.

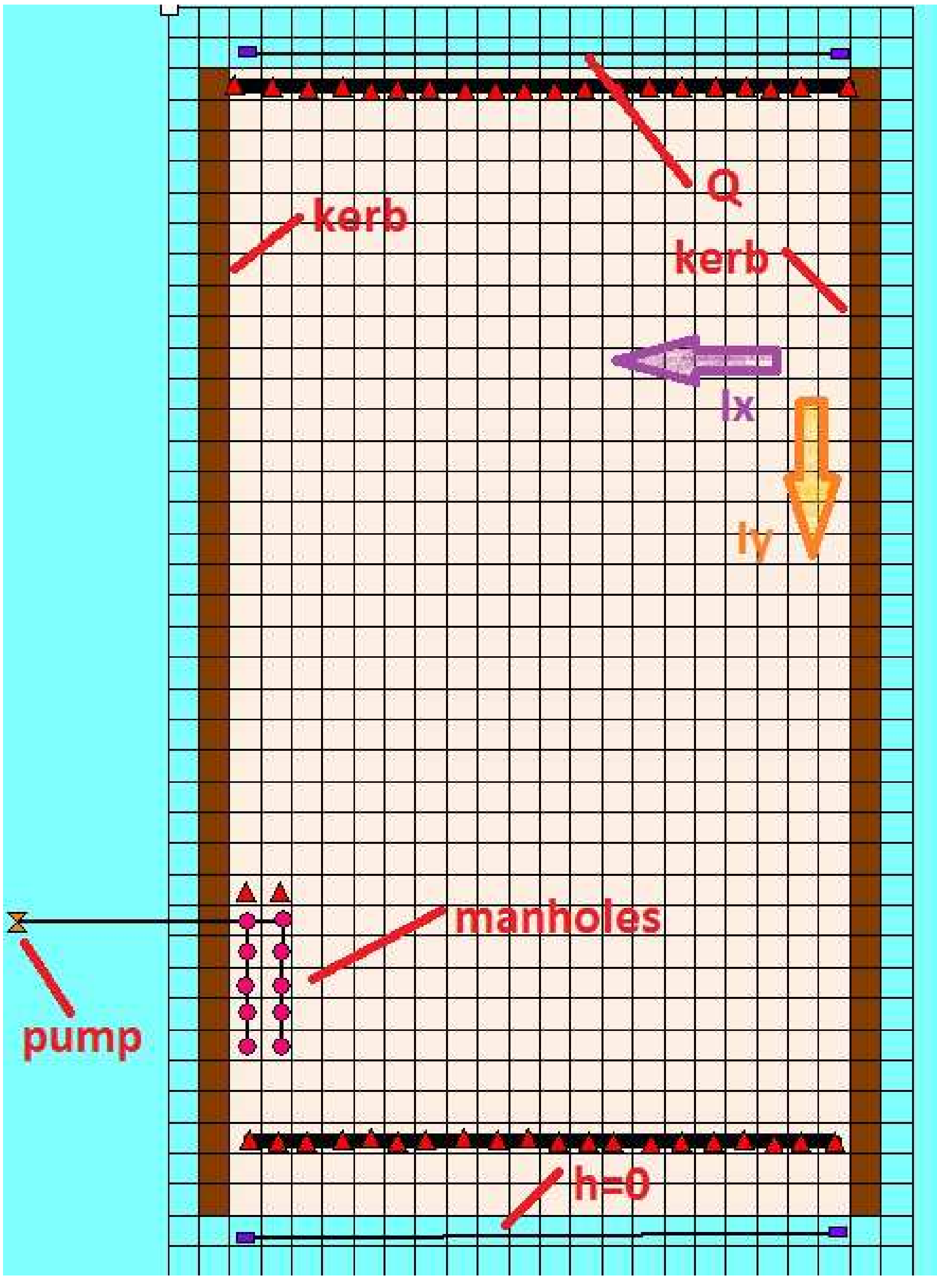

Figure 15. Platform representation in SOBEK

This configuration is optimal because the interception process can be modelled, setting a Q-y relationship according to the geometry of the grate of the drain inlet, using the formula proposed by Gómez and Russo (2010). With this relationship, drain inlets can be simulated considering their efficiency, being more realistic than the current wrong hypothesis of having all the flow drained by the element.

Some considerations should be taken into account:

- There is no limitation for the inflow from the 2D-grid to the manholes. Hence, all the runoff that enters the cell where the manhole is located will be drained out the system. The only possible limitation might be a backwater effect, but this is not the case in our situation.
- It is not possible to visualize this inflow from 2D-grid to manhole as an output in SOBEK. As stated before, discharges are computed in the reaches between calculation points, not in the nodes (see Figure 9).
- The diameter of the pipe and the bottom level of the manhole might have an influence in the application of the Q-y relationship. The smaller the diameter and the shallower the manhole are, the faster the water will reach the pump and the sooner the Q-y relationship will be set. However, this fact does not have any important influence in the model because it is only a delay of seconds and only the steady phase is analysed.

During a simulation, it can be seen how the water spread at the beginning of the platform is progressively flowing towards the kerb side, following the transversal slope. At the end of the platform, part of this water is drained by the manholes that represent the drain inlet. When the discharge that reaches these cells is larger than the hydraulic capacity, it can be seen that some flow continues towards the end of the platform without being drained (Fig.16).

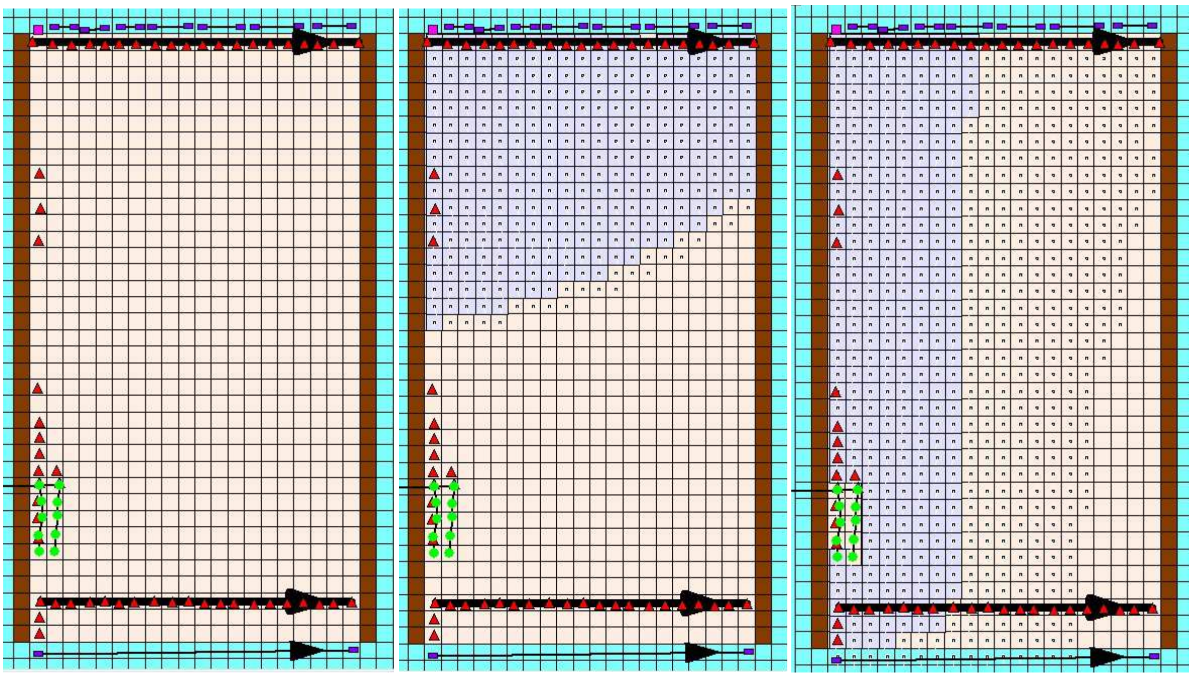

Figure 16. Runoff over the platform. Initial time step (left), 5 sec (centre) and 3 min (right).

4. PROCESS CHARACTERIZATION

A first simulation is run in order to check the situations in which the numerical model differs more to the physical model. A second simulation is carried out with two different approaches:

- In the cases with larger differences the roughness coefficient is modified to quantify its influence in the reliability of the model.
- In two cases with large differences a finer grid size is implemented to check the effect in the model.

The modules of 1D Flow (Rural), 1D Flow (Urban), Overland Flow (2D) and RTC are selected during the simulations. There is no precipitation because the discharge is spread homogeneously by the 2D-Line Boundary, therefore the RR (Rainfall-Runoff) module is switched off.

4.1. Simulation

4.1.1. Settings

In Table 4 the values of the parameters used in the first simulation are summarised:

Table 4. Summary of the simulation parameters

Parameter	Value(s)
Grid size (cm)	15x15
Transversal slope (%)	0, 1, 2, 3, 4
Longitudinal slope (%)	0, 0.5, 1, 2, 4, 6, 8, 10
Manning roughness ($s/m^{1/3}$)	0.013
Discharge (l/s)	200, 150, 50, 25
Time step (s)	1 (5 for RTC)
Simulation time (min)	5 (10-20 in some cases of 25 l/s)

2D grid

As stated before, the laboratory tests were performed under different longitudinal and transversal slopes. To emulate these conditions, different grids are created according to the desired slopes. The initial grid size for all the simulations is 15x15 cm, therefore, two cells are required to cover the width of the drain inlet (30 cm) and five cells to cover the whole length of the drain inlet (75 cm) (Fig. 17).

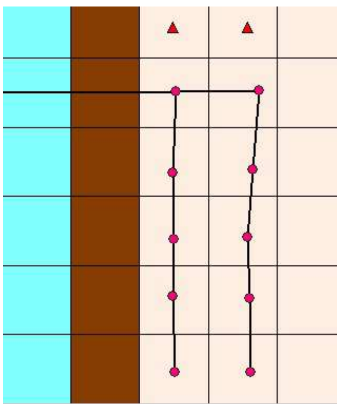

Figure 17. Detail of the grate definition using manholes

A total of 40 grids are created (see Table 4), covering all the combinations from the non-slope state (0% transversal, 0% longitudinal) to the steepest slope state (4% transversal, 10% longitudinal).

The Manning coefficient of the platform is estimated to be around 0.013 because the platform is made of concrete with a smooth and regular surface, however, there is no specific research about this value.

Multiple 2D-History nodes are installed in different points of the platform to track the water depth in those points (see Fig.15).

Discharges

In the laboratory the experiment was done with discharges of 200 l/s, 150 l/s, 100 l/s, 50 l/s and 25 l/s. However, in SOBEK the discharge of 100 l/s is not used because of time limitations. It is an intermediate value; therefore, it does not give added value to the results.

Q-y relationship

The discharge- water depth relationship is set according to the values obtained in the research done by Gómez and Russo (2010). Developing the formula proposed by them (see Chapter 3.1 of this Thesis), a discharge interception can be set depending on the water depth measured just upstream the drain inlet:

$$\frac{Qint}{Qstr} = A\left(\frac{Qstr}{y}\right)^{-B}$$

Where $Qint$ is the discharge intercepted by the drain inlet in l/s, $Qstr$ is the runoff in the street (in our case the discharge spread at the top of the platform) in l/s, A and B are geometrical coefficients depending on the grate of the drain inlet (in this case A is 0.3551 and B is 0.8504) and y is the water depth just upstream the drain inlet in the 2D grid in mm.

This Q-y relationship is implemented using the Real Time Control (RTC) module of SOBEK, as stated before. The water depth that rules the relationship is measured in the 2D-History node located just upstream the drain inlet, in the left side next to the kerb.

The Q-y relationships implemented in the model are stated in Table 5. It is important to note that the whole series are not stated here:

Table 5. Q-y relationship with the different approaching discharges

Water depth (mm)		5	10	15	20	25	30	35	40	45	50	55
Qstr=200 l/s	Q int (l/s)	3.1	5.6	7.8	10.0	12.1	14.1	16.1	18.1	20.0	21.8	23.7
Qstr=150 l/s	Q int (l/s)	3.0	5.3	7.5	9.6	11.6	13.6	15.5	17.3	19.1	20.9	22.7
Qstr=50 l/s	Q int (l/s)	2.5	4.5	6.4	8.1	9.8	11.5	13.1	14.7	16.2	17.8	19.3
Qstr=25 l/s	Q int (l/s)	2.3	4.1	5.7	7.3	8.9	10.4	11.8	13.2	14.6	16.0	17.4

Time step

The time step for the 1D and 2D modules is 1 second, the minimum available in SOBEK. However, the time step for the RTC module is 5 seconds to avoid instability in the calculation. This assumption does not induce any important error as far as the analysis is done in the final steady state.

Simulated event

In almost all the cases the model is run for an event of 5 min because it has been observed that this is enough to reach the steady state. However, in the situation of non-slope platform combined with small discharges it was required to extend the event to 20 min to reach the final state.

Matrix of simulations

The combination of 5 transversal and 8 longitudinal slopes leads to 40 different configurations. The simulations are done under 4 different discharges, therefore, 160 different models are run. In Table 6 the matrix for a 200 l/s discharge is shown.

The simulations are named according to the following criteria:

- Transversal slope [0,1,2,3,4]+ Longitudinal slope [a=0, b=0.5, c=1, d=2, e=4, f=6, g=8, h=10]+ Discharge in l/s

For instance, 3c50 represents a transversal slope of 3%, longitudinal slope of 1% and discharge of 50 l/s.

Table 6. Simulation matrix for a discharge of 200 l/s

NAME	Q (m3/s)	Ix (%)	Iy (%)	Grid size (cm)	n (Manning)	Time step(s)	Grid name
0a200	0.2	0	0	15	0.013	1	0x0y
0b200	0.2	0	0.5	15	0.013	1	0x05y
0c200	0.2	0	1	15	0.013	1	0x1y
0d200	0.2	0	2	15	0.013	1	0x2y
0e200	0.2	0	4	15	0.013	1	0x4y
0f200	0.2	0	6	15	0.013	1	0x6y
0g200	0.2	0	8	15	0.013	1	0x8y
0h200	0.2	0	10	15	0.013	1	0x10y
1a200	0.2	1	0	15	0.013	1	1x0y
1b200	0.2	1	0.5	15	0.013	1	1x05y
1c200	0.2	1	1	15	0.013	1	1x1y
1d200	0.2	1	2	15	0.013	1	1x2y
1e200	0.2	1	4	15	0.013	1	1x4y
1f200	0.2	1	6	15	0.013	1	1x6y
1g200	0.2	1	8	15	0.013	1	1x8y
1h200	0.2	1	10	15	0.013	1	1x10y
2a200	0.2	2	0	15	0.013	1	2x0y
2b200	0.2	2	0.5	15	0.013	1	2x05y
2c200	0.2	2	1	15	0.013	1	2x1y
2d200	0.2	2	2	15	0.013	1	2x2y
2e200	0.2	2	4	15	0.013	1	2x4y

2f200	0.2	2	6	15	0.013	1	2x6y
2g200	0.2	2	8	15	0.013	1	2x8y
2h200	0.2	2	10	15	0.013	1	2x10y
3a200	0.2	3	0	15	0.013	1	3x0y
3b200	0.2	3	0.5	15	0.013	1	3x05y
3c200	0.2	3	1	15	0.013	1	3x1y
3d200	0.2	3	2	15	0.013	1	3x2y
3e200	0.2	3	4	15	0.013	1	3x4y
3f200	0.2	3	6	15	0.013	1	3x6y
3g200	0.2	3	8	15	0.013	1	3x8y
3h200	0.2	3	10	15	0.013	1	3x10y
4a200	0.2	4	0	15	0.013	1	4x0y
4b200	0.2	4	0.5	15	0.013	1	4x05y
4c200	0.2	4	1	15	0.013	1	4x1y
4d200	0.2	4	2	15	0.013	1	4x2y
4e200	0.2	4	4	15	0.013	1	4x4y
4f200	0.2	4	6	15	0.013	1	4x6y
4g200	0.2	4	8	15	0.013	1	4x8y
4h200	0.2	4	10	15	0.013	1	4x10y

4.1.2. Results

In this chapter, intercepted discharges and water depths of the model implemented in SOBEK are compared to the ones of the physical model. Although water depths are included here, they are not the main source of analysis because their direct measurement under small discharges has low accuracy regarding the use of an invar scale.

The complete lists of the measured and simulated values are attached as part of the Appendix at the end of this document.

Intercepted discharge

The interception process has a characteristic graph, with a similar shape under all the simulated conditions. There is an increasing branch that presents some intermediate peaks until it reaches an asymptotic value, corresponding to the steady state (see Figure 18). These peaks are caused by the delay necessary to fill the pipe that connects the pump and the 2D-grid, therefore, they are not object of analysis. Nevertheless, this circumstance might be useful in the case of networks of new construction where the effects of connections between drain inlet and sewer pipe can be studied.

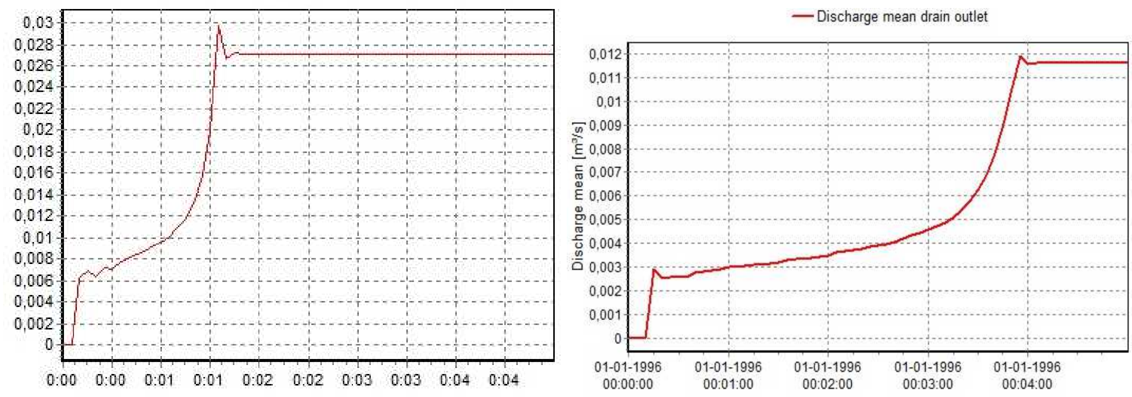

Figure 18. Intercepted discharges for simulations 2e200 (left) and 1c50 (right).

The intercepted discharge increases when the transversal slope increases. The interception decreases, in general, when the longitudinal slope increases, as it can be seen in the following figures (Fig. 19-Fig. 22):

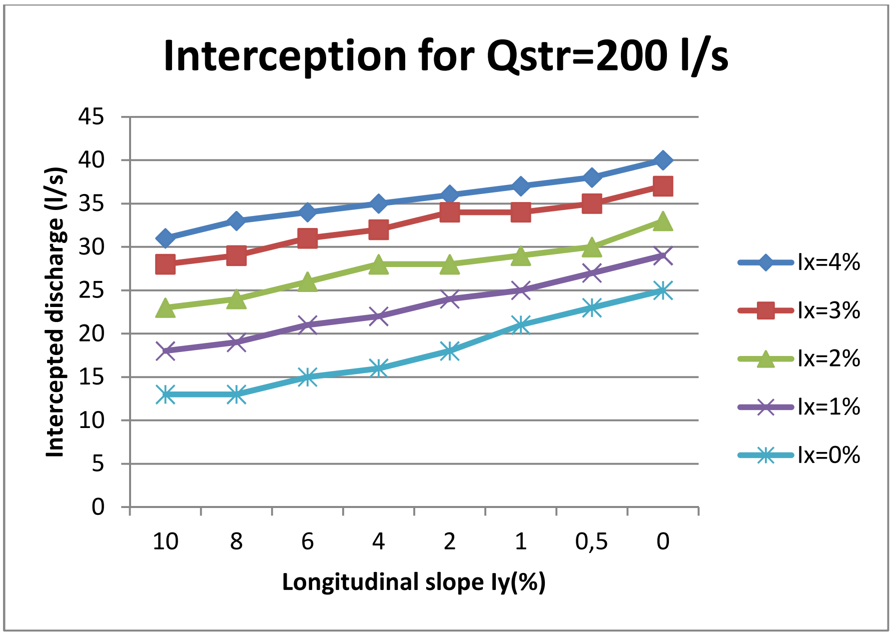

Figure 19. Intercepted discharge in SOBEK for an approaching flow of 200 l/s

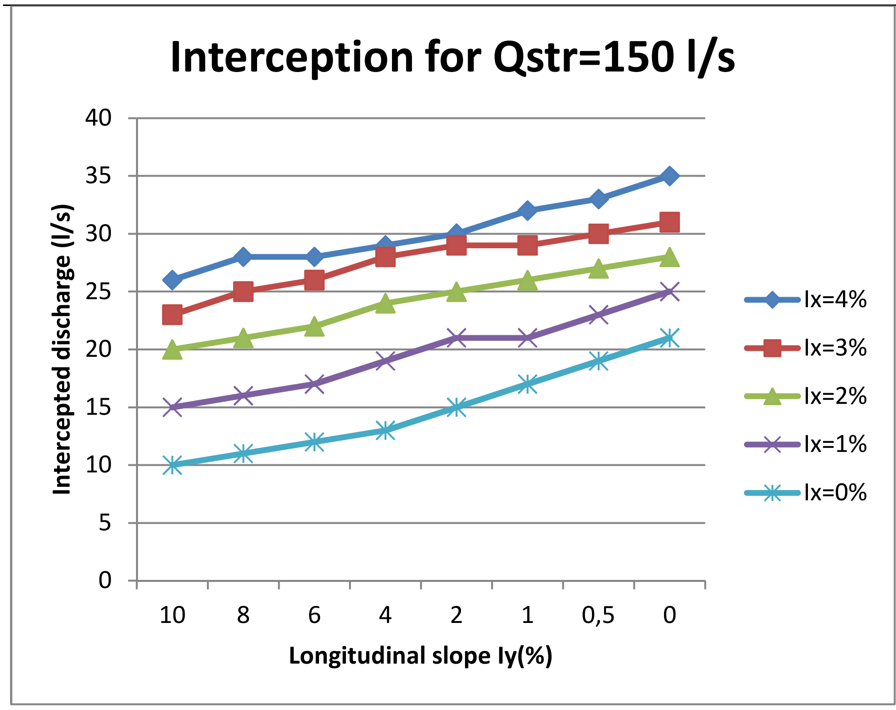

Figure 20. Intercepted discharge in SOBEK for an approaching flow of 150 l/s

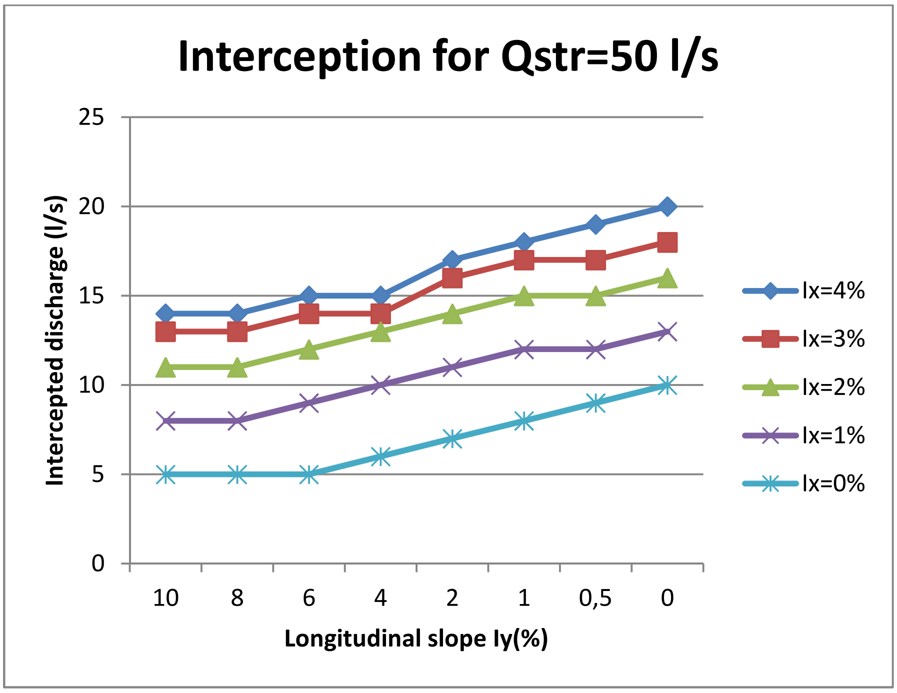

Figure 21. Intercepted discharge in SOBEK for an approaching flow of 50 l/s

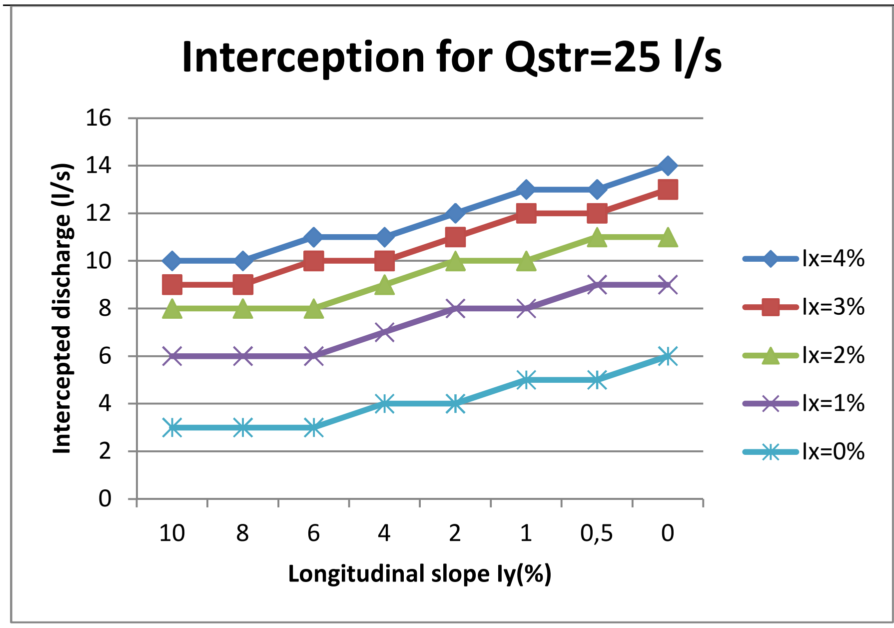

Figure 22. Intercepted discharge in SOBEK for an approaching flow of 25 l/s

Differences in intercepted discharge

The difference in discharges is represented according to this expression:

$$Q\ difference\ (\%) = \left(\frac{Qupc - Qsbk}{Qupc}\right) \times 100$$

Where $Qupc$ (l/s) is the intercepted discharge in the model of Gómez and Russo and $Qsbk$ (l/s) is the intercepted discharge in the SOBEK model.

The values below 15% are highlighted in green, from 15 to 20% in yellow and above 20% in red:

Table 7. Differences in intercepted discharges for an approaching discharge of 200 l/s

Q difference (%)						
Qstr		200 l/s				
				Ix(%)		
		4	3	2	1	0
	10	3,33	16,67	15,00	12,50	8,33
	8	3,13	11,54	9,09	18,75	7,14
	6	5,56	3,33	0,00	5,00	6,25
Iy(%)	4	16,67	11,11	12,50	8,33	11,11
	2	21,74	15,00	17,65	7,69	10,00
	1	19,57	19,05	19,44	10,71	4,55
	0,5	17,39	12,50	11,76	3,57	4,55
	0	16,67	11,90	13,16	9,38	10,71

Table 8. Differences in intercepted discharges for an approaching discharge of 150 l/s

Q difference (%)						
Qstr		150 l/s				
				Ix(%)		
		4	3	2	1	0
	10	1,96	2,22	2,56	0,00	16,67
	8	3,70	4,17	7,69	6,67	8,33
	6	6,67	1,96	4,76	3,03	11,11
Iy(%)	4	15,94	6,67	6,67	2,56	3,70
	2	31,03	19,44	12,28	0,00	0,00
	1	28,89	25,64	17,46	17,65	3,03
	0,5	26,67	23,08	18,18	14,81	2,56
	0	24,73	26,19	18,84	16,67	12,50

Table 9. Differences in intercepted discharges for an approaching discharge of 50 l/s

Q difference (%)						
Qstr		50 l/s				
				Ix(%)		
		4	3	2	1	0
	10	30,00	21,21	18,52	5,88	25,00
	8	33,33	25,71	18,52	5,88	25,00
	6	34,78	28,21	17,24	0,00	25,00
Iy(%)	4	41,18	34,88	16,13	5,26	33,33
	2	35,85	33,33	20,00	10,00	55,56
	1	23,40	22,73	16,67	4,35	45,45
	0,5	15,56	12,82	9,09	4,35	20,00
	0	14,89	7,69	13,51	3,70	4,76

Table 10. Differences in intercepted discharges for an approaching discharge of 25 l/s

Q difference (%)						
Qstr		25 l/s				
				Ix(%)		
		4	3	2	1	0
	10	36,51	32,08	11,11	26,32	100,00
	8	37,50	34,55	13,51	26,32	100,00
	6	34,33	32,20	17,95	20,00	71,43
Iy(%)	4	31,25	33,33	16,28	33,33	128,57
	2	7,69	15,38	13,04	28,00	77,78
	1	1,89	2,13	4,76	14,29	100,00
	0,5	3,70	2,13	15,79	24,14	33,33
	0	1,75	6,12	4,76	0,00	7,69

Differences in water depth

The difference in discharges is represented according to this expression:

$$Y\ difference\ (\%) = \left(\frac{Yupc - Ysbk}{Yupc}\right) \times 100$$

Where $Yupc$ (mm) is the water depth measured in the model of Gómez and Russo and $Ysbk$ (mm) is the water depth measured in the SOBEK model.

The values below 15% are highlighted in green, from 15 to 20% in yellow and above 20% in red:

Table 11. Differences in water depths for an approaching discharge of 200 l/s

Y difference (%)						
Qstr		200 l/s				
		Ix(%)				
		4	3	2	1	0
	10	9	16	20	14	8
	8	8	16	26	13	4
	6	8	0	7	9	3
Iy(%)	4	11	1	0	7	20
	2	13	9	12	10	11
	1	12	13	11	13	11
	0.5	10	11	4	11	18
	0	6	5	7	8	12

Table 12. Differences in water depths for an approaching discharge of 150 l/s

Y difference (%)						
Qstr		150 l/s				
		Ix(%)				
		4	3	2	1	0
	10	4	0	5	0	12
	8	6	3	4	3	15
	6	5	3	4	2	14
Iy(%)	4	8	1	5	2	6
	2	17	12	6	4	13
	1	23	22	27	6	5
	0.5	18	19	26	20	30
	0	16	17	17	13	23

Table 13. Differences in water depths for an approaching discharge of 50 l/s

Y difference (%)						
Qstr		50 l/s				
				Ix(%)		
		4	3	2	1	0
	10	21	11	3	0	0
	8	22	10	6	5	8
	6	25	12	3	15	8
Iy(%)	4	28	24	6	18	13
	2	31	28	16	10	16
	1	28	25	23	17	10
	0.5	27	23	21	24	28
	0	24	20	17	17	17

Table 14. Differences in water depths for an approaching discharge of 25 l/s

Y difference (%)						
Qstr		25 l/s				
				Ix(%)		
		4	3	2	1	0
	10	27	11	5	36	200
	8	28	16	12	33	133
	6	26	20	15	21	75
Iy(%)	4	23	25	19	6	60
	2	18	21	26	5	43
	1	16	19	28	15	20
	0.5	22	27	24	17	17
	0	19	24	28	16	13

The Weber number of the different sets of parameters and discharges is shown in the next table (Table 15). Its value, in general, increases with larger longitudinal and transversal slopes:

Table 15. Range of values of Weber number in the simulations

Discharge (l/s)	Max We	Grid	Min We	Grid
200	16282	4h200	1154	0b200
150	12384	4h150	832	0a150
50	4529	4h50	239	0c50
25	2327	4h25	87	0b25

Interception distribution

The grid resolution allows to study how the different parts of the drain inlet capture the discharge, making a distinction between different flows (see Figure 23):

- Frontal flow: It is the flow that comes following mainly a longitudinal pathway and it is intercepted by the top part of the drain inlet.
- Lateral flow: It is the flow that arrives to the lateral part of the drain inlet due to the transversal slope of the platform.
- Backflow: It is an upward flow that arrives to the drain inlet from the bottom part of the platform due to the transversal differences of the water depths in the platform.
- Overflow: It is the flow that passes over the drain inlet without being drained.

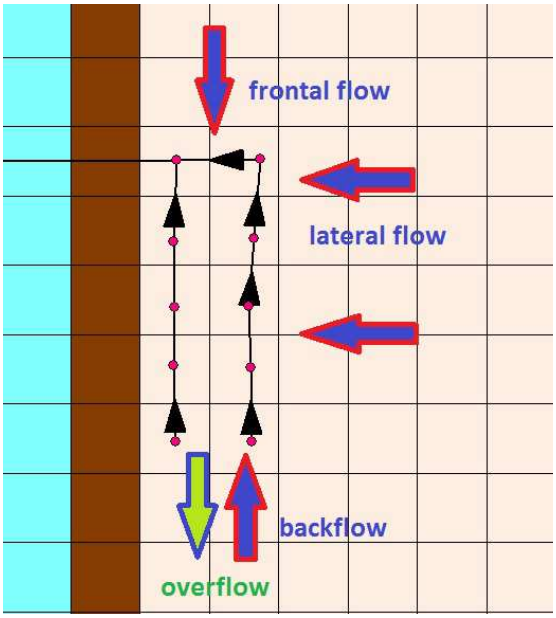

Figure 23. Flows within a drain inlet

Therefore, the drain inlet interception can be defined as:

Interception= frontal flow + lateral flow + backflow – overflow

The results of different simulations show that the relative weights of these flows vary with the discharge spillage and the transversal and longitudinal slopes (see Table 16). This analysis cannot be made in the physical model as soon as all the drain inlet drains to a unique pipe, therefore, the results cannot be validated.

Table 16. Flow distribution for different simulations

Case	2b200	2b150	2b50	2b25	2d200	2d150	2d50	2d25
Q frontal (%)	52	50	53	45	79	79	79	80
Q lateral (%)	48	50	47	55	21	21	21	20
Q overflow (%)	0	0	0	0	0	0	0	0

Case	2e200	2e150	2e50	2e25	2f200	2f150	2f50	2f25
Q frontal (%)	88	119	131	122	157	158	150	150
Q lateral (%)	13	0	0	0	0	0	0	0
Q overflow (%)	0	-19	-31	-22	-57	-58	-50	-50

Some considerations should be pointed out:

- In the cases of low longitudinal slopes (Iy<2%) the interception is divided almost equally between lateral and frontal flow.
- In the simulations of high longitudinal slopes (Iy≥2%) the interception is mainly done by the frontal part of the drain inlet (around 80%).
- In the cases of very high longitudinal slopes (Iy≥4%) the overflow can even be 50% of the intercepted flow.

However, the model set up has some disadvantages:

- Backflow can be seen during the simulation (see Figure 24) but cannot be quantified. When the overland flow that arrives to the drain inlet is higher than its efficiency, this excess of runoff flows downstream, so this flow cancels the backflow.
- Overflow cancels lateral flow due to the connection between manholes; therefore, both effects cannot be measured at the same time.

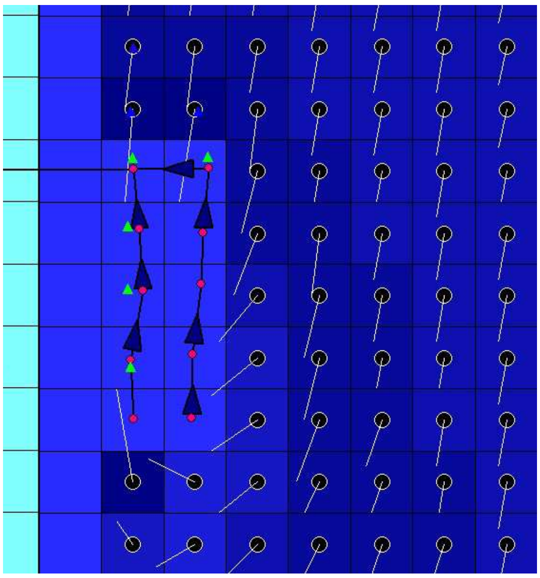

Figure 24. Velocity field nearby the drain inlet. Backflow effect.

4.1.3. Analysis of the results

After the simulation carried out with the settings explained in chapter 4.1, the following analysis can be done:

- The runoff interception process is reproduced with high accuracy in the case of a discharge of 200 l/s. In the 75% of the cases the difference between the observed and simulated interception is lower than 15%. The accuracy is lower in the cases of high transversal slope (4% -2%) combined with small and medium longitudinal slope (0-4%) (see Table 7 and Figure 19).
- The runoff interception process is reproduced with acceptable accuracy in the case of a discharge of 150 l/s. In the 62.5% of the cases the difference between the observed and simulated interception is lower than 15%. The accuracy is lower in the cases of high transversal slope (4% -3%) combined with small longitudinal slope (0-2%) (see Table 8 and Figure 20).
- The runoff interception process is reproduced with lower accuracy in the case of a discharge of 50 l/s. In the 55% of the cases the difference between the observed and simulated interception is lower than 20%. The agreement decreases in the cases of high and zero transversal slope (4%, 3%, 0%) for almost any longitudinal slope (10-0%) (see Table 9 and Figure 21).
- The runoff interception process is reproduced with low accuracy in the case of a discharge of 25 l/s. In the 50% of the cases the difference between the observed and simulated interception is lower than 20%. The accuracy is lower in the cases of almost any transversal slope (except 2%) combined with medium and high longitudinal slope (10-4%) (see Table 10 and Figure 22). Nevertheless, it is important to point out that with such a small flow, water depths and intercepted discharges are so small that the precision of the measurement element can affect the result largely.

4.1.4. Conclusions

The general trends that can be observed from the results are:

- The model, in general, underestimates the runoff interception process.
- The model is more reliable with higher approaching discharges rather than with smaller ones.
- In the cases of larger discharges, the results follow the same pattern. The higher is the longitudinal slope the more reliable is the model. The smaller is the transversal slope, the broader is the range of longitudinal slopes in which the model simulates the process properly. That fact can be observed in the formation of the green-upper-right corner in Tables 7 and 8.
- The smaller is the discharge, the less predictable is the model performance. There is no common trend in the results. Part of this behaviour can be attributed to the precision of the measurement elements in the laboratory for so small water depths and discharges.
- The values of the Weber number are high for all sets of flows and slopes, therefore, differences cannot be explained through this number.

4.2. Analysis of the influence of the roughness on model results

In a second simulation, the different models set up with low accuracy are revised (cases above 20% difference in Tables 7-10). The roughness of the 2D grid is increased with the aim of reproducing better the sheet flow conditions.

4.2.1. Settings

The same settings from the basic simulation are kept with the exception of the roughness and the simulation time, as it can be seen in Table 17.

Table 17. Summary of the second simulation parameters

Parameter	Value(s)
Grid size (cm)	15x15
Transversal slope (%)	0, 1, 2, 3, 4
Longitudinal slope (%)	0, 0.5, 1, 2, 4, 6, 8, 10
Roughness ($s/m^{1/3}$)	0.02, 0.1
Discharge (l/s)	200, 150, 50, 25
Time step (s)	1 (5 for RTC)
Simulation time (min)	5 (10-20 in some cases of 25 l/s)

2D grid

The roughness value (Manning coefficient) is increased from 0.013 $s/m^{1/3}$ to 0.02 and 0.1 $s/m^{1/3}$. The last figure is out of the range of Manning values used in common practice, however, it is applied to check the sensitivity of the model to this parameter.

Simulated event

In some cases of the 25 l/s discharge the simulated even has to be increased because the steady state is not reached in 5 min: In 025h the simulation time is 20 min, in 0g25-0f25-1h25 it is 15 min and in 0e25-1e25-1f25-1g25-3h25 it is 10 min.

4.2.2. Results

Intercepted discharge

In general, the intercepted discharge increases with larger values of roughness, as it can be seen in the following figures (Fig. 25-Fig. 26).

It is important to point out that above a Manning value of 0.2 $s/m^{1/3}$ any roughness coefficient leads to same results, so it can be said that SOBEK establish 0.2 as an upper limit.

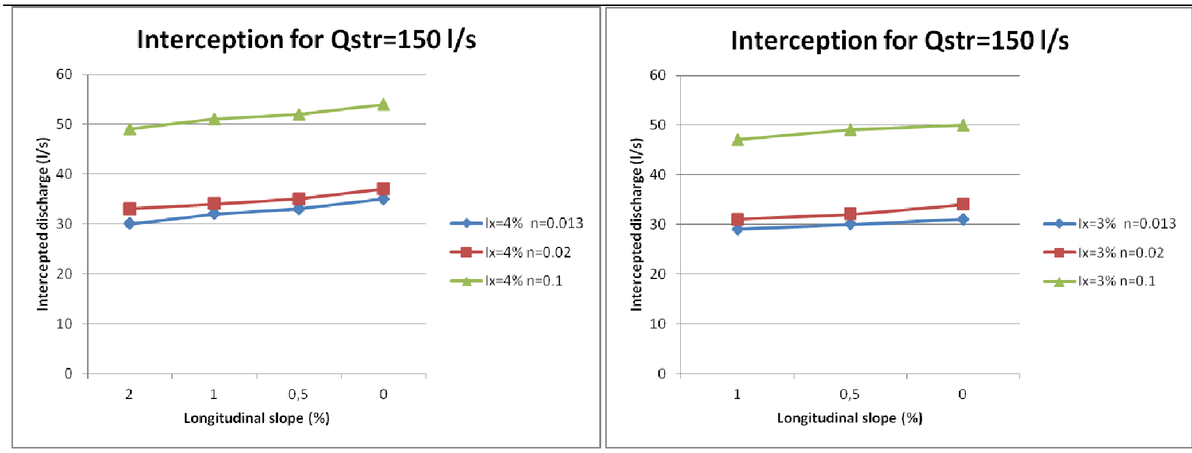

Figure 25. Interception under different roughness coefficients. Approaching flow of 150 l/s

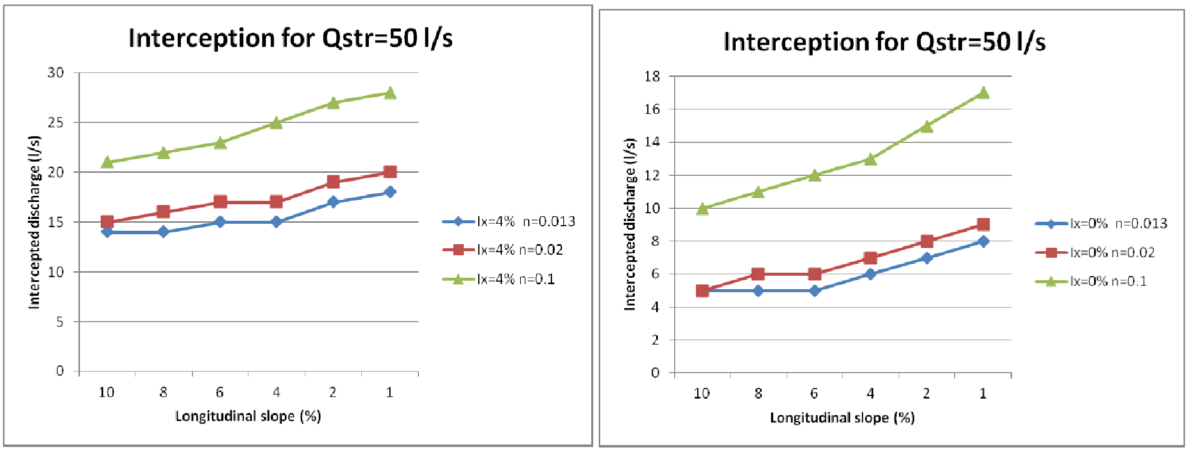

Figure 26. Interception under different roughness coefficients. Approaching flow of 50 l/s

Differences in intercepted discharge

A value of 0.1 s/m$^{1/3}$ leads to a better model performance in most of the cases, especially for larger transversal slopes. However, in the case of discharges of 50 l/s and 25 l/s the more suitable roughness coefficient varies in every situation (see Figures 27- 29).

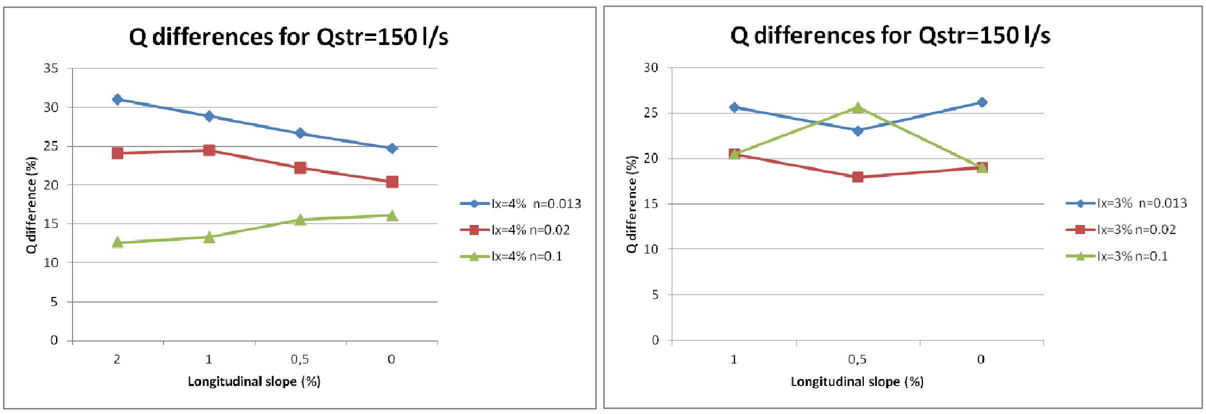

Figure 27. Percentage differences with different roughness values. Approaching flow of 150 l/s

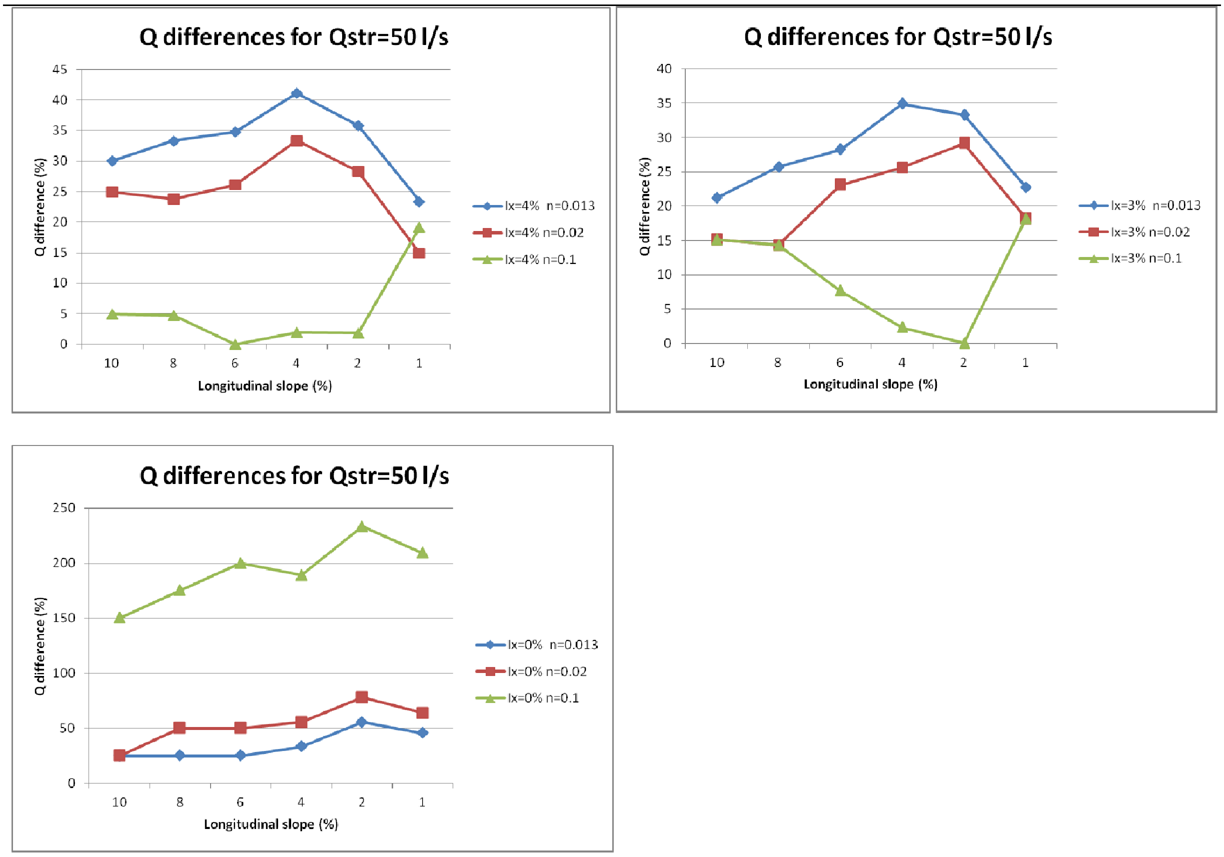

Figure 28. Percentage differences with different roughness values. Approaching flow of 50 l/s

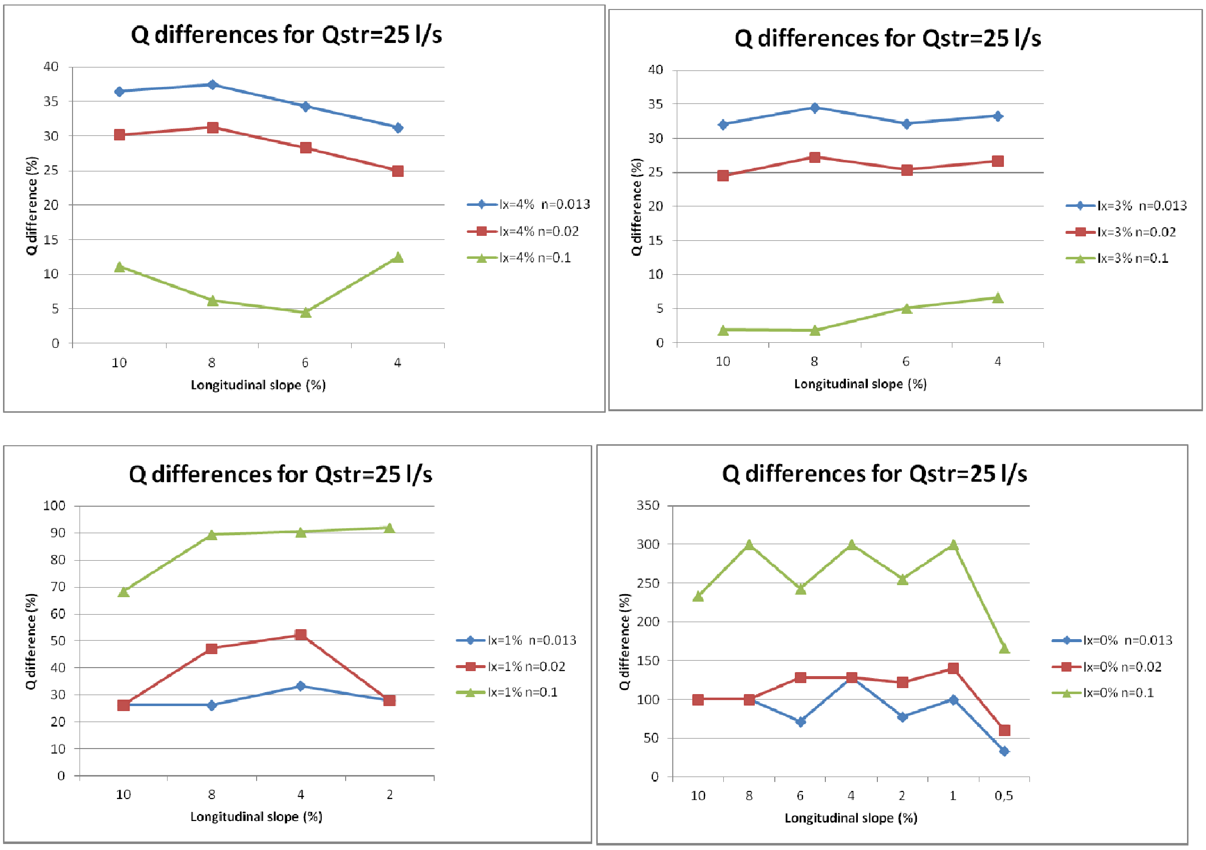

Figure 29. Percentage differences with different roughness values. Approaching flow of 25 l/s

Differences in water depth

The effect of the roughness coefficient in the model does not follow a clear pattern, depending on each case. However, it can be said in general that an increase of the roughness coefficient represents a worse model performance (see Table 18). It should be noticed again that water depths were measured with an invar scale in the physical model; hence, there is some uncertainty about the registered values.

Table 18. Water depth deviations (%) for different roughness compared to physical model

simulation	Manning		
	0.013	0.02	0.1
4d200	13	9	46
4d150	17	11	41
4c150	23	16	32
4b150	18	13	36
4a150	16	10	37
3c150	22	18	34
3b150	19	13	41
3a150	17	9	43
4h50	21	11	32
4g50	22	10	39
4f50	25	13	28
4e50	28	16	26
4d50	31	24	14
4c50	28	21	20
3h50	11	0	49
3g50	10	3	49
3f50	12	2	45
3e50	24	14	29
3d50	28	20	22
3c50	25	19	24
0h50	0	20	150
0g50	8	8	133
0f50	8	15	138
0e50	13	0	119
0d50	16	11	121
0c50	10	10	124

simulation	Manning coefficient		
	0.013	0.02	0.1
4h25	27	16	19
4g25	28	20	15
4f25	26	19	14
4e25	23	14	19
3h25	11	0	43
3g25	16	6	35
3f25	20	11	26
3e25	25	15	23
1h25	36	45	118
1g25	33	50	108
1e25	6	17	67
1d25	5	5	55
1b25	17	7	38
0h25	200	300	550
0g25	133	167	367
0f25	75	125	300
0e25	60	100	280
0d25	43	71	229
0c25	20	50	170
0b25	17	42	150

4.2.3. Conclusions

After a simulation carried out with different roughness coefficients and applying the settings explained in chapter 4.2.1, the following analysis can be done:

- The Manning roughness coefficient should be increased in one order of magnitude, from 0.013 to 0.1 s/m$^{1/3}$, in order to reproduce the sheet flow conditions. That value cannot be derived directly from the characteristics and the material of the surface, but from the range of discharges and slopes.

- The use of a higher roughness coefficient leads to a better model performance in the cases of large transversal slopes (3-4%).
- The modification of the roughness coefficient does not solve the uncertainty of the cases of low transversal slope for the smallest discharges.

4.3. Analysis of the influence of the grid resolution on model results

In a third batch of simulations, two different configurations are run under different grid sizes to check their influence in the results.

4.3.1. Settings

The same settings from the basic simulation are kept with the exception of the grid size, as it can be seen in Table 19.

Table 19. Summary of the second simulation parameters

Parameter	Value(s)
Grid size (cm)	5.0x5.0 cm
Transversal slope (%)	0
Longitudinal slope (%)	10
Manning roughness ($s/m^{1/3}$)	0.013
Discharge (l/s)	150, 50
Time step (s)	1 (5 for RTC)
Simulation time (min)	20

2D grid

A grid of 5.0x5.0 cm is tested. The drain inlet surface has to be mimic using 96 nodes: 6 to represent the width and 16 to cover the length (see Figure 30).

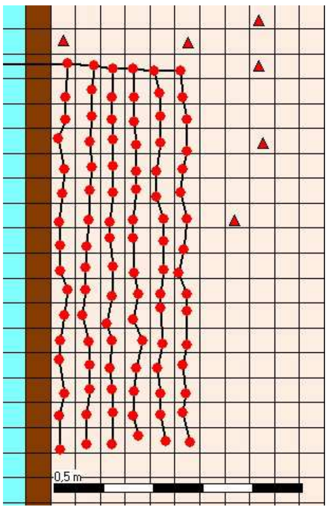

Figure 30. Drain inlet representation within a 2.0 x 2.0 cm grid.

4.3.2. Results

Intercepted discharge and model performance

The influence of the grid size in the model is not clear, as it can be seen in Table 20.

Table 20. Intercepted discharge for different grid sizes and physical model

simulation	grid size (cm)		physical model
	15	5	
0h50	5,0	2,0	4,0
0h150	10,0	8,0	12,0

Although it is not an expected result, the finer grid performs worse in these two cases. This happens because of such a detailed grid requires a large number of manholes and pipes to mimic the drain inlet; therefore, there are more interactions that cannot be controlled, leading to more uncertainty. More research is needed to overcome this problem, however, this model set up already gives some added value regarding the representation of velocities field in the platform (see Figure 31).

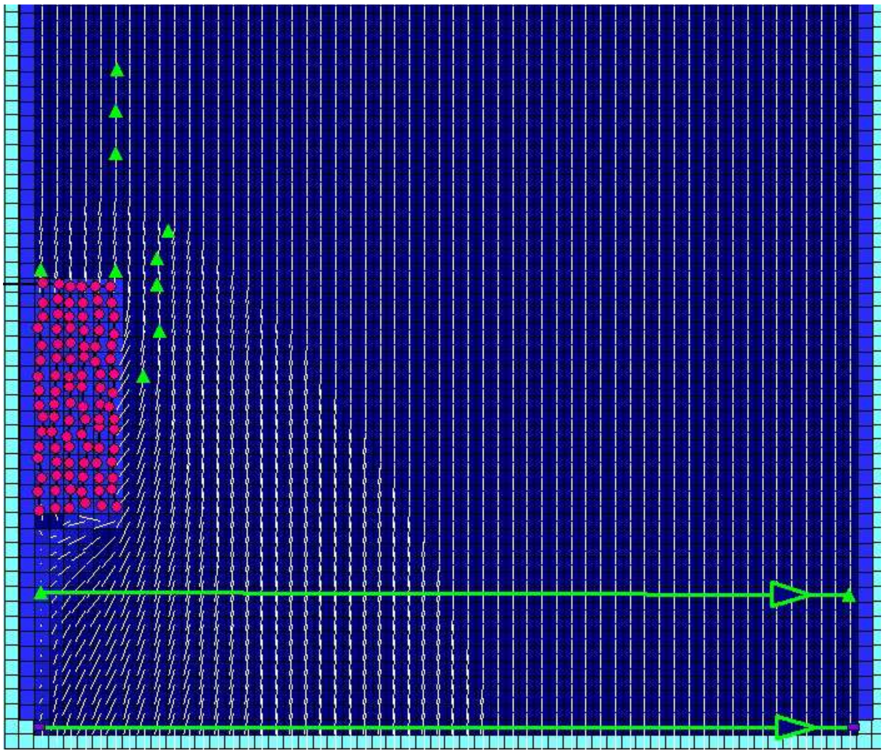

Figure 31. Velocity field in the platform for a 2 cm grid.

4.3.3. Conclusions

After the simulation carried out with the different grid sizes the following conclusions are obtained:

- There is not a clear relation between grid size and model performance. The finer is the grid, the more uncertainty in the results due to the influence of the representation (manholes and pipes).

- A grid size of 15 cm seems to be a good trade-off because of its good performance for a wider range of slopes and discharges and its short computational time.
- This grid size might be implemented just in the vicinities of the drain inlet, having a coarser grid in the rest of the schematization to save computational time. SOBEK allows the combination of different grids.

5. DISCUSSION

Some aspects of the research object of this Thesis should be discussed:

1. The poor accuracy in water depth measurement and roughness coefficient in the physical model imply uncertainty in the comparison with the numerical model, especially regarding sheet flow conditions. More extensive research about these two topics is essential to have more reliable conclusions.
2. The reliability of the model set up implemented in this research is low when describing flow in flat or nearly flat areas, especially with small discharges.
3. It can be argued that modelling drain inlet interception using a commercial software package is not the most efficient approach. The difficulties to just model a drain inlet also drive to the same thought. Nevertheless I tried to proceed in that direction with the aim of bridging the gap between research (CFD and physical models) and software used in engineering practice.
4. This research lacks of a case study in which simulation times and model performance can be compared to a traditional "runoff-to-node" approach. The use of more detailed grids nearby drain inlets combined with coarser grids in the rest of the domain helps to not increase computational times.
5. The simulations are run either with different grids or different roughness coefficients, but both parameters have not been modified at the same time to see their influence into each other. The same applies to time step. The simulation of these additional combinations is interesting to check the applicability of the model set up.
6. Simulations are only run in SOBEK, therefore, the possibilities and limitations of this software cannot be extrapolated to the so-called "commercial software".

6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Research questions

The aim of this research is to include the runoff interception process in a 1D-2D dual drainage model, reproducing a hydraulic process that is not considered in multiple urban drainage models. To study that, different model set ups are implemented and validated with a physical model.

After modelling and analysing the results, the two research questions can be answered:

1. *How can the runoff interception by drain inlets be modelled using commercial software packages?*

Runoff interception can be modelled combining a 2D overland flow, a Real Time Control module and 1D flow module. The drain inlet itself is modelled as a manhole, working as a connection between surface flow (2D) and sewer system (1D). RTC is used to fix a discharge-water depth relationship, therefore, drain inlet efficiency can be considered depending on the water depth measured just upstream its position.

The drain inlet area, which determines the discharge that might be intercepted potentially, is modelled in the 2D grid using as many grid cells as required. In the first simulation of 15 cm grid, two cells are used to cover the 30 cm width and five cells to cover the 75 cm length of the grate of the drain inlet. Hence, all the flow that intercepts these ten cells might be potentially drained by the drain inlet, which is already an improvement from the traditional "runoff-to-node" approach. In addition to that, the implementation of Q-y relationship allows the engineer to consider in the simulation the hydraulic efficiency of the drain inlet. That means that all the approaching discharge cannot be drained because of the effects of turbulences and flow conditions derived from the grate geometry and the street slopes, something that would not be feasible without a CFD simulation.

2. *What level of detail in roughness and topography is it desirable to mimic the runoff interception process in a 1D-2D dual drainage model?*

The basic model set up is already a good approximation of the interception process in the cases of large discharges combined with medium to high longitudinal slopes. In this set up, the roughness coefficient is estimated from the characteristics of the surface material (smooth concrete, roughness Manning value of 0.013 $s/m^{1/3}$) and the grid size is 15 cm.

In cases of large discharges in areas with low longitudinal slopes and in case of small discharges under almost any combination of slopes, the roughness coefficient has to be increased in order to reproduce sheet flow conditions while using shallow water equations. The value of the roughness cannot be derived directly from the surface characteristics but it is used as a calibration parameter. As far as it is the only degree of freedom in the equations, the roughness coefficient is used to compensate the effect of the surface tension, a force that is not considered in shallow water equations and has a significant influence in sheet flow conditions. This increase is estimated to be in one order of magnitude when using Manning coefficient.

A combination of flat or nearly flat areas and small approaching discharges leads to flow conditions that cannot be described with the configuration proposed in this thesis. The shallow water equations might not be suitable for these circumstances. In those situations, 2D drainage models should include the equations to model sheet flow in order to achieve a reliable model performance. However, it should be pointed out that such small approaching discharges lead to water depths of maximum few centimetres; therefore, their impact on the surface drainage is limited.

The grid size of 15 cm seems to be a good option because gives a good performance under a broader range of slopes and discharges. Although this circumstance should be tested in a case study to check their influence in the computational time, it is important to note that this resolution is only required nearby the drain inlet, where water depths define its hydraulic efficiency. Nevertheless, it is important to point out that the accuracy of the results change significantly depending on the grid size, even when using pretty similar grid sizes. This circumstance represents another source of uncertainty for the modeller, as soon as the computational time is commonly the only criteria for this election.

6.2. Recommendations

Based on the research exposed in this report, the following recommendations for further research are given:

1. More extensive research is required to explain runoff and interception processes in flat areas, especially with small discharges. Proper equations to model sheet flow conditions should be implemented in 2D drainage models to achieve reliable results in those situations.
2. In case of using shallow water equations when representing sheet flow, the roughness coefficient must be increased to correct the lack of tension forces in those equations. This increase is necessary when the water depths have the same order of magnitude than the surface roughness.
3. An interesting approach might be to run the same set of simulations using the parameters of the grate geometry (A and B) to calibrate the numerical model, instead of modifying the roughness coefficient.
4. Research should be carried out in the interconnections between roughness and grid resolution. The influence of the grid size in the model results should be also studied.
5. The same approach can be tried in other software packages.
6. This thesis focuses on the simulation of the runoff interception process; however, a case study is required to check the applicability of this approach in engineering practice.

6.3. Research contribution

The main outcome of this Thesis is the development of a strategy to model runoff interception in SOBEK, taking into account the geometry of the drain inlet. With the combination of a 2D grid with a Real Time Control module, a discharge-water depth relationship (Q-y) is implemented. Hence, the hydraulic efficiency of the drain inlet is considered in the interception process. The roughness coefficient must be analysed deeply in case of flat areas and small approaching discharges.

When using this approach in a case study, drain inlet efficiency is obtained from its geometrical characteristics beforehand. This efficiency will determine which fraction of the approaching runoff will be drained and which one will just pass over the grate. Roughness coefficients and grid sizes of every area should be adjust to the local conditions of slopes and predicted flows.

REFERENCES

Barroca B., Bernardara P., Mouchel J.M., Hubert G. (2006) Indicators for identification of urban flooding vulnerability. *Nat. Hazards Earth Syst. Sci., 6, 553–561.*

Camino A.G., Zhu D.Z., Rajaratnam N., (2011). Hydraulics of stacked drop manholes. *Journal of Irrigation and Drainage Engineering. ASCE. Vol 137, No 8, 537–552.*

Carvalho R.F., Leandro J., David L.M., Martins R., Melo N. Numerical research of the inflow into different gullies outlets (2011). *Google scholar.*

Carvalho R.F., Leandro J., Martins R., Abreu J., de Lima J.L.M.P. (2011). 2DV numerical modeling of different flows occurring in gullies. *12th International Conference on Urban Drainage, Porto Alegre/ Brazil, 11-16 September 2011.*

Chanson H., (2004) Hydraulics of Rectangular Dropshafts. *Journal of Irrigation and Drainage Engineering. ASCE. Vol 130, No 6, 523–529.*

Chen A., Djordjevic S., Leandro J., Savic J. (2007) The urban inundation model with bidirectional flow interaction between 2D overland surface and 1D sewer networks. *Novatech 2007*

Djordjevic S., Saul A., Tabor G., Blanksby J., Galambos I., Sabtu I., Sailor G. (2011) Experimental and numerical investigation of interactions between above and below ground drainage systems. *12nd International Conference on Urban Drainage, Porto Alegre/Brazil, 10-15 September 2011*

Gómez M. (2008). Curso de Hidrología Urbana. *Chapters 7 and 8*.

Gómez M., Hidalgo G., Russo B. (2013) Experimental campaign to determine grated inlet clogging factors in an urban catchment of Barcelona. *Urban Water Journal, 10:1, 50-61. doi: 10.1080/1573062X.2012.690435*

Gómez M. and Russo B. (2005) Comparative study of methodologies to determine inlet efficiency from test data. HEC-12 methodology vs UPC method. *Proceedings of the Conference Water Resources Management III, Wessex Institute of Technology. WIT Press Southampton, Boston, UK, pp. 633–642.*

Gómez M. and Russo B. (2010) Methodology to estimate hydraulic efficiency of drain inlets. *Proceedings of the Institution of Civil Engineers. Water Management 164 February 2011 Issue WM2 Pages 81–90 doi: 10.1680/wama.900070.*

Hager W.H., Gisonni C. (2006) Supercritical flow in sewer manholes. *Acqua e Città. I Convegno Nazionale di Idraulica Urbana. Sant' Agnello (NA), 28-30.*

Izzard, C.F., (1946) Hydraulics of Runoff from Developed Surfaces. *Highway Research Board, Proc., Vol 26, pp 129-150.*

Lamb R., Crossley M., Waller S. (2009) A fast two-dimensional floodplain inundation model. *Proceedings of the Institution of Civil Engineers. Water Management 162 Issue WM6, pp 363-370.*

Llasat M. C., Llasat-Botija M., Prat M.A., Porcú F., Price C., Mugnai A., Lagouvardos K., Kotroni V., Katsanos D., Michaelides S., Yair Y., Savvidou K., Nicolaides K. (2010) High-impact floods and flash floods in Mediterranean countries: the FLASH preliminary database. *Advances in Geosciences, 23, pp 47–55.*

Llasat M. C., Llasat-Botija M., Rodriguez A., Lindbergh S. (2010) Flash floods in Catalonia: a recurrent situation. *Advances in Geosciences, 26, pp 105–111.*

Mark O., Weesakul S., Apirumanekul C., Aroonnet S.B., Djordjevic S.(2004) Potential and limitations of 1D modelling of urban flooding. *Journal of Hydrology, 299 pp 284–299.*

Myers, T.G. (2002) Modeling laminar sheet flow over rough surfaces. *Water Resources Research, 38 (11), 1230.*

Peakall J., Warburton J. (1996) Surface tension is small hydraulic river models – the significance of the Weber number. *Journal of Hydrology (NZ) 35(2): 199-212.*

Russo B., Suñez D., Velasco M., Djordjevic S. (2012) Flood hazard assessment in the Raval District of Barcelona using a 1D/2D coupled model. *9th International Conference on Urban Drainage Modelling Belgrade 2012.*

Saul A.J. (2007), Integrated surface and sub-surface interactive flooding and inundation model. *Flood Risk Management Research Consortium (FRMRC). Research Report UR4.*

Smith L.S., Liang Q., Quinn P.F. (2013) A flexible hydrodynamic modelling framework for GPUs and CPUs: Application to the Carlisle 2005 floods (p.217). *International Conference on Flood Resilience. Experiences in Asia and Europe. Exeter, United Kingdom September 2013.*

Smith M.B. (2005) Comment on “Analysis and modelling of flooding in urban drainage systems”. *Journal of Hydrology 317 (2006) 355-363.*

United Nations. World Urbanization Prospects: The 2011 revision. *New York: United Nation Population Division, Department of Economic and Social Affairs, United Nations, 2012.*

U.S. Department of Transportation. Federal Highway Administration. Urban Drainage Design Manual. August 2001.

Vojinovic Z., Tutulic D. (2009) On the use of 1D and coupled 1D-2D modelling approaches for assessment of flood damage in urban areas. *Urban Water Journal Vol. 6, No. 3, September 2009, 183–199*

Zhao C.H., Zhu D.Z., Rajaratnam N., (2006) Experimental study of surcharged flow at combining sewer junctions. *Journal of Hydraulic Engineering. ASCE. Vol 132, No 12, 1259-1271. December 1, 2006.*

APPENDIX

A. Intercepted discharges in the model of Gómez and Russo

Q intercepted (Gómez and Russo) (l/s)						
Qstr	200	l/s				
		Ix(%)				
		4	3	2	1	0
	10	30.0	24.0	20.0	16.0	12.0
	8	32.0	26.0	22.0	16.0	14.0
	6	36.0	30.0	26.0	20.0	16.0
Iy(%)	4	42.0	36.0	32.0	24.0	18.0
	2	46.0	40.0	34.0	26.0	20.0
	1	46.0	42.0	36.0	28.0	22.0
	0.5	46.0	40.0	34.0	28.0	22.0
	0	48.0	42.0	38.0	32.0	28.0

Q intercepted (Gómez and Russo) (l/s)						
Qstr	150	l/s				
		Ix(%)				
		4	3	2	1	0
	10	25.5	22.5	19.5	15.0	12.0
	8	27.0	24.0	19.5	15.0	12.0
	6	30.0	25.5	21.0	16.5	13.5
Iy(%)	4	34.5	30.0	22.5	19.5	13.5
	2	43.5	36.0	28.5	21.0	15.0
	1	45.0	39.0	31.5	25.5	16.5
	0.5	45.0	39.0	33.0	27.0	19.5
	0	46.5	42.0	34.5	30.0	24.0

Q intercepted (Gómez and Russo) (l/s)						
Qstr	50	l/s				
		Ix(%)				
		4	3	2	1	0
	10	20.0	16.5	13.5	8.5	4.0
	8	21.0	17.5	13.5	8.5	4.0
	6	23.0	19.5	14.5	9.0	4.0
Iy(%)	4	25.5	21.5	15.5	9.5	4.5
	2	26.5	24.0	17.5	10.0	4.5
	1	23.5	22.0	18.0	11.5	5.5
	0.5	22.5	19.5	16.5	11.5	7.5
	0	23.5	19.5	18.5	13.5	10.5

Q intercepted (Gómez and Russo) (l/s)						
Qstr		25 l/s				
				Ix(%)		
		4	3	2	1	0
	10	15.8	13.3	9.0	4.8	1.5
	8	16.0	13.8	9.3	4.8	1.5
	6	16.8	14.8	9.8	5.0	1.8
Iy(%)	4	16.0	15.0	10.8	5.3	1.8
	2	13.0	13.0	11.5	6.3	2.3
	1	13.3	11.8	10.5	7.0	2.5
	0.5	13.5	11.8	9.5	7.3	3.8
	0	14.3	12.3	10.5	9.0	6.5

B. Intercepted discharges in SOBEK for first simulation (see Table 4)

Q intercepted (SOBEK) (l/s)						
Qstr	200	l/s				
		Ix(%)				
		4	3	2	1	0
	10	31	28	23	18	13
	8	33	29	24	19	13
	6	34	31	26	21	15
Iy(%)	4	35	32	28	22	16
	2	36	34	28	24	18
	1	37	34	29	25	21
	0.5	38	35	30	27	23
	0	40	37	33	29	25

Q intercepted (SOBEK) (l/s)						
Qstr	150	l/s				
		Ix(%)				
		4	3	2	1	0
	10	26	23	20	15	10
	8	28	25	21	16	11
	6	28	26	22	17	12
Iy(%)	4	29	28	24	19	13
	2	30	29	25	21	15
	1	32	29	26	21	17
	0.5	33	30	27	23	19
	0	35	31	28	25	21

Q intercepted (SOBEK) (l/s)						
Qstr	50	l/s				
		Ix(%)				
		4	3	2	1	0
	10	14	13	11	8	5
	8	14	13	11	8	5
	6	15	14	12	9	5
Iy(%)	4	15	14	13	10	6
	2	17	16	14	11	7
	1	18	17	15	12	8
	0.5	19	17	15	12	9
	0	20	18	16	13	10

Q intercepted (SOBEK) (l/s)						
Qstr		25 l/s				
		Ix(%)				
		4	3	2	1	0
Iy(%)	10	10	9	8	6	3
	8	10	9	8	6	3
	6	11	10	8	6	3
	4	11	10	9	7	4
	2	12	11	10	8	4
	1	13	12	10	8	5
	0.5	13	12	11	9	5
	0	14	13	11	9	6

C. Water depths in the model of Gómez and Russo

Water depth (Gómez and Russo) (mm)						
Qstr	200	l/s				
				Ix(%)		
		4	3	2	1	0
	10	70	58	45	35	25
	8	74	61	46	38	27
	6	90	75	58	43	30
Iy(%)	4	98	81	65	55	44
	2	104	91	75	62	46
	1	106	96	80	68	54
	0.5	108	98	80	73	65
	0	108	98	86	77	68

Water depth (Gómez and Russo) (mm)						
Qstr	150	l/s				
				Ix(%)		
		4	3	2	1	0
	10	69	56	44	34	25
	8	72	58	48	36	27
	6	74	62	52	41	29
Iy(%)	4	80	69	56	43	31
	2	94	83	66	50	39
	1	106	96	86	54	41
	0.5	106	94	89	69	63
	0	108	96	86	69	65

Water depth (Gómez and Russo) (mm)						
Qstr	50	l/s				
				Ix(%)		
		4	3	2	1	0
	10	47	37	29	19	10
	8	49	39	31	20	12
	6	53	42	33	20	13
Iy(%)	4	58	51	36	22	16
	2	70	60	44	31	19
	1	71	63	52	36	21
	0.5	73	64	52	42	29
	0	75	65	53	42	30

Water depth (Gómez and Russo) (mm)						
Qstr		25 l/s				
		Ix(%)				
		4	3	2	1	0
	10	37	28	22	11	2
	8	40	31	25	12	3
	6	42	35	27	14	4
Iy(%)	4	43	40	31	18	5
	2	44	42	38	22	7
	1	45	43	40	27	10
	0.5	51	49	41	29	12
	0	52	51	46	32	15

D. Water depths in SOBEK for first simulation (see Table 4)

Water depth (SOBEK) (mm)						
Qstr		200	l/s			
				Ix(%)		
		4	3	2	1	0
	10	76	67	54	40	27
	8	80	71	58	43	28
	6	83	75	62	47	31
Iy(%)	4	87	80	65	51	35
	2	90	83	66	56	41
	1	93	84	71	59	48
	0.5	97	87	77	65	53
	0	101	93	80	71	60

Water depth (SOBEK) (mm)						
Qstr		150	l/s			
				Ix(%)		
		4	3	2	1	0
	10	66	56	46	34	22
	8	68	60	50	37	23
	6	70	64	54	40	25
Iy(%)	4	74	68	59	44	29
	2	78	73	62	48	34
	1	82	75	63	51	39
	0.5	87	76	66	55	44
	0	91	80	71	60	50

Water depth (SOBEK) (mm)						
Qstr		50	l/s			
				Ix(%)		
		4	3	2	1	0
	10	37	33	28	19	10
	8	38	35	29	21	11
	6	40	37	32	23	12
Iy(%)	4	42	39	34	26	14
	2	48	43	37	28	16
	1	51	47	40	30	19
	0.5	53	49	41	32	21
	0	57	52	44	35	25

Water depth (SOBEK) (mm)						
Qstr		25	l/s			
		Ix(%)				
		4	3	2	1	0
	10	27	25	21	15	6
	8	29	26	22	16	7
	6	31	28	23	17	7
Iy(%)	4	33	30	25	19	8
	2	36	33	28	21	10
	1	38	35	29	23	12
	0.5	40	36	31	24	14
	0	42	39	33	27	17

E. Intercepted discharges in SOBEK for roughness of 0.02 s/m$^{1/3}$ (see Table 17)

Q intercepted (SOBEK) (l/s)						
Qstr		200 l/s				
		Ix(%)				
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	38				
	1					
	0.5					
	0					

Q intercepted (SOBEK) (l/s)						
Qstr		150 l/s				
		Ix(%)				
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	33				
	1	34	31			
	0.5	35	32			
	0	37	34			

Q intercepted (SOBEK) (l/s)						
Qstr		50 l/s				
		Ix(%)				
		4	3	2	1	0
	10	15	14			5
	8	16	15			6
	6	17	15			6
Iy(%)	4	17	16			7
	2	19	17			8
	1	20	18			9
	0.5					
	0					

Q intercepted (SOBEK) (l/s)						
Qstr		25 l/s				
		Ix(%)				
		4	3	2	1	0
	10	11	10		6	3
	8	11	10		7	3
	6	12	11			4
Iy(%)	4	12	11		8	4
	2				8	5
	1					6
	0.5				9	6
	0					

F. Water depths in SOBEK for roughness of 0.02 $s/m^{1/3}$ (see Table 17)

Water depth (SOBEK) (mm)						
Qstr		200	l/s			
		Ix(%)				
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	95				
	1					
	0.5					
	0					

Water depth (SOBEK) (mm)						
Qstr		150	l/s			
		Ix(%)				
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	84				
	1	89	79			
	0.5	92	82			
	0	97	87			

Water depth (SOBEK) (mm)						
Qstr		50	l/s			
		Ix(%)				
		4	3	2	1	0
	10	42	37			12
	8	44	40			13
	6	46	41			15
Iy(%)	4	49	44			16
	2	53	48			21
	1	56	51			23
	0.5					
	0					

Water depth (SOBEK) (mm)

Qstr 25 l/s

		Ix(%)				
		4	3	2	1	0
Iy(%)	10	31	28		16	8
	8	32	29		18	8
	6	34	31			9
	4	37	34		21	10
	2				23	12
	1					15
	0.5				27	17
	0					

G. Intercepted discharges in SOBEK for roughness of 0.1 s/m$^{1/3}$ (see Table 17)

Q intercepted (SOBEK) (l/s)						
Qstr		200	l/s			
		Ix(%)				
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	56				
	1					
	0.5					
	0					

Q intercepted (SOBEK) (l/s)						
Qstr		150	l/s			
		Ix(%)				
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	49				
	1	51	47			
	0.5	52	49			
	0	54	50			

Q intercepted (SOBEK) (l/s)						
Qstr		50	l/s			
		Ix(%)				
		4	3	2	1	0
	10	21	19			10
	8	22	20			11
	6	23	21			12
Iy(%)	4	25	22			13
	2	27	24			15
	1	28	26			17
	0.5					
	0					

Q intercepted (SOBEK) (l/s)

Qstr 25 l/s

		Ix(%)				
		4	3	2	1	0
	10	14	13		8	5
	8	15	14		9	6
	6	16	14			6
Iy(%)	4	18	16		10	7
	2				12	8
	1					10
	0.5				13	10
	0					

H. Water depths in SOBEK for roughness of 0.1 $s/m^{1/3}$ (see Table 17)

Water depth (SOBEK) (mm)						
Qstr		200	l/s			
				Ix(%)		
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	152				
	1					
	0.5					
	0					

Water depth (SOBEK) (mm)						
Qstr		150	l/s			
				Ix(%)		
		4	3	2	1	0
	10					
	8					
	6					
Iy(%)	4					
	2	133				
	1	140	129			
	0.5	144	133			
	0	148	137			

Water depth (SOBEK) (mm)						
Qstr		50	l/s			
				Ix(%)		
		4	3	2	1	0
	10	62	55			25
	8	68	58			28
	6	68	61			31
Iy(%)	4	73	66			35
	2	80	73			42
	1	85	78			47
	0.5					
	0					

Water depth (SOBEK) (mm)

Qstr 25 l/s

		Ix(%)				
		4	3	2	1	0
	10	44	40		24	13
	8	46	42		25	14
	6	48	44			16
Iy(%)	4	51	49		30	19
	2				34	23
	1					27
	0.5				40	30
	0					