The use of integrated modelling in an urban water system and its influence on flood estimation

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Preface

This report is the result of my research for my master thesis. I wrote this thesis at the end of my study period in Enschede, where I followed the Master Water Engineering and Management. Since I witnessed the flooding of the Rhine River when I was very young, water always interested me. During my bachelor Civil Engineering and Management the modelling and water courses were the most appealing to me and in my bachelor thesis I learned the basics of modelling using SOBEK. During my master modelling and quantitative assessment were the most interesting courses. For my master thesis I wanted to combine the knowledge from these courses into something new. At Royal Haskoning integrated modelling was used not very often and with mixed results and they were eager to know whether integrated modelling really influences model results and if so, what method is the most appropriate in the current situation. Based on the little knowledge of sewer systems and with the help of the people at Royal Haskoning Nijmegen I learned a lot about integrated modelling and the design and practices of sewer systems in the Netherlands.

I want to thank the people at Royal Haskoning Nijmegen and my supervisors at the University of Twente for their support and time during my research. Furthermore I want to thank Anne, for her time and patience with me around.

Summary

In an urban catchment there are several systems present: a sewer system (a combined or separate system), a receiving water body and surface flood pathways created during extreme events.

Regulating urban flooding is very complex because of the interactions between the sewer system and the surface water system. Presently each of the policies regulates a different part of the urban water system, but there are no policies that consider the urban water system as a whole. In practice this can easily lead to problems. If the water levels of the receiving water body are too high there can be no free discharge of combined sewer overflow, resulting in backwater in the sewer system. These backwater effects can cause flooding in the urban area if the storage of the sewer system is filled by a rainfall event. Furthermore combined sewer overflows can have a significant effect on the peak discharge of the receiving water body. To determine the impact of flooding models are used which calculate a scenario that occurs on average once every few years, the so called design-event. If flooding is caused by the interaction of the sewer system and the receiving water system it is unclear which design-event should be used to assess the flood risk and the return period of the event, because the flooding can be caused by multiple types of events.

Although it is possible that interactions occur between the subsystems in an urban water catchment, water systems in the urban area are often modelled without little cross-reference to each other, although in more complicated situations this may be required. To determine whether integrated modelling should influence the design of the urban water system a case study was performed. The study area is the industrial area De Vosdonk in Etten-Leur, a town in the Dutch province *Noord-Brabant*. Near the *Vosdonk* are frequent problems with flooding due to the limited discharge capacity of the receiving water body and the insufficient capacity of the sewer system.

The objective of this study is to compare different methods of integrated modelling and determine the influence of integrated modelling on return periods of flooding of the urban water system near the *Vosdonk*.

There are different methods of integrated modelling available, each with their own strengths and weaknesses:

- The models can be run separately and allow for interaction using level hydrographs, this method is easy to set up, but because a number of iterations are required to increase the accuracy of this method, the calculation times are higher than with the other methods.
- Coupling of existing models using a modelling framework. A relatively new modelling framework is the Open Modelling Interface (OpenMI). At the moment, only a few case studies have been done using OpenMI and none of them used the models that are used in the Netherlands.
- Fully integrated models. Fully integrated models are difficult to create because of software limitations, but once they are finished they are easy to use. The main difficulty in creating fully integrated models is that current models often cannot be used because they were not built with integration in mind.

To determine which integrated modelling method is preferable to determine the flood risk of the urban water system, the different methods of integrated modelling are evaluated on a number of criteria. Since the calculation times for the method using level hydrographs are too high and the fully integrated model gave memory errors for long simulation periods, the model framework OpenMI was the preferred method in this study.

The influence of integrated modelling on the calculated number of floods is determined using a time-series of precipitation data of measurement stations near the study area. Using fifteen years of precipitation data, two types of calculations were performed. The first one is a stand-alone calculation of the sewer system and the receiving water body and the second one a calculation using the integrated model in OpenMI. The number of floods in the sewer system that were calculated in both methods was compared and there was a small, but no significant, increase in the number of floods calculated with the integrated model. Although the number of floods did not change much using integrated modelling, the flood depth increased compared to the stand-alone calculations. The "stand-alone" model of the receiving water body already uses a simple schematization of the urban area and this proved a good estimation of the water levels in the receiving water body.

From the results of the integrated model it can be concluded that integrated modelling is of no added value for the sewer system in this case when the policy is only based on the frequency of flooding, since there is no significant increase in the number of flooding events. However, when the policy is based on flood risk, integrated modelling is of importance, since the calculated flood depths increase when using the integrated model. The added value of integrated modelling for the receiving water body is limited since the stand-alone models often incorporate a simple schematization of the sewer system which can give a good insight in the outflow from the sewer system to the receiving water body.

Policy makers which incorporate flood risk in their plans should determine the need for integrated modelling in their plans. A first insight whether it is necessary to create an integrated model is to determine how sensitive the urban water system is for interactions between the subsystems. Since this study showed that integrated modelling influences the total flood risk, this will be likely the case in other urban areas as well, especially those with similar characteristics as the *Vosdonk*. Future research should focus on whether there is an effect of integrated modelling on the flood risk in the urban water system for urban areas with other characteristics, such as a smaller urban catchment compared to the total catchment size, as well.

Contents

1 Introduction

This chapter starts with a problem description, followed by an introduction to the study area. After this introduction the objective of this study and its research questions are posed. This chapter is concluded with an outline for this report.

1.1 Problem description

In an urban catchment there are several systems present: a sewer system (a combined or separate system), a receiving water body and surface flood pathways created during extreme events (Bamford, Halmforth, Lai, & Martin, 2008). Groundwater also plays an important role in the urban water system, but is in most cases not responsible for urban flooding and in general causes only minor inconveniences (Vos & van den Heuvel, 2006). Each of the different systems in the urban water cycle is considered with little cross-reference to other systems (Butler & Davies, 2000). However, in many cases the complexity of the urban water system requires that the system is considered as a whole, examples are surface water quality, urban flooding and groundwater recharge (Gehrels et al., 2005).

In recent years many municipalities in the Netherlands experienced flooding of the urban area. This was due to flooding of the surface water system and/or the sewer system (Vos & van den Heuvel, 2006). Many municipalities are in need of implementing measures to prevent flooding of the urban area during future climate changes; this is often done in cooperation with the water boards.

The sewer system is the responsibility of the municipality and it is designed to discharge a design-event with a return period of two years (NEN, 2008; Stichting RIONED, 2004). This means that flooding as defined in NEN-EN-752 (NEN, 2008), is allowed to happen once every two years, but since this is not defined in law, municipalities have a certain freedom to determine a reasonable return period (Stichting RIONED, 2009). The urban area consists to a large extent of impervious area and this causes a quick reaction to precipitation and leads to a system which responds to high intensities of precipitation.

The receiving water system is the responsibility of the water board (Ministerie van Verkeer en Waterstaat, 2010). To prevent frequent flooding of the urban area, the receiving water body must be able to discharge a flood wave with a return period of 100 years (Ministerie van Verkeer en Waterstaat, 2008), although a more frequent flooding of rural areas is allowed. The receiving water body has a high response time in comparison with the sewer system, because of the storage in the rural area. In the rural area there is little to none impervious area and therefore precipitation typically infiltrates to the saturated and unsaturated zone before it is transformed into runoff. This process is slower than surface runoff over impervious areas and thus allows for more storage in the system. This is also the reason why the system is triggered by rather large amounts of precipitation instead of high intensities. An overview of the relevant properties for both water systems is presented in Table 1.

Table 1 Properties of relevant water systems for urban flooding

Water system	Return period of design-event	Trigger	Timescale
Sewer System	2 years	High intensity precipitation	Minutes / hour
Receiving water system	100 years	Large volumes of precipitation	Several hours / days

Regulating urban flooding is very complex because of the interactions that can occur between the sewer system and the surface water system. Presently each of the policies regulates a different part of the urban water system, but there are no policies that consider the urban water system as a whole. In practice this can lead to problems. If the water levels of the receiving water body are too high there can be no free discharge of combined sewer overflow, resulting in backwater in the sewer system. These backwater effects can cause flooding in the urban area by limiting the discharge capacity. Furthermore combined sewer overflows can have a significant effect on the peak discharge of the receiving water body (Vaes, Feyaerts, & Swartenbroekx, 2008). If flooding is caused by the interaction of the sewer system and the receiving water system it is unclear which design-event should be used to assess the flood risk and the return period of the event, because the flooding can be caused by multiple events. It is even more difficult to decide which of the policies should be used to assess whether the flooding is not happening too often. To determine if flooding occurs too often and whether interactions between water systems are important, a model of the water systems was built to assess them. This study focuses on the modelled interactions between the water systems and the consequences of these interactions.

1.1.1 Sewer system

The sewer system is the responsibility of the municipality. Rainwater is the responsibility of the land owner, unless it cannot be reasonably expected that he is able to drain the rainwater. In that case municipalities are required to efficiently collect and process incoming rainwater (Waterwet, art. 3.5). According to the *National Agreement on Water* municipalities are required to define areas that are susceptible to flooding and implement measures to prevent flooding in current and future conditions. In the current practice this means that sewer systems are designed to drain a synthetic rainfall event with a return period of two years, without any flooding of the sewer system.

When flooding in the urban area occurs, it is not in all cases problematic because of the strict definition of flooding in NEN-EN-752 (NEN, 2008). In case the flood depths are low and for a short period of time, the flooding is often termed as hindrance since most of the water can be stored in the street profile. With increasing flood depths and durations, the chance of damage to properties and economic damage increases and can cause severe problems in the urban area. The economic damage of urban flooding also depends on the housing density and the economic activities in the area. In a sewer plan (*Verbreed Gemeentelijk Rioleringsplan*) municipalities must define their measures to prevent flooding and the situations in which flooding will not be prevented. Etten-Leur defines three different area types where flooding can occur (Tauw, 2008):

- The city centre and the main roads;
- Residential areas;
- Industrial areas.

Flooding of the city centre and the main roads is only acceptable during extreme conditions, while in residential areas flooding may occur if the flood water remains in the street profile and for only a limited time. Flooding of industrial areas is permitted as long as flood water cannot enter the properties (Gemeenteraad Etten-Leur, 2008). In its sewer plan, the municipality defined *Bui 9,* a synthetic rainfall event with a return period of five years, as the design event to assess the hydraulic functioning of the sewer system.

1.1.2 Receiving water body

In the Netherlands the receiving water bodies are the responsibility of the water boards when they are not one of the primary water courses (Waterwet, art. 3.2, subsection 2). The water courses in the study area are not one of the primary water courses, so they are the responsibility of the water board. The *Waterwet* offers no concrete return period, but only states that this must be further specified by provincial regulations. This was done in 2003 in the *National Agreement on Water (Ministerie van Verkeer en Waterstaat, 2003)*. In this agreement the return periods as stated in Table 2 are defined.

Table 2 Allowed flooding frequencies receiving water body (Ministerie van Verkeer en Waterstaat, 2003)

Land Type	Flood frequency [1/yr]
Grass land	1/10
Agricultural fields	1/25
Intensive agriculture	1/50
Greenhouse horticulture	1/50
Urban area	1/100

These allowed flooding frequencies are based on a flood risk approach where the flood risk is the product of the frequency of flooding and the impact of flooding, see Equation (1.1).

$$risk = frequency \cdot impacts \tag{1.1}$$

Since flooding in urban areas has more consequences than flooding in grass lands, the allowed flooding frequency is much lower. By calculating the flood risk, the cost of mitigation measures can be compared to the reduction of the flood risk and therefore make more economic choices whether measures should be implemented. Although this study focuses on changes in the frequency of flooding, this directly influences the flood risk. Any change in flooding frequency is therefore important for the water managers.

1.2 Case description

To determine whether the interaction between the receiving water body and the sewer system occur in practice, a case study is performed. The study area is situated around Etten-Leur in the western part of the Dutch province *Noord-Brabant*, see Figure 1. This area is chosen because a previous study was done in the area and this showed that there are frequent interactions between the sewer system and the receiving water body. In the west part of Etten-Leur the industrial area *"De Vosdonk"* is situated. At the *Vosdonk* there are frequent problems with flooding, caused by the limited discharge capacity of the receiving water body, the rapid discharge of the paved surface and the insufficient capacity of the sewer system (van Dijk, 2009).

In this case the water courses downstream of Etten-Leur are considered regional water courses (Gedeputeerde Staten Noord-Brabant, 2010) and therefore must be able to discharge an event with a return period of hundred years. The remainder of the water courses are not considered in regulations and are therefore without strict flooding regulations. However, in a previous agreement, the water board defined a minimum return period of flooding in its work area of fifty years (Hoogheemraadschap West-Brabant, 1999), awaiting national regulations. Since there are no further regulations for these water courses that agreement still determines the required flooding frequency (Waterschap de Brabantse Delta, 2008).

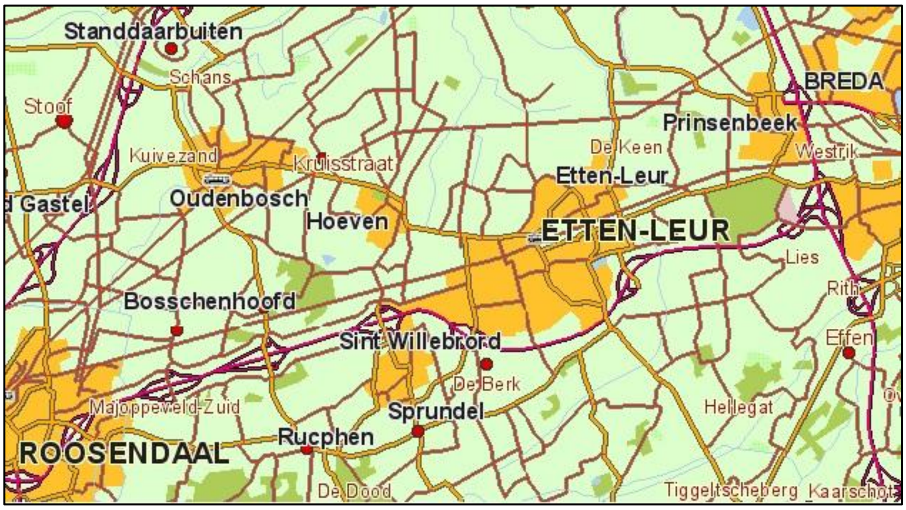

Figure 1 The study area and its surroundings

Part of the problems is due to the surface water system in the Vosdonk which is too small to store the runoff. This leads to inundations in and around the study area and sewer overflows are likely to occur regularly. In the summers of 2002 and 2006 there were problems with flooding and inundation of the industrial area as well of the city centre of Etten-Leur (van Dijk, 2009).

The sewer system is also not able to perform as required. This is due to the fact that more than sixty percent of the area, for which the sewer system was designed, is connected to it. This leads to inundations when using *Bui 8,* a synthetic rainfall event with a return period of two years, as defined in the *Leidraad Riolering*, Module C2100 (Stichting RIONED, 2004), but based on that policy document the sewer system must be able to discharge this storm without flooding. The sewer system is very sensitive to the water levels in the receiving water body. Most sewer overflow locations are drowned when the water levels in the receiving water body reach a level with a return period of two years. This leads to more flooding of the industrial and residential areas (van Dijk, 2009).

Because of the reasons above, the small dimensions of the receiving water body do not only influence inundations from the receiving water system, but also influence flooding of the sewer system. The urban water system must be improved to prevent flooding in the future. However, it is difficult to determine the design event because there are no criteria for flooding events which are caused by flooding from the surface water system and the sewer system combined. An integrated model is in this case a first step towards determining the problems in the urban water system and can contribute to prevent flooding in future situations. There are different methods to create an integrated model and it is unclear which method is preferable.

1.3 Objective and research questions

The objective of this study is to compare different methods of integrated modelling and determine the influence of integrated modelling on return periods and severity of flooding of the urban water system. The main research question is:

How can integrated modelling be used in the design of an urban water system and what is the influence on flooding in and around "de Vosdonk"?

The research question can be divided in several sub questions to help answering the main question:

- What are the advantages of different forms of integrated modelling? (Chapter 2)
- What are the differences in the model results of the various forms of integrated modelling and how can they be explained? (Chapter 4)
- What method of integrated modelling is preferable in this case? (Chapter 4)
- What is the effect of integrated modelling on return periods and severity of flooding? (Chapter 5)

1.4 Outline

This report will answer the research question and sub questions in the following chapters. In the second chapter the basics of integrated modelling are explained and the different methods of integrated modelling are presented. In the third chapter the integrated modelling techniques are applied to the study area and in the fourth chapter the different forms of integrated modelling are compared and finally one method for use in this study is selected. With this method the influence of integrated modelling on flood risk is analyzed in the fifth chapter. This study is finalized with the conclusions and recommendations in Chapter 6.

2 Integrated modelling

This chapter introduces the different forms of integrated modelling, followed by the (dis-)advantages of the different methods of integrated modelling. In the final paragraph of this chapter the criteria for ranking the integrated modelling methods are presented.

2.1 Introduction

Current developments in water policies call for integrated water management to be put into practice and identify whole catchment modelling as a key part of integrated management. The challenge that this presents is not only that individual catchment processes should be modelled but also their interactions. The problems related to the interactions between the sewer system and the receiving water body are becoming ever clearer, and therefore in some cases an integrated approach is required. To support this integrated approach the models of the water systems must be integrated as well. This can be done in several ways (Bamford, et al., 2008):

- Run the models separately but allow for interaction using level hydrographs
- Coupling of existing models using a modelling framework
- Fully integrated models

2.2 Level hydrographs

In the current practice of integrated modelling the various models are run separately, and the interaction with other models is done using level hydrographs. This so-called offline coupling is done by using the output from model A as input for model B, and vice versa, until the results vary little between two successive iterations. One of the disadvantages of this coupling method is the accuracy of the results. Furthermore the method is error prone, because the number of manual operations is very high.

Integrated modelling using level hydrographs is currently a frequently used method. The method is relatively simple to set-up and run. The method works as follows:

- The model of the sewer system is run for the entire simulation period.
- The resulting outflow of the sewer system is used as lateral inflow for the model of the receiving water body.
- The water levels of the receiving water body are used as a boundary condition for the model of the sewer system.

These steps are iterated until the results vary little between two consecutive steps. Since the interactions between the models are defined before each model simulation, the resulting interactions are not necessarily correct.

2.3 Modelling frameworks

Modelling frameworks can be used to couple different existing models in order to create an integrated model. First an introduction on why the Open Modelling Interface (OpenMI) was developed is given, followed by a short description of the possible methods to exchange data in modelling frameworks.

2.3.1 Introduction

In order to be able to use existing models for the creation of an integrated model, modelling frameworks were developed (Gehrels, et al., 2005; Singh, Subramanian, & Refsgaard, 1999). The objective of modelling frameworks is not to provide a new modelling tool, but to provide a mechanism by which models can be linked in a consistent manner (Hutchings, 2002), and allow the output of one model to be used as input for the next (Sonnenberg, 2008).

There are currently a number of modelling frameworks available, all with their advantages and disadvantages (Hutchings, 2002). However, most of the frameworks are hardly used because of limitations in the frameworks, the small number of involved organizations and the lack of open and published standards (Sonnenberg, 2008). The main limitations of the currently available modelling frameworks are scale and dimensionality (Hutchings, 2002).

Scale is one of the most important issues for modelling frameworks, since all models can be configured at a range of temporal and spatial scales with varying resolution. An example of differences in temporal scale is the linking of groundwater models with a large time step to rainfall event surface water models with a much shorter time step. An example of the differences in spatial scale is a lumped rainfall runoff models linked to detailed hydraulic models. Most of the existing modelling frameworks have resolved this issue by limiting the spatial and temporal scale at which linking can occur. Another method to solve the scales issue is to create some form of buffer so data from one model can be stored until it is valid for use in the next model. Besides the Open Modelling Interface there is currently no modelling framework that allows for buffering the exchanged data (Hutchings, 2002).

Models used for water management have a wide variety of dimensions, ranging from zero to three dimensional models, which in turn are either steady state or transient. Linking mechanisms between steady state and transient models is possible in almost all of the modelling frameworks, but the linking of different dimensional models is much more complex. Some modelling frameworks allow these links at all levels, but often they must be made on a manual basis (Hutchings, 2002).

Because of these shortcomings the development of a new modelling framework, which had to be specifically designed for the water management domain, was proposed. This resulted in the development of the Open Modelling Interface (Hutchings, 2002).

2.3.2 The Open Modelling Interface (OpenMI)

Until 2002, no modelling framework for the generic linking of models was developed. The need for such a generic modelling framework arose with the technological advances in computing and the Water Framework Directive. Co-funded by the European Commission, the FP5 (the Fifth Framework Programme) project HarmonIT developed the Open Modelling Interface in 2001. Development was primarily led by major commercial developers, such as DHI, Delft Hydraulics (Deltares) and HR Wallingford (Moore, Gijsbers, Fortune, Gregersen, & Blind, 2007). After four years of development, OpenMI is now becoming widely accepted, but to become a global standard for linking models in the water domain more models must be implemented. Since organisations and developers will only invest in OpenMI when it is widely available and supported, the OpenMI Association was created (Moore, et al., 2007). The OpenMI Association is a not for profit organisation that promotes the development, use, management and maintenance of the Open Modelling Interface (OpenMI Association).

The linking of the models is done in three steps, displayed in Figure 2. In the data exchange step the data between the linked models is exchanged. The OpenMI configuration keeps track of what quantities and locations must be exchanged. The model engines perform the actual calculations. For more information about the concepts of OpenMI see Appendix I.

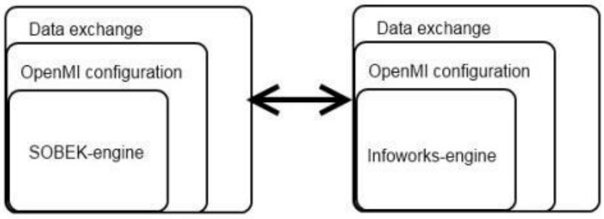

Figure 2 Working of OpenMI

Currently, OpenMI is still in development and there have been only a limited number of case studies in which OpenMI was used. Most municipalities in the Netherlands have a model of their sewer system in Infoworks CS, and the water boards have a model of the receiving water body in SOBEK. Theoretically it is possible to couple these two models using OpenMI, but there have been no studies so far to test how reliable the integration of Infoworks CS and SOBEK really is and what the potential pitfalls are.

2.3.3 Link types in OpenMI

When using OpenMI to couple different models there are different approaches to define the exchange of data.

Explicit approach

In the explicit or sequential non-iterative approach the sets of equations for both models are solved for their respective time steps. At the end of each time step the data is exchanged between the models and is used as input for the next time step. If the time steps of the models are not equal, the exchange is at the end of the larger time step (Vergroesen, van de Giesen, & van de Ven, 2010). An overview of the calculation steps is shown in Appendix I.

The advantage of this approach is that it is easy to implement and is computational efficient because there is no iteration (Vergroesen, et al., 2010). A disadvantage of this is that numerical instability can occur if the time steps are too large (LaBolle, Ahmed, & Fogg, 2003). Another disadvantage is the possibility of large errors in the calculation if there is a sudden change in input conditions (Vergroesen, et al., 2010). Large changes in input conditions can result in a significant change in the calculated flux for one model, but this is only propagated in the next model in the next time step. This results in large convergence errors for the current time step. However the error in the water balance for an entire calculation period will be negligible because no water is lost or gained in the calculations.

OpenMI is by default using the explicit approach in its calculations (Brinkman, Gregersen, S.Hummel, S.J.P., & Westen, 2005).

Implicit approach

The implicit or sequential iterative approach is based on the explicit approach, but the main difference is that the implicit approach iterates the flux between the models until the difference between two successive iterations is smaller than the convergence criterion (Vergroesen, et al., 2010). Because of these iterations the calculation time for this approach is longer than in the explicit approach. It is also important to note that in the implicit approach at each time step a small balance error remains. Over the entire calculation period this balance error keeps increasing, in opposition to the balance error in the explicit approach.

The implicit approach can be implemented in OpenMI by using the iteration controller (Brinkman, et al., 2005), but its implementation in the current version (v1.4.0) is rather limited and cannot be used for models with more than ten interaction points.

2.4 Fully integrated models

Fully integrated models are the most advanced type of integrated models, because the data exchange is performed using a single calculation scheme to solve the equations for the entire water system. Fully integrated models are easy to use once they are finished; results are easily accessible in the same format which makes communicating them easier (Bamford, et al., 2008). But fully integrated models also have some disadvantages. The most problematic one is that most of the existing models cannot be used directly in the integrated model, because they were not built with integration in mind. Rebuilding the models is a very time consuming task, which requires expertise and data that often are not available.

Although the method is technically advanced, calculations with this type of integrated model present a practical problem. Because the calculation scheme is solved for the entire system at once, it is not possible to use different time steps for the various subsystems. This means that the time step is either tailored to the slowest flow component, so the results for the faster component are less accurate, to the fastest flow component, resulting in very long calculation times (Ivanov, Vivoni, Bras, & Entekhabi, 2004) or an intermediary time step size. Fully integrated modelling is considered the most accurate form of integrated modelling, but also the most complex and time consuming method (Jacques, Simunek, Mallants, & van Genuchten, 2006; Steefel & MacQuarrie, 1996).

Apart from using a modelling framework it is also possible to create a fully integrated model. In order to do this a choice must be made in which software package this will be done. Since the receiving water body is more complex than the model of the sewer system, the choice was made to convert the model of the sewer system to SOBEK, the software package in which the model of the receiving water body was already built.

To locate potential problems while creating the fully integrated model an analysis was made to determine any differences in modelling approach between Infoworks CS and SOBEK. Both SOBEK and Infoworks CS use the Saint-Venant equations to calculate the water levels and discharges. The Saint-Venant equations are a system of two coupled equations, the continuity equation and the momentum equation, see equation (2.1) and equation (2.2). The exact description of the fourth term in equation (2.2) can vary, depending on the hydraulic roughness type used in the model. The fifth term describes the wind friction and is for the sewer system equal to zero.

The water levels in the sewer system are determined in Infoworks CS at the calculation nodes, which are the manholes and overflow locations, and the discharges are determined in the links, the conduits between the manholes. The calculation solves the Saint-Venant equations by using a Preismann 4-point scheme (Wallingford Software Ltd., 2008). The water levels and discharges in the receiving water body are calculated in SOBEK by using the Delft-scheme, which is based on a staggered grid (WL Delft Hydraulics, 2009).

Continuity equation

$$\frac{\partial A_f}{\partial t}+\frac{\partial Q}{\partial x}=q_{lat} \tag{2.1}$$

Momentum equation

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\frac{Q^2}{A_f}\right)+g\cdot A_f\cdot\frac{\partial h}{\partial x}+\frac{gQ|Q|}{C^2RA_f}-W_f\frac{\tau_{wi}}{\rho_w}=0 \tag{2.2}$$

Table 3 Explanation of symbols in equations (2.1) and (2.2) with their units

Symbol	Meaning
A_f	Flow area [m^2]
t	Time [s]
Q	Discharge [m^3/s]
x	Location [m]
q_{lat}	Lateral discharge per unit length [m^2/s]
G	Gravitational acceleration [m/s^2]
h	Water level [m]
C	Chézy coefficient [$m^{0.5}/s$]
R	Hydraulic radius [m]
W_f	Flow width [m]
τ_{wi}	Wind friction [N/m^2]
ρ_w	Water density [kg/m^3]

Since the calculation schemes are the same it is possible to import a model built in Infoworks CS in SOBEK Urban. However, this is not an easy task and very time consuming because the model in Infoworks CS cannot be exported in a format that can be directly imported in SOBEK Urban. It is therefore necessary to import the various layers and shape-files from Infoworks CS individually into SOBEK Urban. After this is done, only the nodes and links are imported in SOBEK Urban, but there are no catchment areas, dimensions and input data specified. These must all be imported by hand, which is error prone.

One of the differences between SOBEK Urban and Infoworks CS are the method of modelling rainfall runoff and runoff routing. The calculation of water levels and discharges are using the same equations in both SOBEK and Infoworks CS, see equations (2.1) and (2.2). A short explanation of the rainfall runoff and runoff routing models used is given below, for a more detailed explanation see Appendix II.

Rainfall-runoff concepts

The rainfall-runoff in both models is based on the same schematization. Precipitation falls on the surface, where part of it will infiltrate and another part evaporates. What remains is the net precipitation, which is transported to the sewer system via overland flow. This process is schematized in Figure 3. The net precipitation is determined by the rainfall-runoff models, the routing to the sewer system is calculated by the runoff routing models.

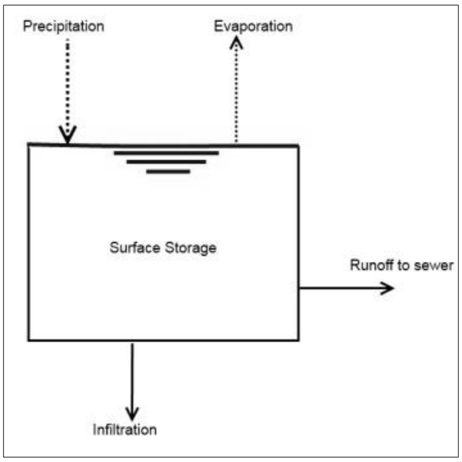

Figure 3 Rainfall-runoff concepts

In Infoworks CS there are two different models used for rainfall-runoff modelling. For the pervious areas this is a modified Horton Infiltration model (Verma, 1982), see equation (2.3) and for the impervious areas this is the fixed infiltration model, see equation (2.4). In SOBEK Urban there is only one rainfall-runoff model, the NWRW model, as described in Leidraad Riolering, Module C2100 (Stichting RIONED, 2004). It is similar to the modified Horton Infiltration model used in Infoworks CS, but works slightly different (WL Delft Hydraulics, 2009), see equations (2.5) and (2.6). Equation (2.5) applies to the decrease in infiltration capacity, while equation (2.6) applies to the increase in infiltration capacity.

$$f = f_c + \left(f_0 - f_c \right) e^{-kt} \tag{2.3}$$

Table 4 Symbols and units in equation (2.3), modified Horton infiltration model

Symbol	Meaning
f	Infiltration rate [mm/hr]
f_c	Limiting infiltration rate [mm/hr]
f_0	Initial infiltration rate [mm/hr]
k	Coefficient of exponential tem [1/hr]
t	Time [hr]

$$R = r \cdot P \cdot I \cdot t \cdot \tfrac{1}{1000} \tag{2.4}$$

Table 5 Symbols and units in equation (2.4), fixed infiltration model

Symbol	Meaning
R	Runoff [m3/hr]
r	Ratio, between 0 and 1 [-]
I	Precipitation intensity [mm/hr]
A	Area [m2]
t	Time [hr]

$$f_t = f_e + \left(f_b - f_e \right) \cdot e^{-k_a t} \tag{2.5}$$

$$f_t = f_b - \left(f_b - f_e \right) \cdot e^{-k_h t} \tag{2.6}$$

Table 6 Symbols and units in equations (2.5) and (2.6)

Symbol	Meaning
f_t	Infiltration Capacity at time t [mm/hr]
f_e	minimum infiltration capacity [mm/hr]
f_b	maximum infiltration capacity at time t=0 [mm/hr]
k_a	time factor decreasing infiltration capacity [1/hr]
k_h	time factor increasing infiltration capacity [1/hr]
t	time [hr]

In Infoworks CS the runoff-routing is determined using the SPRINT-model. This is a single linear reservoir model which is depending on a number of observations originating from the U.S.A. and France (Wallingford Software Ltd., 2008) and is only applicable for lumped catchments. SOBEK Urban is using a different method to determine the delay in runoff. Here the Rational method is used. The Rational method is a lumped method and is depending on the net rainfall, the length to the nearest inflow to the sewer and the roughness and slope of the area (WL Delft Hydraulics, 2009). This can influence the results of the model of the sewer system in SOBEK compared to the model in Infoworks CS. In the case study it will be determined whether these differences are significant.

2.5 Criteria for ranking integrated models

To be able to determine a preferred method of integrated modelling a number of criteria must be defined. In this paragraph these criteria are defined and explained and will be used later on in this report to determine what type of integrated modelling should be used. Since the different methods of integrated modelling all have certain properties which must be addressed by the criteria it is important to first define the goal of the criteria in this paragraph.

The ultimate goal of these criteria is to help choosing one method of integrated modelling which will be used to determine the effect of integrated modelling on the flooding of the urban water system when compared to the standalone models. Since there is no design event available for the integrated urban water system, the chosen form of integrated modelling must be able to perform calculations of long simulation periods.

In most cases, model selection is based on the ability of the model to reproduce gauged data, the quality of the schematization and parameter values. Since the integrated models in this study use the same schematization and parameters, these criteria cannot be used for the evaluation and selection of an integrated model. In literature there are a number of studies which deal with this problem such as Becker (2010) and Bamford (2008). The criteria in Becker (2010) are leading in the model selection since this study is comparing similar models as are used in this study, although there are some additional criteria which are tailored for his purposes that are not suitable for this study. Bamford (2008) is using a number of criteria to justify the use of a fully integrated model, but there is no evaluation included in his paper. Therefore those criteria are additional to those from Becker (2010).

The selected criteria cover the model performance and the technical aspects of modelling, the other aspects of modelling, such as scales and quality of the schematization are equal for each of the integrated modelling techniques and are therefore not considered in this selection. The selected criteria are:

- Calculation times
    - Preparation time
    - CPU time
    - Post-processing time
- Precision (Becker, 2010)
- Robustness
- Usability
- Suitability for time-series calculations

Calculation times (Becker, 2010) are an important characteristic in modelling. For short calculation periods calculation times are less important, but the longer the simulation period, the efficiency of the calculations is becoming more important. Long calculation times can become an obstacle when multiple scenarios have to be modelled or during model calibration and are therefore considered as a negative aspect for a modelling method. Since the preparation time and post-processing time also plays a role in the total calculation time of a model, these parts are equally important as the CPU-time. Therefore the total calculation time is a combination of these parts. Infoworks CS is able to perform calculations on multiple cores, the so-called multithreading. SOBEK can only run on one core and that will have an impact on calculation times. Since multithreading can save time in the coupled model this can be considered an advantage; the models are not run after each other but can perform calculations simultaneously.

Precision (Becker, 2010) indicates the exactness of the exchanges between the models. A good precision indicates that there are little or no differences between the exchanged values from one model to another. A lower precision indicates that there are differences between the exchanged data, up to the point where there is little relation between the exchanged data.

Robustness (Becker, 2010) is the chance of failures due to model limitations or more straightforward user errors. Manual operations are error prone and therefore limit the robustness of the model. But also software bugs have an influence on the robustness of the solution.

Usability (based on Bamford, et al., 2008) is a combination of the possibility to make changes in the model structure and the accessibility of results.

Suitable for time-series calculations indicates whether the integrated model can be used for long simulation periods. When this is not the case the integrated model cannot achieve the goal of this study and can therefore not be used to determine the influence of integrated modelling on flooding of the urban water system.

3 Integrated modelling of the study area

In this chapter the models of the receiving water body and the sewer system are presented, followed by a description of the various integrated models. After the description of the various models, the input data for this study are presented. This chapter concludes with a discussion of the limitation of the models and input data.

3.1 Introduction

The study area is situated in the Western part of the Dutch province *Noord-Brabant*, see Figure 1. *De Vosdonk* is an industrial area near the town of Etten-Leur, where extensive flooding occurs more often than it should based on the current policies (Tauw, 2008). In the study area there are a number of water basins present, an overview of them is presented in Figure 4 and Table 7. The main water bodies in the area are the *Lokkervaart*, which after the Vosdonk is called the *Laaksche Vaart*, and the *Kibbelvaart*, which flows into the Laaksche Vaart. The Laaksche Vaart finally discharges into the *Mark,* which in turn is a small tributary of the Meuse River. As can be seen in Figure 4, the Vosdonk is mainly situated in the basin of the Lokkervaart, with a small part in the Kibbelvaart basin. In the years 2002 and 2006 extensive flooding of the Vosdonk and parts of the city centre occurred.

Table 7 Size of the catchment areas in the study area (source: GIS-data water board *Brabantse Delta*)

Name	Catchment Area [km^2]
Lokkervaart	17.4
Kibbelvaart	14.2
Laaksche Vaart	16.4
Total	**48.0**

In a first study (Westein, 2009), the sewer model in Infoworks CS was coupled with the surface water model in SOBEK using level hydrographs. The sewer system model receives precipitation input in the form of *Bui 8*, a design storm with a return period of two years as specified in the Leidraad Riolering, Module C2100 (Stichting RIONED, 2004), while the receiving water model uses a nine day stochastic design storm derived from historic precipitation data in the Netherlands (STOWA, 2004), in this case with a return period of two years. The results of these calculations show that flooding of the urban area is more severe compared to the standalone model, because outflow locations are drowned, limiting the outflow capacity of the sewer system.

In the study area there are very little data available for model calibration and validation. There are no discharge data for the flooding event in 2006 and for the event in 2002 there are only daily averages. Precipitation data are available for both flooding events. Based on the few data available it is not possible to calibrate and validate the current or the integrated model, but the current model is able to reasonably reproduce peak discharges and inundation patterns (Westein, 2009). The SOBEK-model of the receiving water body was calibrated during an *integrale gebiedsanalyse* using an event in 1998 with over 100 mm precipitation in two days. The results of this calibration were that peak discharges and water levels were reproduced correctly, but the model retains water longer than in reality. The model of the sewer system, built in Infoworks CS, was not calibrated, but based on observations during floods it can be concluded that the model calculates flooding at the same locations as in reality (van Dijk, 2009).

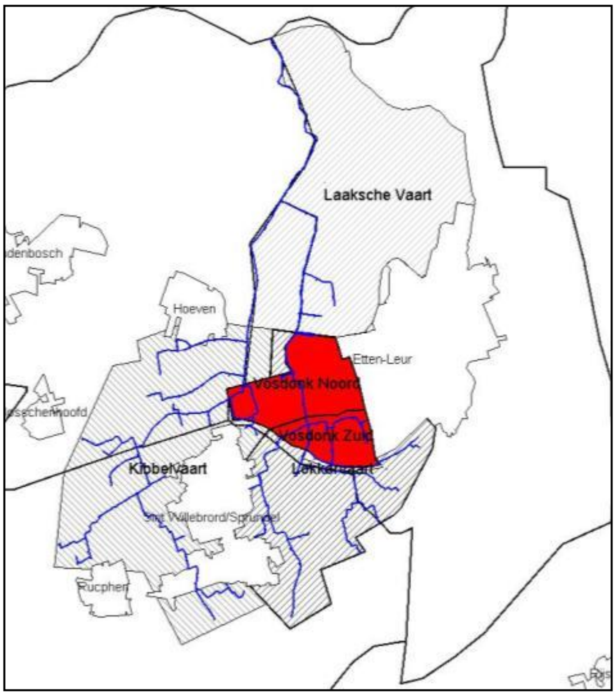

Figure 4 Study area (red), river basins and modelled water courses (blue)

3.2 Model of the receiving water body

The SOBEK model has been built in 2008 to check whether the chance of flooding in the study area was equal to or lower than the design criterions norms (van Dijk, 2009). The model is originally calibrated for the period in September 1998, when 100 mm of rainfall fell in two days. The model receives input from the rainfall-runoff module in SOBEK. The rural area consists mainly of unpaved area, while in the urbanized areas the paved area becomes more important. Also the urban area of Etten-Leur was schematized with the rainfall-runoff module in SOBEK. Later on the SOBEK model was changed with respect to the modelling of the urban area. The rainfall-runoff locations in the urban area were removed and lateral flows were added to facilitate the coupling with Infoworks CS (van Dijk, 2009). The receiving water body with the sewer overflow locations in Etten-Leur is shown in Figure 5.

The original SOBEK model also used the 1D-2D overland flow module. By using this module an elevation map of the area is connected to the water system and when water levels rise over the river banks, the floodwater is routed over the surrounding area. This is a very time consuming procedure and calculation times of the SOBEK model were very long. Since OpenMI is not compatible with the 1D-2D overland flow module, it was disabled. This sped up the calculations, but the resulting water levels in the system were not calculated correctly anymore, since flooding stored a great volume of water in the upper part of the catchment. To compensate the missing storage, different retention areas were added. These retention areas are so constructed that they can store a large volume. The result of this remodelling is that the water levels at the sewer overflow locations match more or less to the model with the 1D-2D overland flow module, see Appendix III. To ensure the calculations were relatively smooth in dry periods, a very small discharge was added to the model boundaries, otherwise the receiving water body would be completely dry and this causes numerical instabilities which leads to long calculation times.

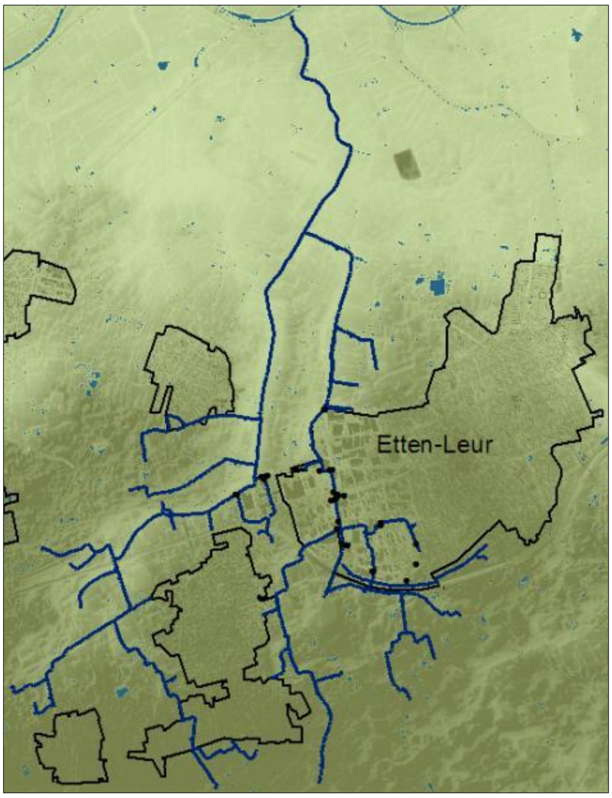

Figure 5 Receiving water body in SOBEK (blue) with sewer overflow locations (black dots)

3.3 Model of the sewer system

The model of the sewer system is originally built in Infoworks CS. The model contains information about land use, the diameters of the pipes and the dimensions of manholes. Most models of sewer systems have difficulties in modelling floods. When water is starting to flow from the sewer system over the street it changes into surface flow. In literature, there are a number of studies which consider this limitation in modelling the flooding of the sewer system.

- Consider all the flood water that leaves the sewer system as lost;
- Store the flood water in a virtual basin above the manhole;
- Create an additional layer of (open) pipes, these should represent the street profile; or
- Couple the model of the sewer system with a surface flow model.

The loss method can be considered as a realistic option when the flood water can infiltrate in the ground or flow directly towards another water system. Since this is often not the case in an urban environment, this method is not used in this study.

The most advanced method to model flooding of the sewer system is to couple it with a surface flow model (Smith, 2006). Using this method the flood water flows over the surface towards another inlet of the sewer system or to another surface water body. To accurately describe the flow of water over the surface a high resolution grid is required (Mark, Weesakul, Apirumanekul, Aroonnet, &

Djordjevic, 2004). A drawback of this method is the increase in calculation times required for these models, since surface flow is more complicated to calculate than pipe flow.

Storing the flood water in a virtual basin above the manhole is an in-between solution to the problem. It is not as realistic as the surface flow models, but it retains all the flood water in the sewer system. The size of the basins above the manholes can have an influence on the model results and must therefore be estimated for each sewer system separately. Although this solution is easier to implement, it provides less reliable results than the models with a combined surface flow model, the differences between these two methods can increase up to 20 centimetres, although it depends on the size of the virtual basins (Mark, et al., 2004). In this case the absolute values are of less importance since the results of the integrated model will be compared to the standalone model.

The Infoworks CS model in this study uses a basin with an area of 10 m^2 at the street level, widening to 12 m^2 at a height of two meters above the street level. Since maximum flood levels are likely to be less than one meter, the average area of each basin is between 10 and 11 m^2. The size of the virtual basin influences the calculation result through the pressure gradient. When the basin is chosen too small, the resulting pressure will be high, resulting in higher discharge capacities than in reality and vice versa. When the water height in the virtual basins is used to determine the impact of flooding, extra care must be taken in the interpretation of these values. Since the manholes are spaced about fifty meters apart, the basin size may be too small to correctly indicate flood depths. Therefore the flood volume at each of the nodes is used for analysis, since this is will be less influenced by the basin size.

The modelled sewer system consists of a combined system and a separated system. Unfortunately the model is not calibrated since there is no data available to perform a calibration. But a previous study showed that the model is able to calculate inundation patterns which match with the locations where flooding is observed during the floods in the years 2002 and 2006 (van Dijk, 2009). The sewer system with the sewer overflow locations is shown in Figure 6. This means that although the absolute value of the flood depth may be inaccurate, it gives an indication on the size of the flooding in that area.

Figure 6 Sewer system in Infoworks CS (red) with sewer overflow locations (black dots)

3.4 The integrated models

The integrated model is a combination of the models of the sewer system and the receiving water body and is shown in Figure 7. The interactions between the models are at the sewer overflow locations, indicated with black dots. All of the overflow locations are present in both models, so water levels from the receiving water body can be used as input for the sewer system and outflow from the sewer system can be used as a lateral discharge to the receiving water body.

Before using OpenMI to couple the SOBEK and Infoworks CS models, first must be established whether OpenMI itself introduces an error in the model calculations. This is done by setting up the integrated model in OpenMI using rainfall events where the models should not interact. The details of these events are discussed in the next paragraphs.

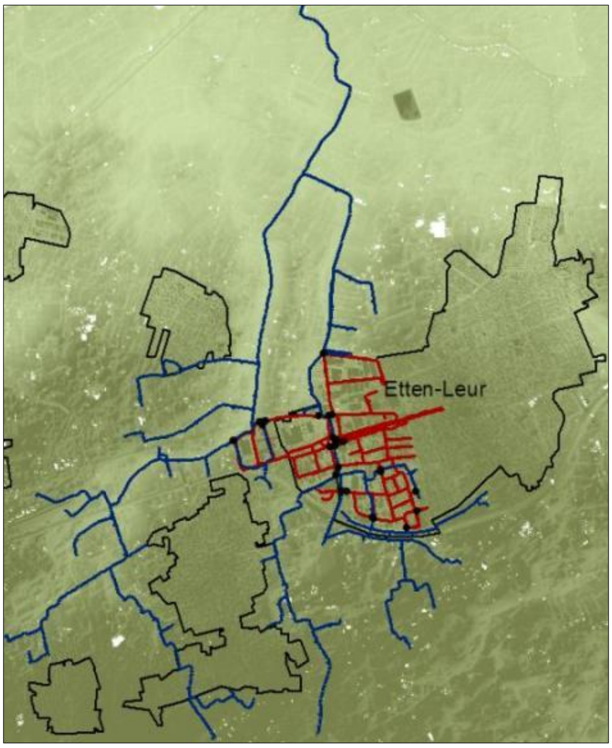

Figure 7 Integrated model with receiving water body (blue), sewer system (red) and overflow locations (black dots)

3.4.1 The integrated model using OpenMI

The integrated model in OpenMI will be using explicit links, since there are more interaction points than supported by the iteration controller, see Paragraph 2.3.3. To couple the sewer system to the receiving water system the output from the model in Infoworks CS at the outfall (sewer overflow) locations is the input for the model in SOBEK as a lateral inflow. The water levels in SOBEK near these lateral inflows are the input for the water level at the outfall locations. This way a bidirectional link between the sewer system and the receiving water body is established. The locations where the models are coupled are shown in Figure 7 as black dots.

Influence of the integrated model in OpenMI on SOBEK calculations

In case there is only precipitation on the catchment area of the receiving water body and none in the urban area, there will be no discharge from the sewer system, so the water levels in the integrated model should be equal to the water levels in a stand-alone SOBEK calculation, as long as the water levels in the receiving water body are not above the overflow threshold. To determine this, a simulation is set-up with no precipitation in Infoworks CS and a low intensity precipitation of 1 mm/hr in SOBEK, with a simulation period of one month. The results of the coupled model in OpenMI are equal to the results of the stand-alone SOBEK model for this calculation. From this it can be concluded that OpenMI has no influence on the results of the SOBEK model calculations.

Influence of the integrated model in OpenMI on Infoworks CS calculations

To determine the influence of OpenMI on the results of Infoworks CS an event with the duration of one day with a low intensity precipitation was used to prevent interaction between the coupled model components. In SOBEK the rainfall-runoff module was disabled, so the water depths in the receiving water body were very low and were not affecting the water levels in the sewer system.

Although the water depths in the receiving water body are only a few centimetres in this calculation, this caused difference in model results in the sewer system compared to the stand-alone calculations. This is due to the fact that some of the sewer outfalls are located at the ground level of the receiving water body. In reality there will always be water in those conduits, but that is not considered in the stand-alone calculations. A schematic overview of this is shown in Figure 8 and Figure 9. The locations with differences in calculated water levels can be seen in Appendix IV. At the other locations there were no differences between the integrated model and the stand-alone calculations.

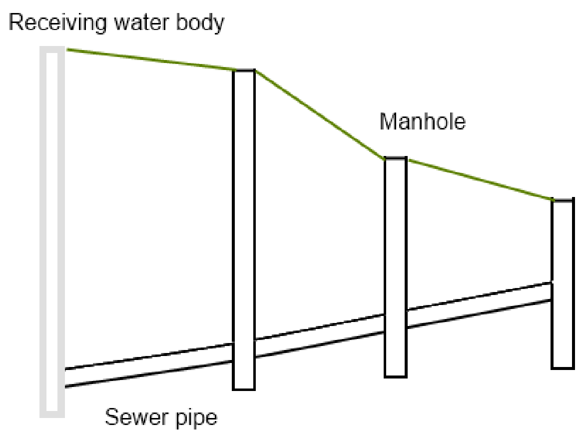

Figure 8 Water levels with no boundary condition from the receiving water body

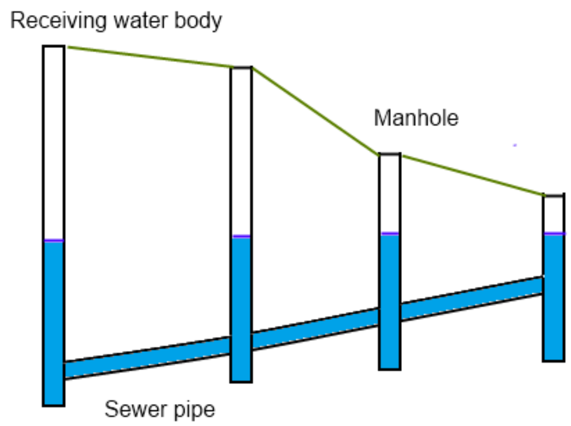

Figure 9 Water levels with boundary condition from the receiving water body

Coupling of water levels, outflow and lateral flow

The last check is to determine whether the sewer overflows and water levels in the receiving water body are exchanged correctly in OpenMI. To make sure that sewer overflow is possible an event with low, constant precipitation intensity is used for the SOBEK-model, while an extreme rainfall event is used for the Infoworks CS model. The outflow of Infoworks CS should match the inflow in SOBEK, but since the connection is an explicit link there will be a lag of one time step in the exchanged discharges. Because of the high discharge from the urban area, the water levels in the receiving water body will also rise above the overflow threshold, so the coupling of water levels can be tested.

As can be seen in Figure 10, the time lag of one time step is clearly visible in the results of both models. The water is discharged from the sewer system towards the receiving water body, but because of the connection type it is used one time step later in the SOBEK calculation. Except for the lag, the discharges are correctly modelled by the integrated model in OpenMI. The discharges from the sewer system match the lateral inflows in the receiving water body.

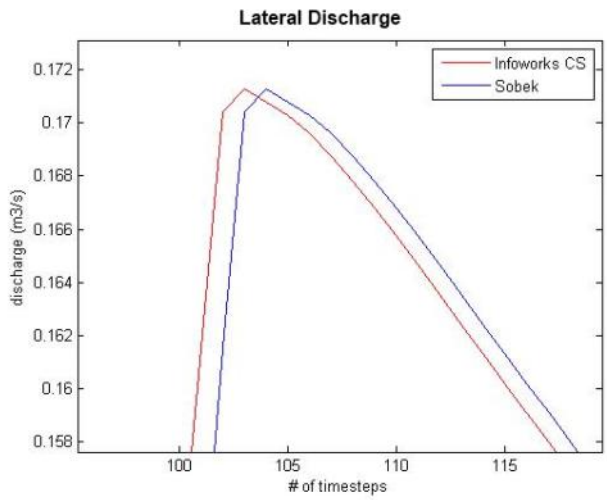

Figure 10 Lag of one time step when exchanging discharges

The water levels are also correctly transferred from the receiving water body to the sewer system. But the lag between the models is not exactly equal to one time step, but less. This is caused by the fact that there is a lag of one time step in the calculated discharges; the calculated water levels in the receiving water body are slightly lagging. The water levels at time *t,* in the receiving water body are depending on the inflow from upstream at time *t* and the outflow from the sewer system at time *t-1*. When the outflows from the sewer system are increasing, this leads to an underestimation of the water levels in the receiving water body in the order of a few millimetres, and when the outflows are decreasing the water levels are too high in the same order of magnitude. From this validation it can be concluded that the differences are very small.

3.4.2 Fully integrated model in SOBEK

It is also possible to export a model in Infoworks CS and import it in SOBEK Urban, see paragraph 2.4. Unfortunately, there are no common file formats in both software packages. Therefore the model of the sewer system must be exported to a shape file, which can be loaded into SOBEK. The results of this import are the nodes and links in the sewer system, without any properties, so all the model properties were manually added. The sewer model in SOBEK Urban is discussed in more detail in Appendix IV. The calculated water levels in the sewer system in SOBEK Urban match with the calculated water levels in Infoworks CS, but there are also some differences in the calculated flood depths since the size of the virtual basin in SOBEK is 10 m^2, slightly smaller than the basins in Infoworks CS. This increases flood depths, but the overall difference should be small.

With the sewer system and the receiving water body in the same software package, it is very little work to create an integrated model. Because of the exporting and importing of the sewer model, the overflow locations in the receiving water body and the sewer system are not at exactly the same location. This is solved by moving and combining the corresponding nodes. A schematic overview of the integrated model is shown in Figure 11.

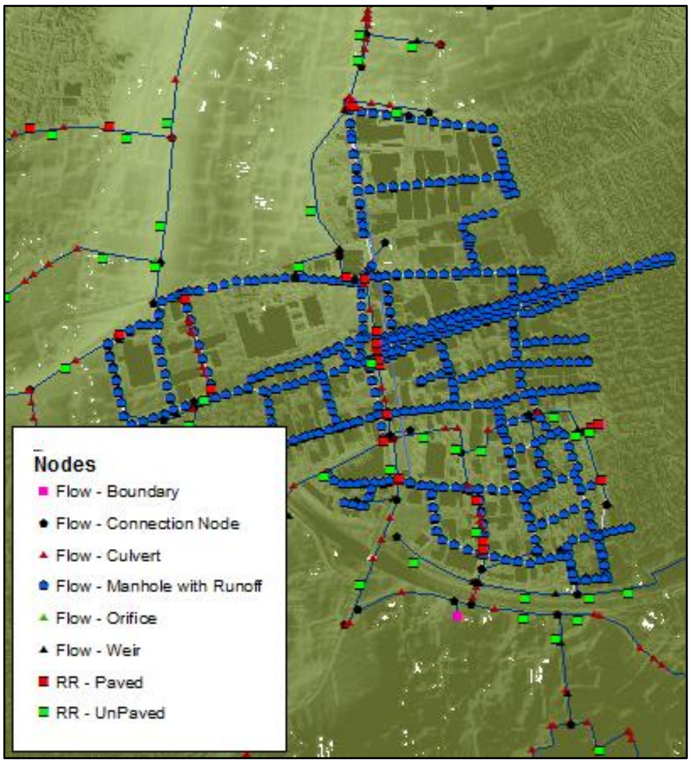

Figure 11 Fully integrated model in SOBEK

3.5 Precipitation data

In the following chapter different forms of integrated modelling will be used to determine what method should be used to determine the change in flood frequency and volume in the study area. For both goals separate precipitation data sets are used. Both are detailed below.

3.5.1 Data set for selection of preferred method

The calculation time required for a time series calculation is too long for the comparison of the different integrated modelling techniques. Therefore a selection of events was made. These events are derived from the time-series for *De Bilt*, the main meteo-station in the Netherlands, which starts in 1955 and ends in 1964. This time-series was used because it is a standard in urban water management. Although this station is not near the study area and precipitation patterns are variable in space, this does not present a problem in this case, since the time-series are not used to calculate an actual flooding frequency, but are used strictly for a comparison of the integrated models.

The moments in time when flooding occurred in either the receiving water body or sewer system were selected for further investigation. Some locations showed flooding after very little precipitation and are probably modelled incorrectly and were therefore not considered in the selection of events. To ensure that an event was well-defined, the time steps of four days prior and two days after the flooding were compiled into one event. As can be seen in Figure 12, the water levels in the receiving water body requires about three days recovering from any errors in initial conditions. The sewer system responds much faster, in the order of an hour.

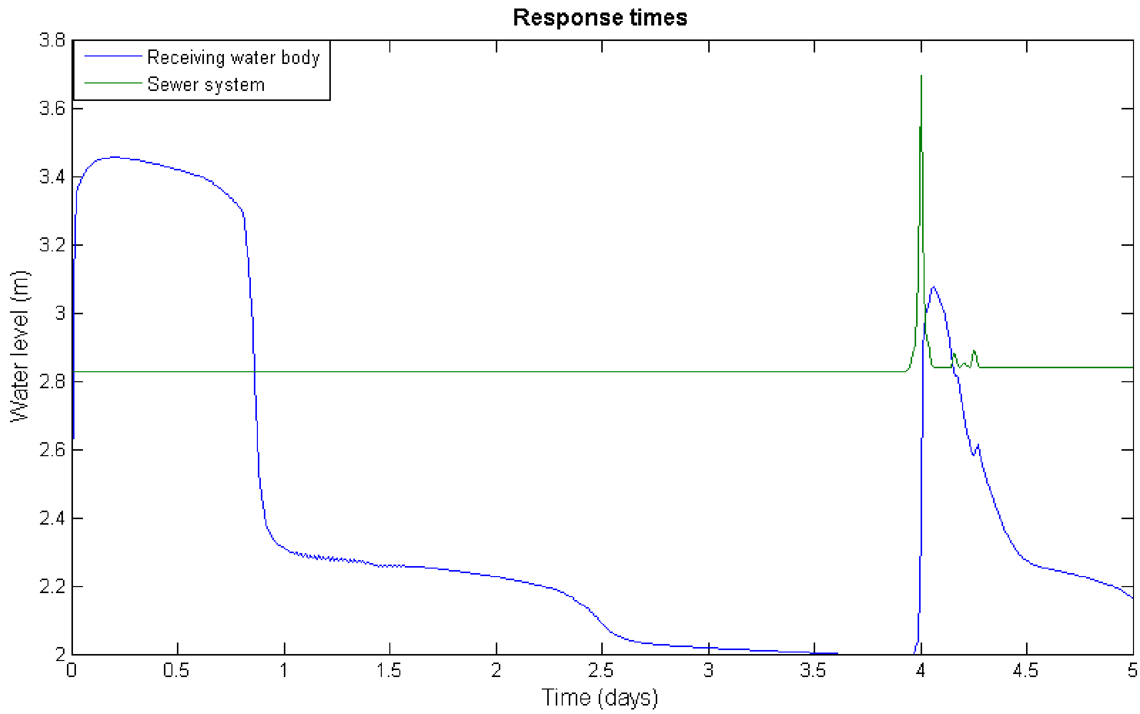

Figure 12 Response times of the subsystems

This finally leads to precipitation events for the sewer system and the receiving water body. There are also some periods where flooding occurs in both systems. In total eleven precipitation events were selected, they are summarized in Table 8.

Table 8 Selected precipitation events

Event number	1	2	3	4	5	6	7	8	9	10	11
Total precipitation (mm)	23	17	38	17	66	33	56	25	18	26	25
Maximum intensity (mm/hr)	30	32	42	50	66	9	26	35	24	58	41
Duration of high intensity (min)	30	30	15	15	45	15	45	60	30	15	15

Most of the selected events have high peak intensities and a relative short duration, but there are also some events with a low maximum intensity and a high volume. The selected precipitation events were used to compare the differences in water levels and discharges between the different forms of integrated modelling. In the next chapter the calculated water levels and discharges will be presented. Events 4, 5, 7 and 8 are events with high intensities, longer peaks and or large volumes. Therefore these events are shown in Figure 13.

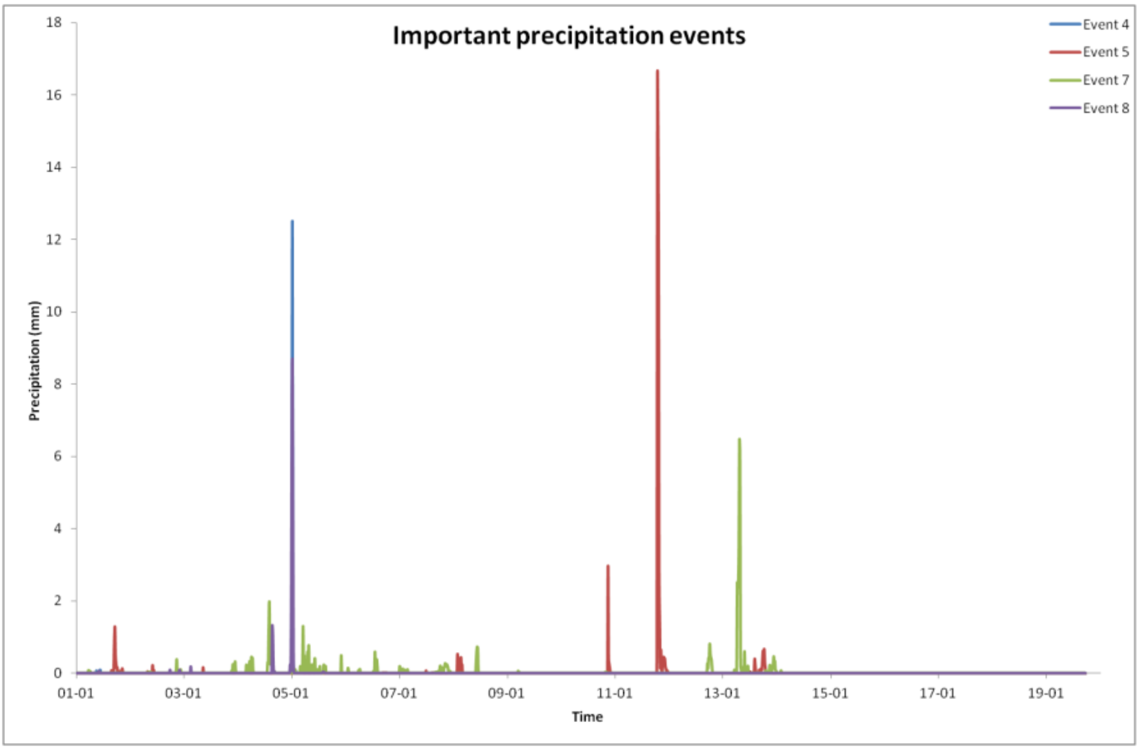

Figure 13 Important precipitation events

3.5.2 Data set to determine the flooding frequency

Since precipitation varies from one region to another it is important to have precipitation data from the study area to determine the return period of flooding. It is also possible to create a design storm for the study area based on a number of parameters (Buishand, Jilderda, & Wijngaard, 2007; STOWA, 2004), but when there is precipitation data available it is preferable to use them over design storms (Kruger- van der Griendt, 2007).

In this case there is precipitation data available at stations near the study area from the water board, see Figure 14, but there are some short periods with missing data. To correct this, the periods with missing data are substituted with zeroes. Since there are only a few days with missing data in a period of over fifteen years the overall effect of this correction will be insignificant. The year totals of precipitation for each of the rainfall stations are shown in Table 9.

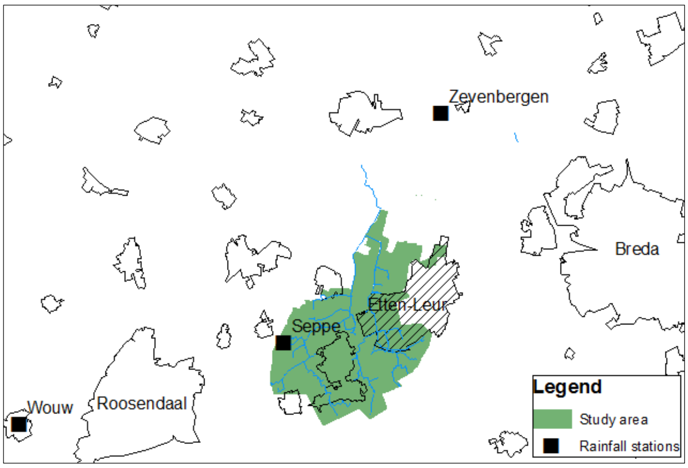

Figure 14 Locations of rainfall stations with available data

Table 9 Year totals of precipitation in mm (derived from quarter of an hour measurements)

Rainfall station	1990	1991	1992	1993	1994	1995	1996
Wouw	684	693	744	776	745	599	486
Seppe	734	763	791	805	911	716	604
Zevenbergen	737	707	602	797	895	706	525
Rainfall station (continued)	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**
Wouw	562	912	725	780	981	861	522
Seppe	617	1108	817	896	957	1007	611
Zevenbergen	656	1068	852	806	966	989	555

To determine whether there is a spatial correlation between the rainfall stations, the corresponding cross-correlograms were calculated and are shown in Figure 15. As can be seen in these cross-correlograms there is a spatial dependence between the rainfall stations, with a time lag of less than an hour. Since the spatial precipitation data is not homogeneous in space, the actual precipitation in the study area is depending on the measurements of more than one rainfall station. To distribute the measured rainfall data over the study area, for each of the schematized rainfall-runoff nodes, see Appendix III, the distances to the three rainfall stations were determined. Using inverse distance weighting the influence of each of the rainfall stations was determined and combined in precipitation for the schematized nodes, see equation (3.1) and Table 10.

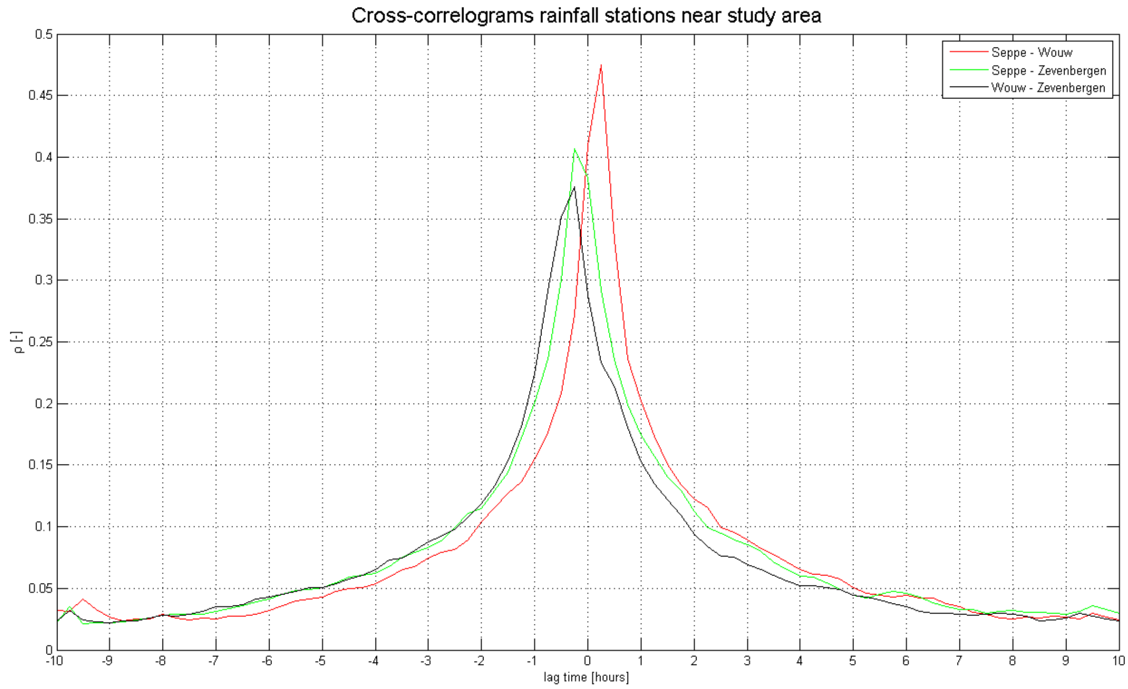

Figure 15 Cross-correlation plot for rainfall stations near the study area

$$P(x,t) = \omega_{seppe}(x)\cdot P_{Seppe}(t) + \omega_{zevenbergen}(x)\cdot P_{Zevenbergen}(t) + \omega_{Wouw}(x)\cdot P_{Wouw}(t) \qquad (3.1)$$

Table 10 Symbols in equation (3.1)

Symbol	Meaning
P	Precipitation at location *x*, for time *t*
ω	Weight obtained by inverse distance weighting

3.6 Discussion

This discussion will focus on the limitations of the models and the input data. First the models will be discussed, followed by the input data.

3.6.1 Limitations of the used models

There are some limitations in the models used in this study. The main limitation is the lack of calibration and validation for both the model of the receiving water body and the sewer system.

Although the model of the receiving water body is originally calibrated for a period in which flooding occurred, the used data set was rather limited. The calibration focuses on a relative short period with large amounts of precipitation. However, in this study the model is used in a much wider application. The model of the receiving water body is not only used for periods with large amounts of precipitation, but also for drier periods, for which the model is not calibrated. Since there are no measurements to verify the performance of the model under different circumstances, one can only assume that the results will be correct for higher discharges and not necessarily for the periods with a lower discharge. This study mainly focuses on periods with flooding, so the model results will be mainly analyzed for cases in which the model was originally calibrated.

The recalibration procedure followed to remove the overland flow module made things even more uncertain. The calculated water levels match with the original model, but this was not verified for all discharge regimes. Since a number of storage locations were added in the system to compensate for the loss of surface storage, the recalibrated model will most likely behave in the same way to drier periods as the original model, because the bottom of these storage locations corresponds roughly to the terrain elevation at those locations.

The model of the sewer system is not calibrated and validated and since there are no measurements for the discharge or amounts of flood water, the model cannot be calibrated at all. Therefore the accuracy of the model can only be determined qualitatively. In the previous studies in the area (van Dijk, 2009; Westein, 2009) it is claimed that the model is able to reproduce the inundation patterns and it can therefore only be assumed that this is correct.

3.6.2 Limitations to the input data

The input data used to determine the flooding frequency is based on a limited number of rainfall stations. As can be seen in Figure 14, the stations *Zevenbergen* and *Wouw* are much further removed from the study area than *Seppe*. Since the influence of each of the rainfall stations is determined by distance from the study area, the stations further away have less influence on the input data. This is most important for *Wouw*, since *Zevenbergen* is more important for the precipitation in the northern part of the study area.

Another difficulty is the temporal variation between the rainfall stations. Because there is a temporal relation between the data, see Figure 15, the peak intensities vary in time between the rainfall stations. Because the precipitation at a point in the study area is determined by a combination of the precipitation from the rainfall stations, the peak intensities in the data set are averaged out. This loss of peak intensities is not a problem for the receiving water body which responds to large volumes of precipitation, but for the sewer system the chosen distribution method can lead to a loss of information. Since *Seppe* is the most dominant rainfall station, the effect of this averaging is limited. A solution to the averaging would be to choose a different technique that can distribute precipitation over an area that retain more characteristics than inverse distance weighting. Unfortunately, those techniques often require more rainfall stations in an area than are available in this case. Since the number of rainfall stations is limited, the distribution of precipitation over the study area is best kept simple, even if this leads to a loss of detail.

4 Differences in integrated modelling methods

In this chapter the different techniques in integrated modelling will be compared. To reduce calculation times, first a selection of locations is made. After this the calculation results of the integrated models are compared and one method of integrated modelling is chosen for the remainder of this study.

4.1 Selection of locations to analyse

Since the models of the sewer system and the receiving water body both consist of over thousand nodes, it is not possible to analyse all locations in the time series calculation. Therefore a selection of the relevant nodes was made beforehand. For the sewer system this was done using *Bui 8* (Stichting RIONED, 2004) and no water levels at the outflow locations. *Bui 8* is a synthetic rainfall event with a return period of two years, which is often used to check the design of a sewer system. All the nodes that showed flooding during *Bui 8* and the nodes at the outfall locations were selected for analysis, they are shown in Figure 16.

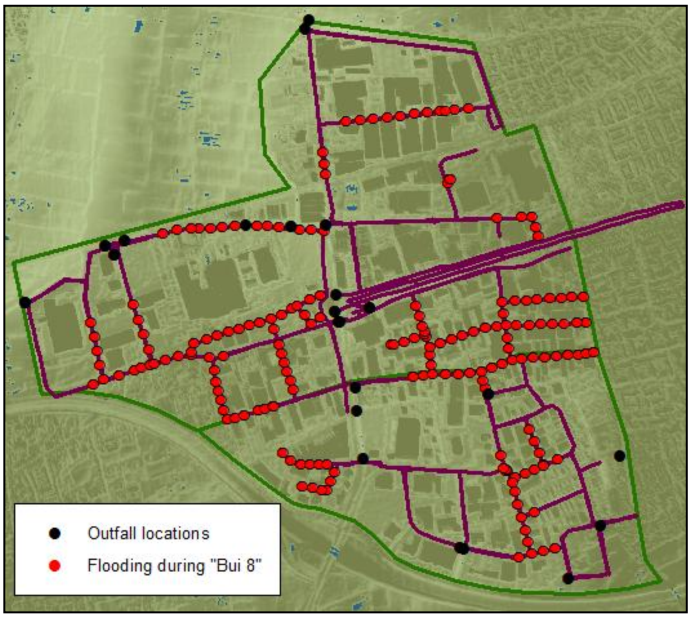

Figure 16 Selected nodes in the model of the sewer system for further analysis

The location selection in the receiving water body was a little more complex. At locations which are not near the Vosdonk, water levels of the receiving water body are not likely to be influenced by integrated modelling. Because of this, a number of locations were chosen in and around the urban area of Etten-Leur. Graphs for the locations are presented in Appendix V. Some of the graphs are presented below to show the results of the different forms of integrated modelling. The nodes for which graphs are presented in this chapter are shown in Figure 17 and Figure 18.

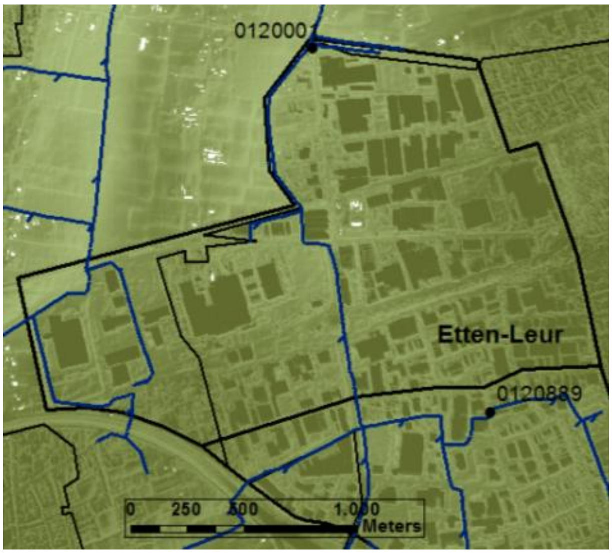

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Figure 17 Selected locations for graphs of the receiving water body

Figure 18 Selected nodes for graphs of the sewer system

4.2 Results of the integrated models

In this paragraph the results of the calculations detailed as above are presented. First are the results of the integrated model with level hydrographs, followed by OpenMI and finally the integrated model in SOBEK. The following calculations are performed using the input data from Paragraph 3.5.1 and Table 8.

4.2.1 Level hydrographs

The calculations were performed as described in Table 11. The first calculation was done for the sewer system and the results were used as input for the model of the receiving water body. An overview of the results of this type of integrated model can be found in Appendix V, but for a few locations the results are presented in this paragraph. The discharges and water levels are exchanged correctly, but the values vary between the consecutive runs. During the first run, there is no constraint on the outflow of the sewer system, thus the outflow of the sewer system towards the receiving water body will be too high. This is followed by an estimation of the water levels in the receiving water body in the second run. In the third run, this overestimation limits the outflow of the sewer system causing more flooding in the urban area and a lower outflow from the sewer system. This reduced outflow reduces the water levels in the receiving water body in the fourth run, which allows a greater outflow and less flooding of the sewer system in the fifth run.

Table 11 Calculation scheme

Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7
Infoworks CS	SOBEK	Infoworks CS	SOBEK	Infoworks CS	SOBEK	Infoworks CS

The differences in the sewer in the consecutive runs are in the order of a few centimetres, which is fairly limited considering that the water levels are a few metres at that point, for a typical pattern of the offline coupled model see Figure 19. This must be caused by the differences in outflow from the sewer system. The water levels in the sewer system show little to no convergence since Run 5 is only a few centimetres lower than Run 1 and Run 3 and Run 7 are nearly identical, see Figure 20.

As can be seen in Figure 19, the number of runs is not really important for the nodes of the sewer system which are not near an overflow location. For these nodes standard modelling techniques would be sufficient, since the difference in the maximum water levels is only a few centimetres between the consecutive runs. For nodes nearer to overflow locations integrated modelling is of more importance, with larger differences between the various model runs, see Figure 20. From these results it can be concluded that for model nodes over two hundred meters from the overflow locations, integrated modelling is of no added value. When comparing Figure 19 and Figure 20 note that the x-axis is slightly different between the figures, but the water levels are from the same event.

The water levels in the receiving water body also show no convergence between the consecutive runs. Figure 21 and Figure 22 show that the outflow from the sewer system in Run 1 is too high, which causes high water levels in the receiving water body in Run 2. In Run 4 this is corrected, but Run 6 shows the same pattern as Run 2. It is not clear what causes this non-convergence, but it is clear that it is difficult based on the results of the integrated model using level hydrographs to determine which number of iterations are sufficient. Therefore the full seven runs are considered for the analysis in Paragraph 4.3.

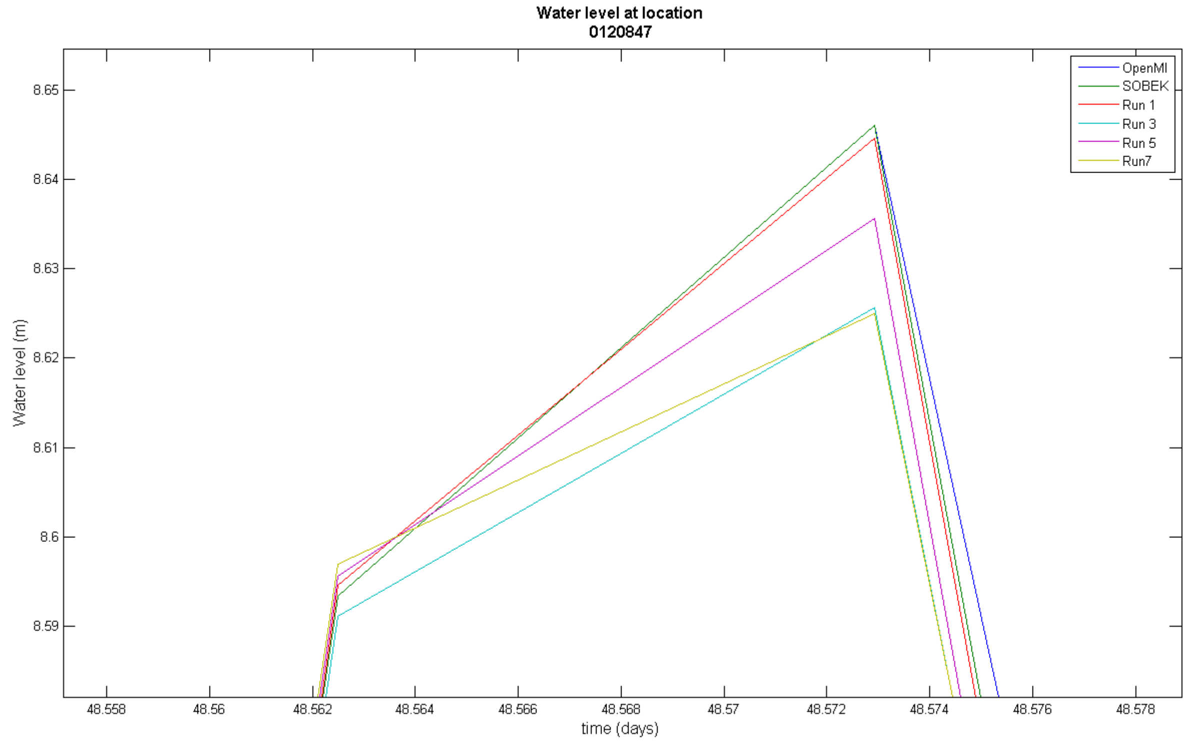

Figure 19 Water levels at node '0120847' in the sewer system for all type of integrated models, the location is shown in Figure 18

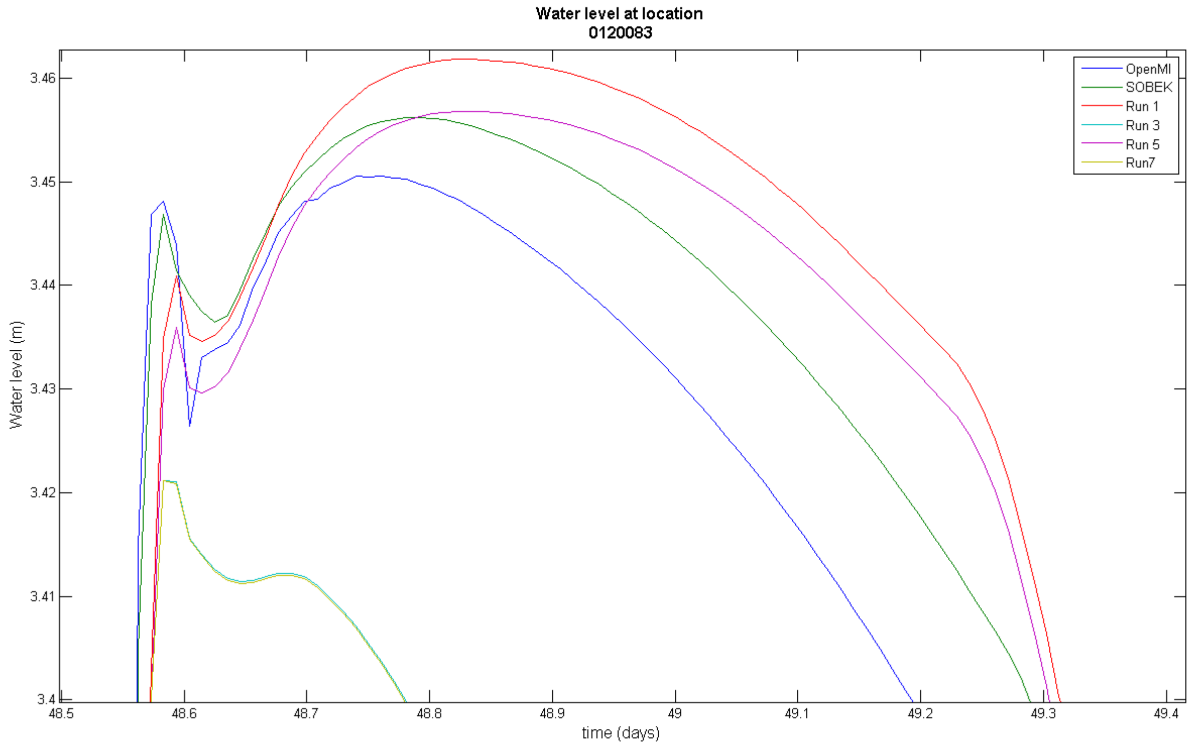

Figure 20 Water levels at node '0120083' in the sewer system for all type of integrated models, the location is shown in Figure 18

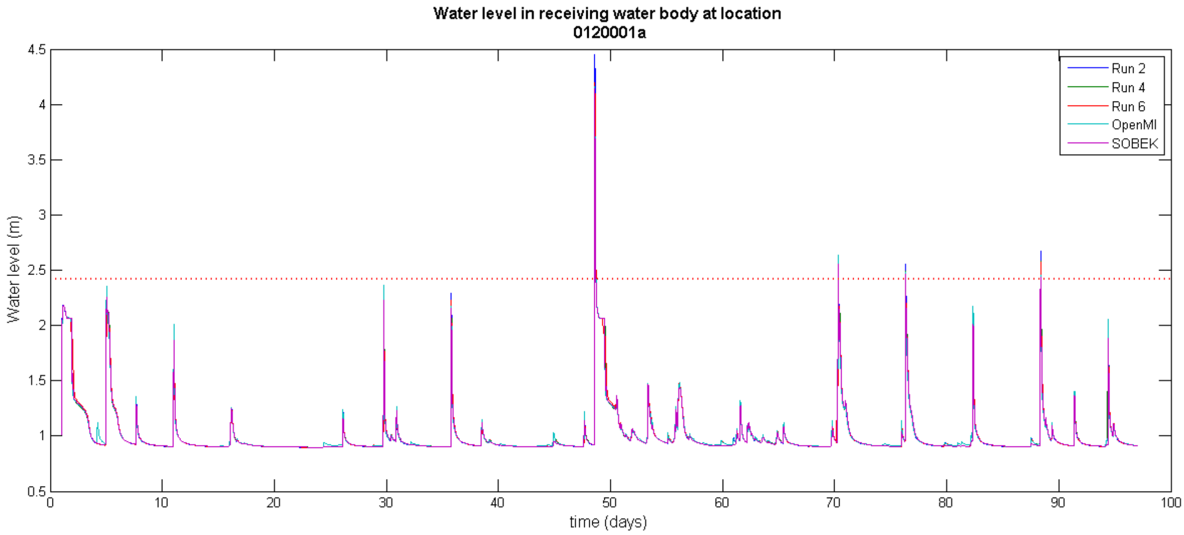

Figure 21 Water levels at node '0120001a' for all type of integrated models, the location is shown in Figure 17

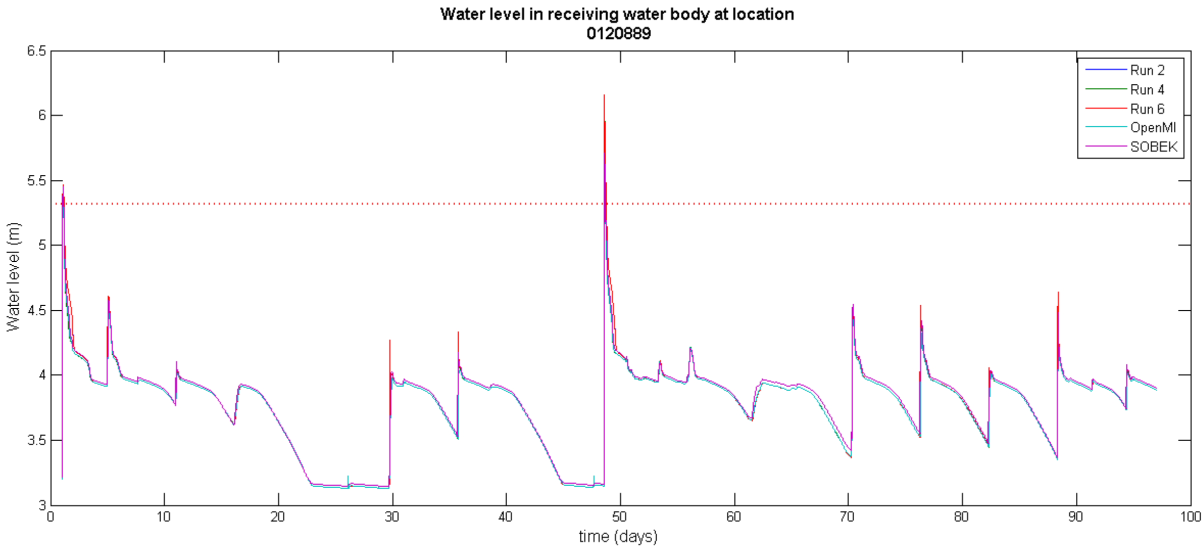

Figure 22 Water levels at node '0120889' for all type of integrated models, the location is shown in Figure 17

4.2.2 OpenMI

Using the integrated model as outlined in the previous chapter the water levels and discharges for both the sewer system and the receiving water body were calculated. The calculations for the receiving water body showed little flooding for the selected events, only Event 5 shows floods on a larger scale in the sewer system and the receiving water body, see Figure 21, Figure 22 and Appendix V.

When the water levels for Event 5 are studied in more detail, Figure 23, it becomes clear that the water levels in the fully integrated model in SOBEK and in OpenMI are lower than the water levels in all of the runs using level hydrographs, especially in Run 2 and Run 6 are the differences large, in the order of ten centimetres.

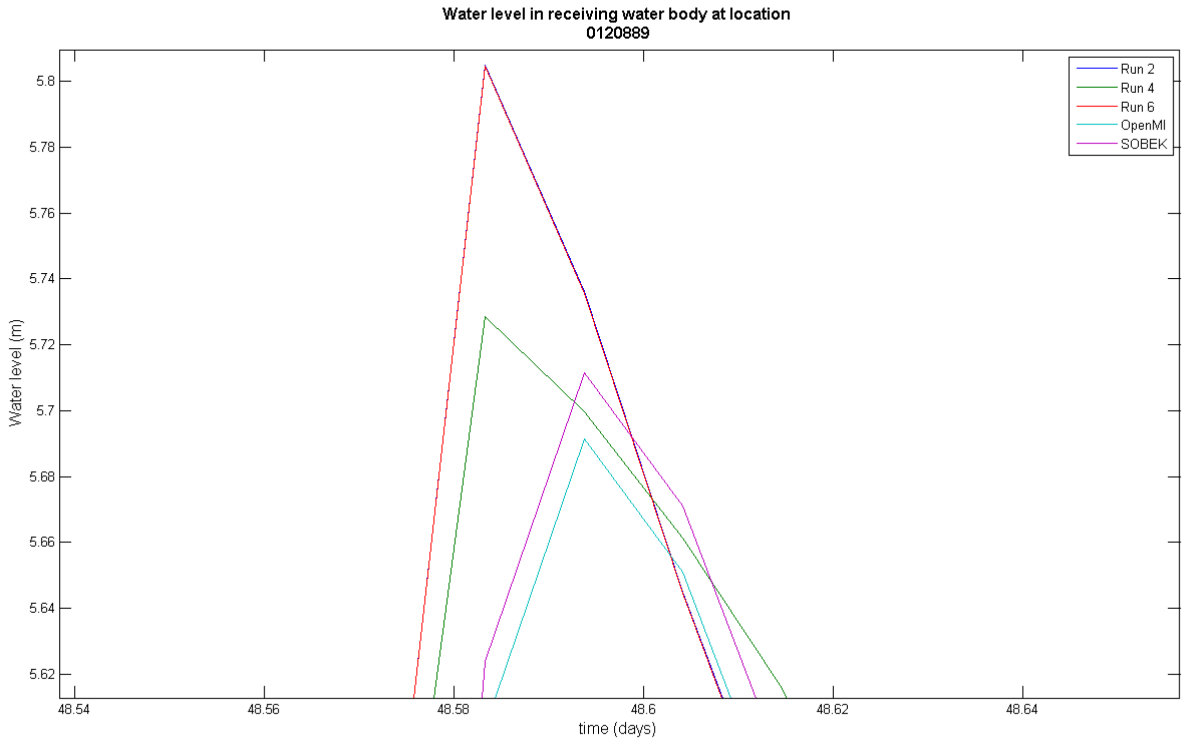

Figure 23 Peak water levels for event 5, at location '0120889' in the receiving water body

Event 1, for details see Table 8, causes flooding of the sewer system and a minor flood in the receiving water body. The exchanges in discharges and water levels match closely, although the lag described in paragraph 3.4 is present.

4.2.3 Fully integrated model

The fully integrated model in SOBEK as described in paragraph 3.4.2, was used to compare this type of integrated model to the other methods of integrating modelling. The number of floods in the sewer system calculated by the integrated model matched with the number of floods in OpenMI. The flood depths in the receiving water body also show the same pattern, see Figure 21, Figure 22 and Appendix V. The difference between the explicit connection in OpenMI and the implicit connection in SOBEK can be seen when water levels begin to rise and fall.

4.3 Comparison of different integrated models

In this paragraph the different integrated modelling techniques are ranked on a number of criteria as mentioned in the second chapter, followed by a selection of a preferred modelling method. The selected method will be used in the remainder of this study to determine how integrated modelling influences the risk of flooding in the urban catchment area.

4.3.1 Level hydrographs

Offline coupling, or coupling using level hydrographs, is very time consuming, because of the iterations that must be performed; apart from the preparations which require time for each run, the CPU-time increases with each run. After each run the obtained water levels and discharges must be compared to the previous runs to determine whether an additional run is necessary. Since the interactions between the models are defined for an entire run beforehand, there are a number of iterations required before the solution is more or less stable. In this study it appears that the number of runs that required is three to at least seven, depending on the location of the node in the network.

Nodes which are not located near interaction points require only three runs, while at other nodes the results show no conversion, see Paragraph 4.2.1.

Modelling using level hydrographs is not very robust, because of the number of operations involved. Since there are no third party programs required there are no software limitations that were not already in the original models. The usability of this type of model is neutral, since the results must be accessed from different programs for each of the iterations and small changes in the model require that the lengthy process must be done all over again.

4.3.2 OpenMI

Calculation times increase by using OpenMI, because of the data exchange between the two models. It is very easy to create an integrated model by using OpenMI, especially from Infoworks CS. OpenMI is not fully integrated in the user interface of SOBEK, making it more difficult to set up the integrated model and more manual operations are required to access the results in SOBEK.

As can be seen in the third chapter, the exchange of water levels and discharges occurs correctly, but with a small lag. This has no significant impact on the model results, since the mass balance error is zero over the calculation as a whole. Because of the versatility of OpenMI this method can be used for many operations and is therefore applicable for any type of calculations.

Furthermore there are a few bugs in the implementation of OpenMI in SOBEK v2.12.001 which make accessing the results more complicated. Because of some rounding errors in the calculation process of SOBEK, time is not exactly synchronized between the models. This causes no problems during the calculations, but it may cause problems during the final time step, since the SOBEK model wants to calculate one more time step, which the Infoworks CS model cannot produce, resulting in an unfinished calculation in Infoworks CS. This had an influence on the robustness of the calculation. To access the results there are some additional actions required, which add to the total calculation time. The CPU-time itself is slightly longer than the standalone, but because of the short preparation time the calculation time is still the shortest of these methods.

4.3.3 Fully integrated model

Fully integrated models in general are highly calculation time efficient, as long as the integrated processes have roughly the same time step (Becker, 2010). Since the time step in the sewer system is much smaller than the time step of the receiving water body, the calculation scheme of this type of integrated model is not very efficient during long simulation periods.

The fully integrated model in SOBEK scores good on CPU time, but the long pre-processing time required to create this type of integrated model increases the total calculation time.

The accessibility of results is very easy, since all data is in one program, therefore this method scores good on usability. Because of the fully implicit approach the water levels and discharges are always transferred one-on-one. The applicability of this type of integrated modelling is limited by the number of nodes and time steps SOBEK can handle. For time series calculations SOBEK v2.12.001 is likely to cause memory errors and therefore not able to perform the calculations. This can be solved by increasing the time step of the model, but since only one step size can be used in the fully integrated model, this influences the calculation of flooding of the urban area. Therefore the fully integrated model is not applicable for time-series to determine the return period of flooding.

4.3.4 Selection of preferred method

When comparing the integrated modelling methods it becomes clear that all of them have their advantages and disadvantages. An overview of the scores on the criteria per type of integrated model is shown in Table 12. Except for the suitability for long simulation periods and the long pre-processing time, the fully integrated model scores best, with OpenMI scoring almost as good as the fully integrated model. However, as was explained in Chapter 1 and Chapter 2, the ultimate goal of this study is to assess the influence of integrated modelling on the size and number of floods in the urban catchment area. Since the fully integrated model in SOBEK cannot perform these calculations the selected method for this study will be OpenMI.

Table 12 Overview of scores on criteria

Type of model	Calculation time (hr)			Precision	Robustness	Usability	Suitability
	Pre-processing	CPU-time	Post-processing				
Level hydrographs	1.0	7.5	0.25	-	-	0	0
OpenMI	0.25	2.5	0.25	+	0	+	+
Fully integrated	4.0	2.25	0	+	+	+	-

4.4 Discussion

This discussion will focus on the results of the calculations for all models in general. This paragraph is concluded with a discussion about the selection method.

4.4.1 Results

In the calculations performed in the previous paragraphs, it becomes clear that there are small differences in the results of the various integrated models. Although these differences are not very large, the different integrated models calculate slightly different flood locations in the sewer system. In the receiving water body there are little to no differences in the calculated water levels. Event 5 has the largest impact on the water system. This was to be expected since it has the highest peak intensity as well as the largest volume of precipitation. When the flood volume in the sewer system is compared to the peak intensity it appears that there is a positive correlation between the two, this also to be expected, since the sewer system is triggered by heavy rainfall events. Flooding of the receiving water body occurred only during Event 5.

4.4.2 Selection method

The selection of a form of integrated modelling as was done in this chapter is based on mostly qualitative criteria. Only the precision and calculation time can be determined quantitative. These criteria were chosen since there are no measurements of discharges and water levels in the study area. In order to make a clear choice between the different forms of integrated modelling, these measurements are required. With them the models can be calibrated and with a validation the quality of the models can be determined. Since this is not possible another selection method had to be found. In literature there are several studies which are dealing with the same problems. Several criteria used in those studies are also used in this study. This way it is possible to rank the different forms of integrated modelling without the required measurements.

Although the chosen selection method allows ranking the models without measured data, a drawback of the chosen approach that it leaves room for speculation, the ranking of the models is therefore done on a simple three point scale which gives a clear overview of the scores on each of the criteria.

5 Return periods and integrated modelling

In this chapter the return periods of the receiving water body and the sewer system will be analysed. First standalone results are presented, followed by the results of the integrated model in OpenMI. The chapter is concluded with a discussion of the results.

5.1 Results of standalone calculation for the sewer system

In this paragraph the results of the standalone calculation for Infoworks CS will be discussed. The results are presented for nodes which show flooding using *Bui 8,* see also Paragraph 4.1 and Figure 16.

Using the precipitation data presented in the Paragraph 3.5.2, a calculation for the sewer system with free outflow at the outfall locations was done. Based on this calculation the number of floods in a period of fifteen years is determined, see Figure 24. As can be seen in this figure, a number of the analysed locations perform as required, with flooding occurring less than once per two years, but a large part of the sewer system shows floods in a higher frequency than should be expected.

The current policy regarding flooding of the sewer system is focussing on the return period of precipitation instead of the return period of the flooding itself. In this study the focus is on the return periods of flooding. Because the nodes in Figure 24 are locations which show flooding using *Bui 8,* the return period of flooding is less than two years using *Bui 8*, but is higher for the locations near the northern and southern borders of the sewer system using time-series.

Since most of the sewer system shows flooding which occurs more often than once every two years, it can be concluded that the sewer system is inadequate to efficiently discharge rainfall events with a return period of two years.

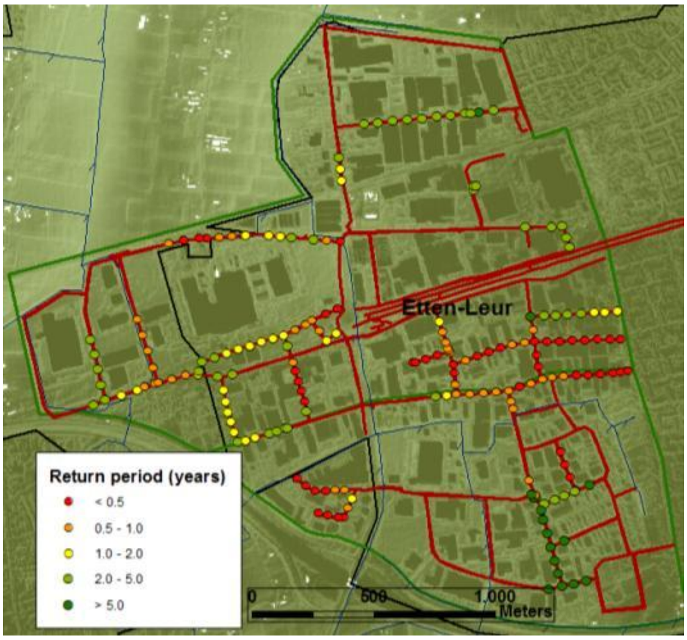

Figure 24 Return period of floods in the sewer system using a standalone calculation in Infoworks CS

5.2 Results of OpenMI calculations for the sewer system

The same period as in the previous paragraph was calculated using the integrated model in OpenMI. The resulting number of floods per location is shown in Figure 25. When comparing Figure 24 and Figure 25, it is clear that the integrated model calculates more floods at some locations, but at most locations there is no difference in the number of floods in the urban area. Although the number of floods does not increase at most of the selected nodes when using an integrated model, the flood volume does increase, see Figure 26. Since the potential for damage in the urban area increases with flood depth, the flood risk increases with the use of integrated modelling.

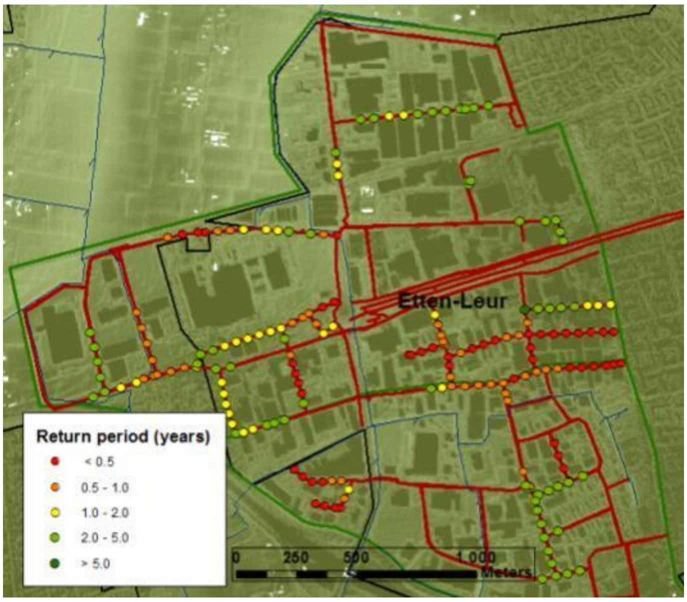

Figure 25 Return period of floods in the sewer system using an integrated model in OpenMI

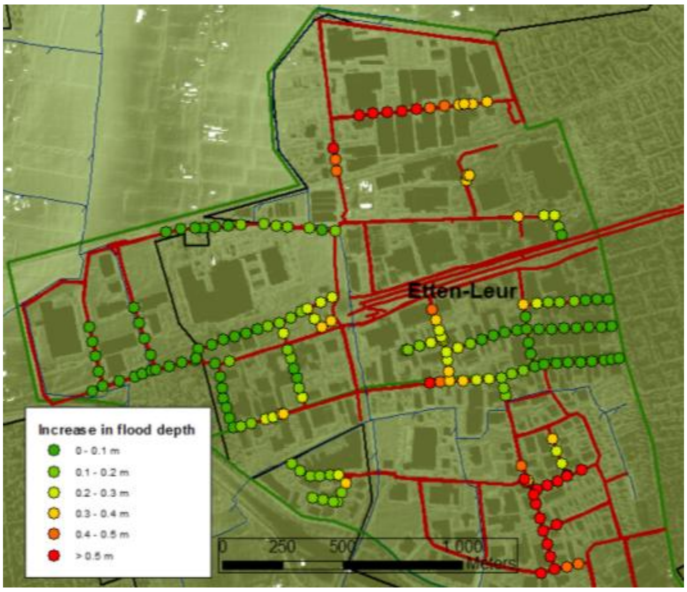

Figure 26 Increase in maximum flood depth when using an integrated model

From both the standalone calculation and the calculation in OpenMI a cumulative density function was determined. This is shown in Figure 27. From this figure it becomes clear that the flood volume increases significantly in the sewer system using integrated modelling.

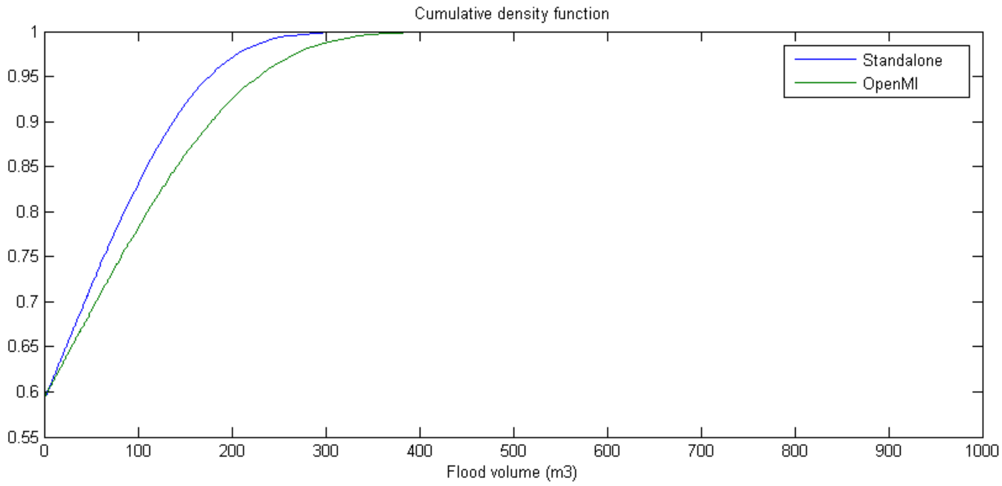

Figure 27 Cumulative density function flood volume

5.3 The effect of integrated modelling on the receiving water body

Using the same calculations as before, the receiving water body will be analyzed in this paragraph. The receiving water body shows little increase in return periods of flooding since the sewer system is roughly used in the schematization, see the third chapter. The differences in water levels at one of the overflow locations during high water levels are shown in Figure 29 and Figure 30 for the nodes displayed in Figure 28. As can be seen in this figure, the water levels in the receiving water body are not significantly influenced by integrated modelling. The rough schematization of the urban area that was originally built in the model is of sufficient quality to calculate the water levels, in both timings and peak water levels. The differences in peak water levels are in the order of ten centimetres.

Any deviations in the return period of flood risk are therefore reduced to shortcomings in the schematization of the sewer system in the model of the receiving water body. Although the differences are relatively small, this does not indicate that integrated modelling cannot be important for the receiving water body.

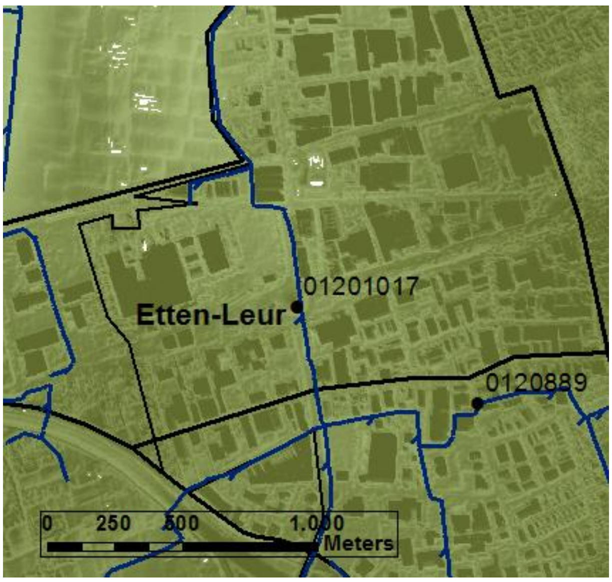

Figure 28 Locations in the receiving water body

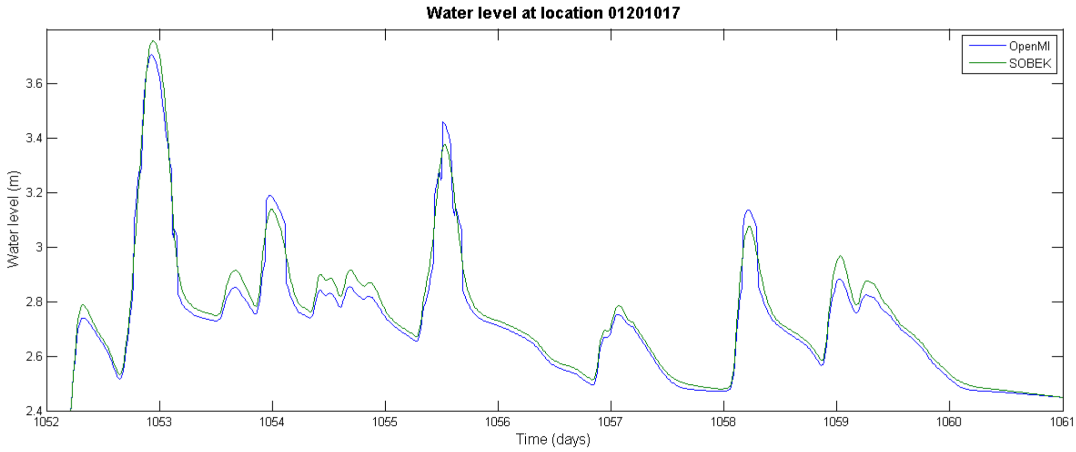

Figure 29 Water levels in the receiving water body at node '01201017', the location is shown Figure 28

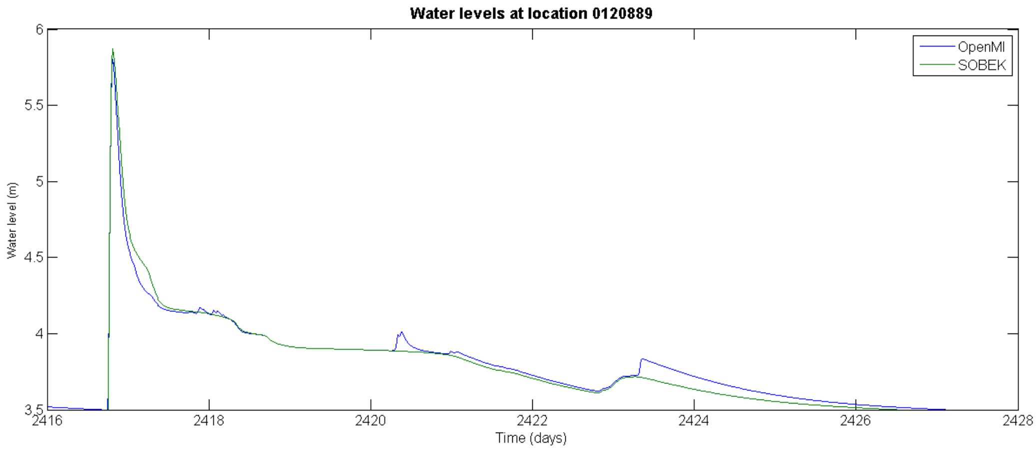

Figure 30 Water levels in the receiving water body at node '0120889', the location is shown in Figure 28

Flooding occurs one to four times at most locations during the simulated period of 15 years, see Figure 31, which shows that the receiving water body is not able to discharge events with the required return period of 50 years (Hoogheemraadschap West-Brabant, 1999).

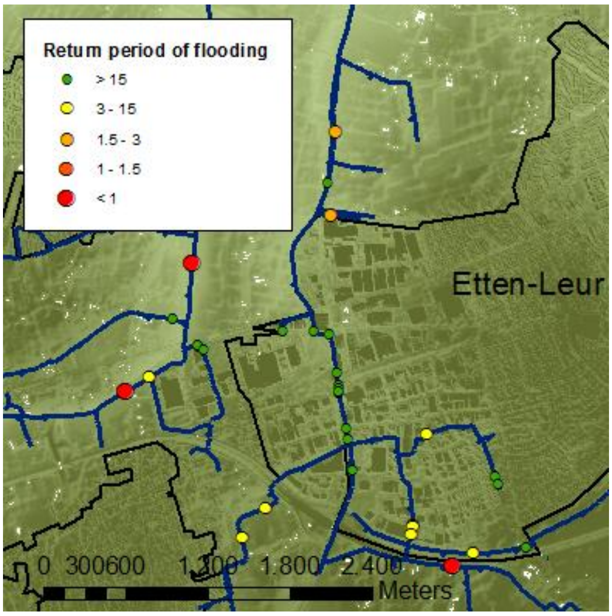

Figure 31 Return period of floods in the receiving water body using an integrated model in OpenMI

5.4 Discussion

In this discussion the influence of integrated modelling on return periods and policies will be further assessed. First the separate systems are considered, followed by a discussion on the integrated urban water system. This paragraph is concluded with a discussion on the possibilities and limitations of integrated modelling for catchments of different sizes.

5.4.1 Flooding of the sewer system

As can be seen in the previous paragraphs, integrated modelling influences the flooding of the sewer system: although the number of floods remains more or less equal compared to the stand-alone model, the total flood volume increases. According to the current policies the return period of precipitation is the main criterion in designing the sewer system, see paragraph 1.1, while the flood depth is only of secondary importance. As long as the area is of relatively little economic importance, such as industrial areas, flooding is not considered problematic, since the potential for damage is considered to be low. However, with increasing flood depths, the potential for damage rises as well. In its sewer plan the municipality states that flooding of industrial areas is allowed, as long as there is no damage to properties (Gemeenteraad Etten-Leur, 2008). This means that the increase in flood depths can lead to damage to properties that is not considered in stand-alone modelling. In that regard integrated modelling should be considered vital to correctly determine whether measures must be implemented to alleviate the flood risk.

The sewer system of the *Vosdonk* is originally designed to discharge *'Bui 9',* an event with a return period of five years without flooding. From the calculations in this study it follows that about two thirds of the selected nodes have a return period of flooding which is lower than two years. Only a few nodes have the required return period of over five years. Since the system is unable to discharge *Bui 8*, an event with a return period of two years and with similar pattern as *Bui 9*, but with a lower peak intensity and volume, it can be concluded that the sewer system does not function as it was originally designed. The calculated return periods of flooding in this study using a time-series calculation confirm this.

5.4.2 Flooding of the receiving water body

The receiving water body floods more often than it should, based on the policies that control the regional water system, see paragraph 1.1. According to those policies flooding is allowed to occur once every fifty years, since the majority of the receiving water body is not a secondary water course. For a simulation period of fifteen years, this means that the chance that more than one flood occurs is about 0.035. Since at some locations in the receiving water body flooding events occur, it can be concluded that the receiving water body is not able to discharge events with higher return periods.

The higher chances of flooding can cause problems in the catchment of the receiving water body. From the simulations in this study the effect of integrated modelling on the *Vosdonk* is fairly limited. This is due to the rough schematization of the urban area in the stand-alone model of the receiving water body. Although the schematization is rough, it provides enough detail to correctly determine the outflow from the sewer system to the receiving water body. The resulting water levels correspond therefore with the water levels calculated using an integrated model. The timing of the peaks is not exactly the same, but if the main interest is in the return periods of flooding the integrated model may be of only limited added value.

5.4.3 The integrated urban water system

As can be seen in the introduction, the regulations with respect to flooding of the urban water systems focus only on the separate systems. To further complicate the matter the sorts of events that are considered are also very different. This is caused by the differences in approach; the return periods for the sewer system are used to check its hydraulic functioning, while for the receiving water body flooding is the main concern (Stichting RIONED, 2006). Although flooding in the sewer system is often not related to high water levels in the receiving water body (Stichting RIONED, 2006), this does not mean that flood events in one subsystem cannot lead to flooding in another subsystem (Vaes, et al., 2008). As can be seen in Paragraph 5.2, the flood volumes increase because of the modelled interactions between the receiving water body and the sewer system, but the number of floods does not increase significantly. Since there is little storage available in the receiving water body and the discharge capacity of such a small water system is also limited, the interactions between the water systems lead to a quick increase in water levels in the receiving water body, which in combination with the positioning of the overflow locations cause higher water levels in the sewer system. Since there was no significant increase in the number of floods in the sewer system, integrated modelling is in this case not required to determine the return period of flooding.

Since in both of the subsystems flooding occurs more regularly than should according to the policies, it is hard to determine which of the subsystems is mainly responsible for the floods in the area. Since integrated modelling did not show an increase in the number of flooding events in the sewer system and the receiving water body, both the municipality and the water board should adopt measures to prevent flooding in the future. The municipality should focus on more storage in the urban area, while the water board can implement measures to retain water further upstream in areas where more frequent flooding is allowed to be able to store more water in the receiving water body near the *Vosdonk*.

In case the sewer system and the receiving water body are both triggered by different events, the current policies on urban flooding are sufficient, although the increased potential for damage must somehow be incorporated in the flood risk. On the other hand, the system can be very sensitive to backwater flows and the discharge capacity of the receiving water body. Although this seems not to be the case in this study, since there is no increase in the number of flooding events in the sewer system, it is worth to determine whether this situation occurs in other urban areas.

5.4.4 Integrated modelling and catchment size and properties

The size of the subsystems can have an influence on the need for integrated modelling. Interactions between the subsystems can be of significant impact on water levels in both the receiving water body and the sewer system. Of main importance are the upstream catchment area of the receiving water body and the ratio between impervious area and the total catchment area (Vaes, et al., 2008). There are some other characteristics of a catchment area that can have an influence on the need for integrated modelling, such as the storage capacity available in the subsystems and the ability to quickly discharge large quantities of water. In this study the total catchment area is quite small and the catchment of the receiving water body is relatively small compared to the size of the sewer system. Therefore it was expected beforehand that integrated modelling would have a significant impact on the calculated return periods of flooding and on the magnitudes of the flooding events.

Since there is no increase in the number of flooding events in a catchment area with these characteristics, it may not be necessary to use integrated models for larger catchment where the water levels between the subsystems can be considered independent.

Another criterion for whether integrated modelling should be used is the policy of a municipality considering the sewer system. When the policy is frequency based there is no need for integrated modelling, based on the results of this study. But when the policy adopts the flood risk approach, the increase in water levels will influence the flood risk. Municipalities which incorporate flood risk in their policies should therefore check whether the current flood risks are correct.

A first insight whether integrated modelling can be of added value can be obtained by checking the following characteristics of the urban water system:

- Calculate the water levels in the subsystems using:
    - For the sewer system the required design event
    - For the receiving water body an event with a return period similar to the design event of the sewer system
- Determine the water levels and discharges at the interaction points between the subsystems and use them as boundary conditions for a new calculation of both systems.
- When the differences between these calculations show that interactions between the systems influence the impact of flooding, an integrated model should be created.

Since it is difficult to determine whether the events in both systems are dependent or independent, it is preferable to use time-series as input for the integrated model. By using time-series it is not required to determine a design event for the entire system, since only measured precipitation data is used as input.

6 Conclusions and recommendations

This final chapter starts with the conclusions of this study, followed by the recommendations. In the conclusions the research questions will be answered, while the recommendations focus on future research.

6.1 Conclusions

The main objective in this study was to compare different methods of integrated modelling and determine the influence of integrated modelling on return periods of flooding of the urban water system. The integrated modelling methods that were compared in this study are:

- Offline coupling using level hydrographs;
- Use a modelling framework;
- Fully integrated modelling.

What are the advantages of different forms of integrated modelling and what are the differences
Offline coupling is very easy to implement, but requires a number of iterations. Therefore it is very error prone and time consuming. Since existing models can be used for this form of integrated modelling and requires no additional software it is the most accessible method available. Since the interactions between the models are defined beforehand, the exchange in data is not very accurate and the results are not converging. Using a modelling framework, such as OpenMI, it also possible to use existing models, but additional software is required. Data exchange between the models is defined by the framework, per time step. In case the time steps are not equal the software can interpolate or extrapolate the data as required. Fully integrated modelling is the most accurate form of integrated modelling. A drawback of this method is that in most cases models must be entirely rebuild to create the integrated model.

What method of integrated modelling is preferable in this case
From these methods, the use of fully integrated modelling gave the best results on calculation times, precision, robustness and usability. Based on those criteria fully integrated modelling should be used when there is a choice between different forms of integrated modelling. However, software limitations meant that SOBEK v2.12.001 could not be used for the whole network with time-series calculations. Therefore OpenMI was the best form of integrated modelling for this study.

What is the effect of integrated modelling on return periods and severity of flooding
The use of an integrated model does lead to a small increase in the number of flooding events in the urban area. Although this increase is limited in its extent, the increase of flooding events at some locations leads to return periods of flooding which are lower than required, where this was not the case using the standalone model. Except for the limited increase in flooding events, the calculated maximum flood depths increase. Flooding events with a very low flood depth give little problems, but as flood depths increase the potential for damage increases as well.

From the results of the integrated model it can be concluded that integrated modelling is of no added value for the sewer system in this case when the policy is only based on the frequency of flooding, since there is no significant increase in the number of flooding events. However, when the policy is based on flood risk, integrated modelling is of importance, since the calculated flood depths increase when using the integrated model.

6.2 Recommendations

It is clear that there are some limitations to this research that limit wide range applicability. In this paragraph the recommendations for future research and for policy makers are presented.

One of the main limitations of this research was the lack of gauged data. There are only a few rainfall stations in the area, there is no gauged data on discharges and water levels in the catchment and there are no flood depths in the urban area available. This made it impossible to quantify the differences between the integrated forms of modelling in a realistic setting. To properly calibrate and validate the model measurements in both the sewer system and the receiving water body are required. A validated model can give possibly more insight whether the integrated models help predicting the flow characteristics in the study area.

To provide a better estimation on the correlation of urban and regional events and its impact on the flood risk in the urban water system, it is preferable that a longer simulation period is used. In this study the longest available period with precipitation data was fifteen years, but this can be too short to provide a good estimation of the return periods for the receiving water body. In this case the receiving water body is not able to discharge a number of events in a simulated period of fifteen years, so the length of the time-series is sufficient to assess the actual flood risk.

Policy makers which incorporate flood risk in their plans should determine the need for integrated modelling in their plans. A first insight whether it is necessary to create an integrated model is to determine how sensitive the urban water system is for interactions between the subsystems. Since this study showed that integrated modelling influences the total flood risk, this will be likely the case in other urban areas as well, especially those with similar characteristics as the *Vosdonk*. Future research should focus on whether there is an effect of integrated modelling on the flood risk in the urban water system for urban areas with other characteristics, such as a smaller urban catchment compared to the total catchment size, as well.

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The use of integrated modelling in an urban water system and its influence on flood estimation

Appendices

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Contents

Appendix I Concepts of OpenMI

The Open Modelling Interface and Environment (OpenMI) defines a standardized way to exchange data between environmentally related, computational models that run simultaneously. OpenMI aims to enhance the representation of process interaction in integrated environmental modelling. Integrated modelling is seen as a key tool for an integrated water management as aimed by the European Water Framework Directive.

In OpenMI a software package like SOBEK or Infoworks CS is called a model application, which consists of a user interface and an engine. Via the user interface the user supplies information upon which the user interface generates the model input. This input is used by the engine for the calculations and after the calculations the results will be written to output files. The moment an engine reads its input it becomes a model. In case the engine can be activated externally it is an engine component, when this engine component read its input data it becomes a model component (Brinkman, Gregersen, S.Hummel, S.J.P., & Westen, 2005). These definitions are graphically displayed in Figure I-I.

OpenMI accesses the model directly at run time and does not use files for data exchange. In order to make this possible, the engine needs to be turned in an engine component and this engine component needs to implement an interface through which the data inside the component is accessible. OpenMI defines a standard interface for engine components that OpenMI compliant models must implement (Brinkman, et al., 2005).

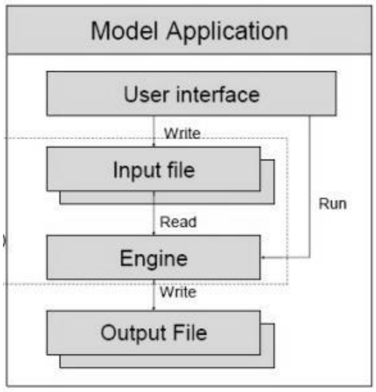

Figure I-I Definitions in OpenMI (Brinkman, et al., 2005)

Model components can exchange data by requesting data from the source component and transferring it through a link to the target component. To do this OpenMI has been designed as a pull-based system where the target component request data from the source component and does not process any new requests until this data is returned. Every OpenMI compliant engine component can be a target component, source component, or both (Brinkman, et al., 2005).

OpenMI allows one component to pull data that it requires from another component through a link. The data that pass across the link are the results of the providing model and form the input of the receiving model. OpenMI enables model engines to compute and exchange data at their own time step, without any external control mechanism. Deadlocks are prevented by requiring a model to always return a vale upon a request. The requested model decides how to provide to requested data.

This can be done by performing a calculation, it can be a best estimate based on interpolation or extrapolation or perhaps it was already in a buffer (Gijsbers et al., 2005). Since the models in OpenMI are called externally, data exchange in OpenMI must also be triggered by an external component. This is done by adding a trigger component at the end of the composition chain. This trigger requests data from the model at the end of the chain for the last time in the time interval. In order to provide this request the models must calculate all previous time steps, see Figure I-II.

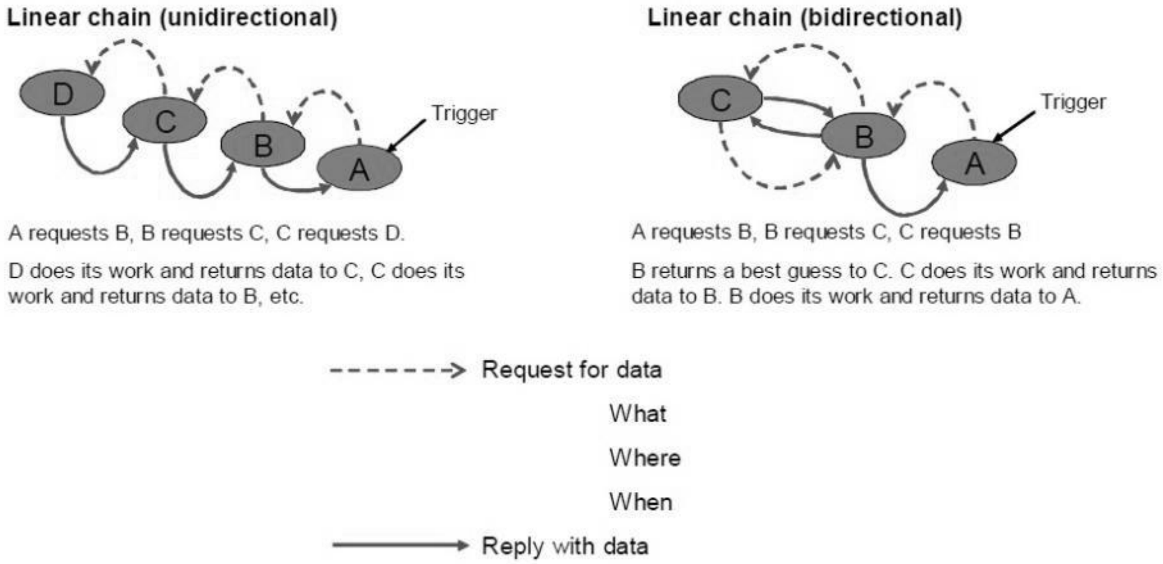

Figure I-II Pull mechanism in OpenMI (Gijsbers, et al., 2005)

Data is described in OpenMI in a distinctive manner, by identifying the values itself, the geometry on which the data is defined, the time for which the data is valid and the quantity it represents. From this it follows that for each model component the calculation intervals must be defined in the same absolute time interval, represented by the Modified Julian Date. Each link is able to define a conversion in the form of $y = a \cdot x + b$ allowing unit conversion from one model to the other (Brinkman, et al., 2005).

One model component can retrieve data from another model component. However this is only possible if the two components have a clear idea on the kind of data that is requested. Therefore it is only possible to exchange data if:

- The accepting component can identify the providing component
- The providing component knows what data to deliver and to what component
- The providing component understand its relation with its internal data

All this information is stored in the link. The link defines the actual data exchange between two components. The link defines the following information:

- The source and target component
- The source and target quantity
- The list of operations that must be applied by the source component before providing data
- The operations that must be applied by the receiving component before accepting the data

A link refers to a single quantity only. This means that for bidirectional communication or with multiple quantities, multiple links must be configured.

The data exchange is in this case at the sewer overflow locations. Here the water levels and discharges are coupled. This means that the water levels in both models can influence each other and that flow from one system to the other is possible. For a bi-directional link a short description of the calculation steps is given below.

Calculation steps for an explicit, bi-directional link. The river model has a time step t_2 which is double the time step t_1 of the sewer model:

1. The trigger requests the water level of the last node of the sewer model, where the time argument determines the time span for which results are expected.
2. The sewer model determines whether it's internal time is before or after the requested time t_1. The sewer model will retrieve the water level from the sewer model for each time step.
3. The river model determines whether it's internal time is before or after the requested time t_2. The river model, currently at time t_0, can only calculate a value at t_2. To compute the requested water level at t_2 it requires the lateral inflow to the river model at t_2.
4. However, the sewer model cannot calculate a lateral discharge at t_2, since it is already calculating the water level at t_1. This deadlock needs to be broken by returning a best guess on the lateral discharge at t_2.
5. Based on the lateral discharge obtained in step 4, the river model can calculate the water level at t_2. This result is then interpolated to a water level at t_1.
6. The sewer model has the required information and now can calculate the lateral discharge at t_1.
7. The sewer model now can go to the next calculation time t_2. The sewer model again asks the river model for its water level at t_2. Since this is calculated in step 5, the river model can immediately return this value.

In case the time steps for SOBEK and Infoworks are equal, the interpolation is not necessary, so the calculation becomes more accurate and a bit simpler.

Appendix II Model equations

In this appendix the various model equations are discussed, starting with the equations used in Infoworks, followed by the equations used in SOBEK.

II.I Infoworks CS

As explained in the second chapter, precipitation falls on a surface where part of it infiltrates or evaporates. The remaining precipitation is the net precipitation, which is routed to the sewer system.

II.I.i Rainfall runoff models

Precipitation in an urban area partly infiltrates in the ground to the unsaturated zone and partly discharges into the sewer system. The amount of precipitation infiltrates to the unsaturated zone is determined by a rainfall runoff model. In the model of the Vosdonk there are two rainfall runoff models used, the fixed PR model and the Horton infiltration model. A short explanation of these models is given below.

II.I.ii Fixed PR model

The fixed PR model, see equation (II.1), is used for the impervious areas. In this model a fixed ratio of the rainfall is transferred into runoff and is independent of antecedent conditions. The ratio is depending on the surface type and ranges between 0.25 for open areas and 1.00 for “high quality paved roads with gullies less than 100 metres apart” (Wallingford Software Ltd., 2008).

$$R = r \cdot P \cdot I \cdot t \cdot \tfrac{1}{1000} \tag{II.1}$$

Table II-I Symbols and units in equation (II.1)

Symbol	Meaning
R	Runoff [m3/hr]
R	Ratio, between 0 and 1 [-]
I	Precipitation intensity [mm/hr]
A	Area [m2]
T	Time [hr]

II.I.iii Horton-infiltration model

For the pervious areas the Horton-infiltration model is used. The Horton-infiltration model is based on an empirical formula, derived from the Horton equation. The initial infiltration rate exponentially drops to a final infiltration rate, using equation (II.2). The cumulative infiltration F can be calculated by using equation (II.3).

$$f = f_c + \left(f_0 - f_c \right) e^{-kt} \tag{II.2}$$

Table II-II Symbols and units in equation (II.2)

Symbol	Meaning
F	Infiltration rate [mm/hr]
f_c	Limiting infiltration rate [mm/hr]
f_0	Initial infiltration rate [mm/hr]
K	Coefficient of exponential tem [1/hr]
T	Time [hr]

$$F(t)=\int_0^t f = f_c \cdot t + \frac{f_0 - f_c}{k}\left(1-e^{-kt}\right) \tag{II.3}$$

The equation above is only valid if the rainfall intensity is higher than the infiltration rate, which makes it not suitable for a continuous simulation. To overcome this, the Horton-infiltration model is transformed into a soil moisture model, see equation (II.4) and Figure II-I.

$$f = f_0 - \theta k \tag{II.4}$$

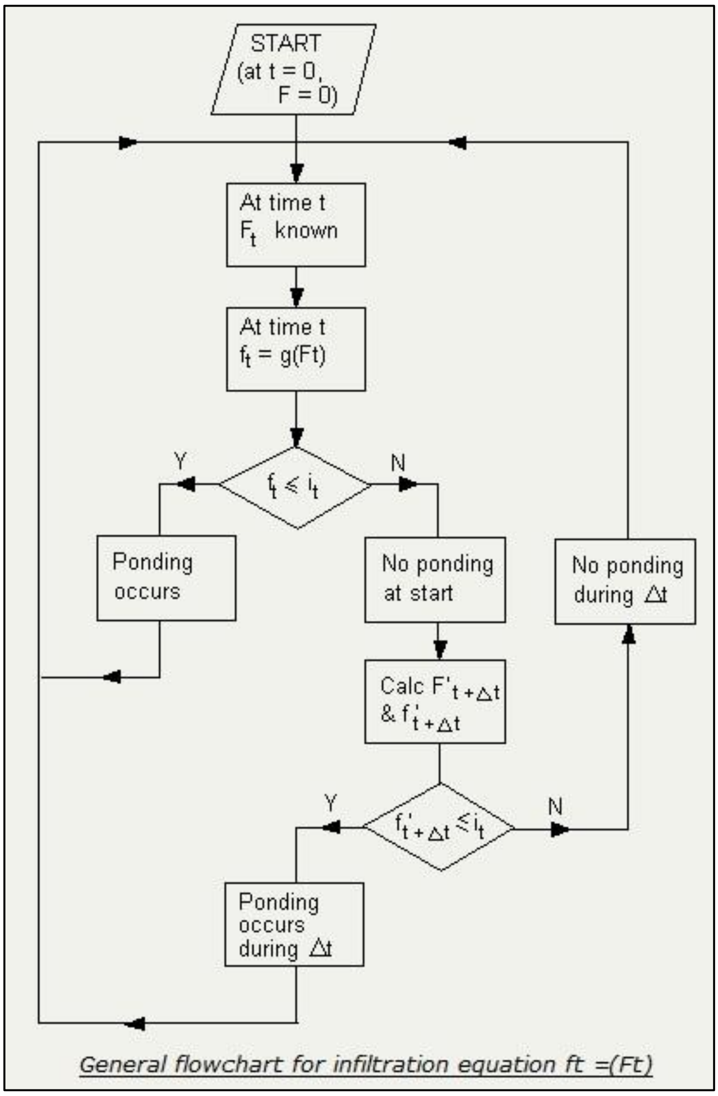

Figure II-I Flowchart for continuous Horton Infiltration calculation (Wallingford Software Ltd., 2008)

If the rainfall intensity (i) is larger than the infiltration rate (f) then ponding occurs and the volume of rainfall losses due to infiltration is calculated directly from equation (II.3) over the time interval t. In case the rainfall intensity is smaller than the infiltration rate two cases can exist.

- If the infiltration rate at the end of the interval is greater than the rainfall intensity, then all the rainfall infiltrates into the soil
- If the infiltration rate at the end of the interval is less than the rainfall intensity, then ponding occurs.

Calculating a new infiltration rate tests the assumption (noted with a " ' " in Figure II-I) that at the end of the interval all the rainfall infiltrates. If the now calculated infiltration rate is greater than the rainfall intensity then calculate the time to ponding (t_p). Following this the rainfall between the interval t to t_p is allowed to infiltrate. A new infiltration rate at time t_p is calculated from equation (II.2). The infiltration volume is now calculated from equation (II.3), substituting $\left(t-t_p\right)$ for t (Wallingford Software Ltd., 2008).

II.I.iv Runoff-routing model

After determining of the net precipitation, the water that is not infiltrated can be discharged, using a routing model. It has been shown that simpler reservoir-based models, which are less onerous computationally, represent the physical processes as accurately as the more complex physically based approaches. Furthermore, in practice the models are applied to catchments comprising the combined behaviour of a number of overland flow planes, gutters and feeder pipes. Therefore the parameters of a physically based approach as applied would not relate directly to parameters representative of individual surfaces (Wallingford Software Ltd., 2008).

The routing model used in Infoworks CS is the SPRINT-model, which is a single reservoir model. The SPRINT-model is using the following equations.

$$S = k \cdot q \tag{II.5}$$

$$k = 5.3 \cdot A^{0.30} \left(IMP/100 \right)^{0.45} \cdot p^{-0.38} \tag{II.6}$$

Combined with the continuity equation (II.7), the runoff of the pervious areas can be determined.

$$\frac{\delta S}{\delta t} = i_n - q \tag{II.7}$$

Table II-III Symbols and units in equations (II.5), (II.6) and (II.7)

Symbol	Meaning
S	Storage [mm]
k	Linear reservoir constant [1/min]
q	Discharge [mm/min]
A	Area [ha]
IMP	Percentage of impervious area [%]
p	Slope [%]
i_n	Net rainfall [mm/min]

II.II SOBEK Urban

SOBEK uses the same main principles in the rainfall-runoff calculations as Infoworks CS does. Only the models used for the processes are different.

II.II.i Rainfall-Runoff model

SOBEK Urban uses the NWRW-model for the rainfall-runoff calculation. This model is based on the Horton equations, but works different then Horton Infiltration model in Infoworks CS. The NWRW-model uses two equations, see equations (II.8) and (II.9). equation (II.8) is used for the decreasing infiltration capacity, while equation (II.9) is used for the increasing infiltration capacity.

$$f_t = f_e + \left(f_b - f_e\right) \cdot e^{-k_a t} \tag{II.8}$$

$$f_t = f_b - \left(f_b - f_e\right) \cdot e^{-k_h t} \tag{II.9}$$

Table II-IV Symbols and units in equations (II.8) and (II.9)

Symbol	Meaning
f_t	Infiltration Capacity at time t [mm/hr]
f_e	minimum infiltration capacity [mm/hr]
f_b	maximum infiltration capacity at time t=0 [mm/hr]
k_a	time factor decreasing infiltration capacity [1/hr]
k_h	time factor increasing infiltration capacity [1/hr]
t	time [hr]

The rate of decreasing and recovering infiltration capacity between the maximum value f_b and the minimum value f_e depends on the time factors k_a and k_h. It is assumed that at the beginning of each rainfall event, the infiltration capacity is at its maximum. Infiltration capacity is decreasing as long as there is water stored on the surface. If infiltration capacity reaches the minimum value, and there is still water on the surface, it will remain at the minimum value. Infiltration capacity will increase as soon as the surface is dry and it is not raining. If infiltration capacity reaches the maximum value and there is no water on the surface, it will remain at the maximum value (WL Delft Hydraulics, 2009).

Runoff-routing model

The net precipitation is routed to the sewer model using the Rational Method, see equation (II.10).

$$q = c \cdot h \tag{II.10}$$

Symbol	Meaning
q	Discharge to sewer system [mm/min]
c	Runoff factor [1/min]
h	Net precipitation [mm]

The runoff factor c is predefined for different types of surfaces and is function of length, roughness and slope (WL Delft Hydraulics, 2009).

Appendix III Hydraulic model of the receiving water body

The model of the receiving water body was built in SOBEK. Except for the channel flow module, the model also used the rainfall-runoff module and the 1D-2D overland flow module. An overview of the original model is presented in Figure IV-II. The model was not performing very well, this was due to the fact that the overland flow module is very time consuming. Since OpenMI was unable to perform calculations of a SOBEK-model using the 1D-2D overland flow module[1], it had to be disabled. A positive side effect of this was that the calculation times improved, allowing longer simulation periods. Disabling the overland flow module also had a negative side effect. The calculated water levels drastically changed. Instead of water depths in the order of a few metres, depths of over 60 metres were calculated. Apparently the overland flow module stored a large volume of water upstream in the catchment area. This problem was even worse because of the rough schematisation of the unpaved areas in the catchment. This leads to the discharge of precipitation for large areas at a single point in the model, instead of a more diffuse discharge. In the narrow cross-sections this caused big flood waves which propagated both downstream and upstream, the weirs and culverts in the model counteract this effect a little, since the small cross-sections limit the flow. Water levels further downstream are therefore less affected by the disabling of the 1D-2D overland flow module.

Since the disabling of the 1D-2D overland flow module removed a large surface storage area, several retention areas were modelled near the study area, see Figure III-II. Because of these retention areas, the water levels at the overflow locations, are comparable to the water levels calculated when using the 1D-2D overland flow module, see Figure III-V to Figure III-XXVI. Peak water levels calculated without the overland flow module often last a bit shorter, while near the end of an event the water levels remain slightly higher. All in all it can be concluded that the water levels are correctly modelled using the retention areas in the study area.

To be able to simulate time-series with prolonged dry periods, very small discharges were added to the model boundaries. During the dry periods the water system would otherwise be completely dry, which causes numerical instabilities and causes a large volume error. Discharges of a few litres per second maintain a water depth of centimetres and therefore speed up calculations with dry periods.

[1] The issue was reported to SOBEK Support, bug number 21313.

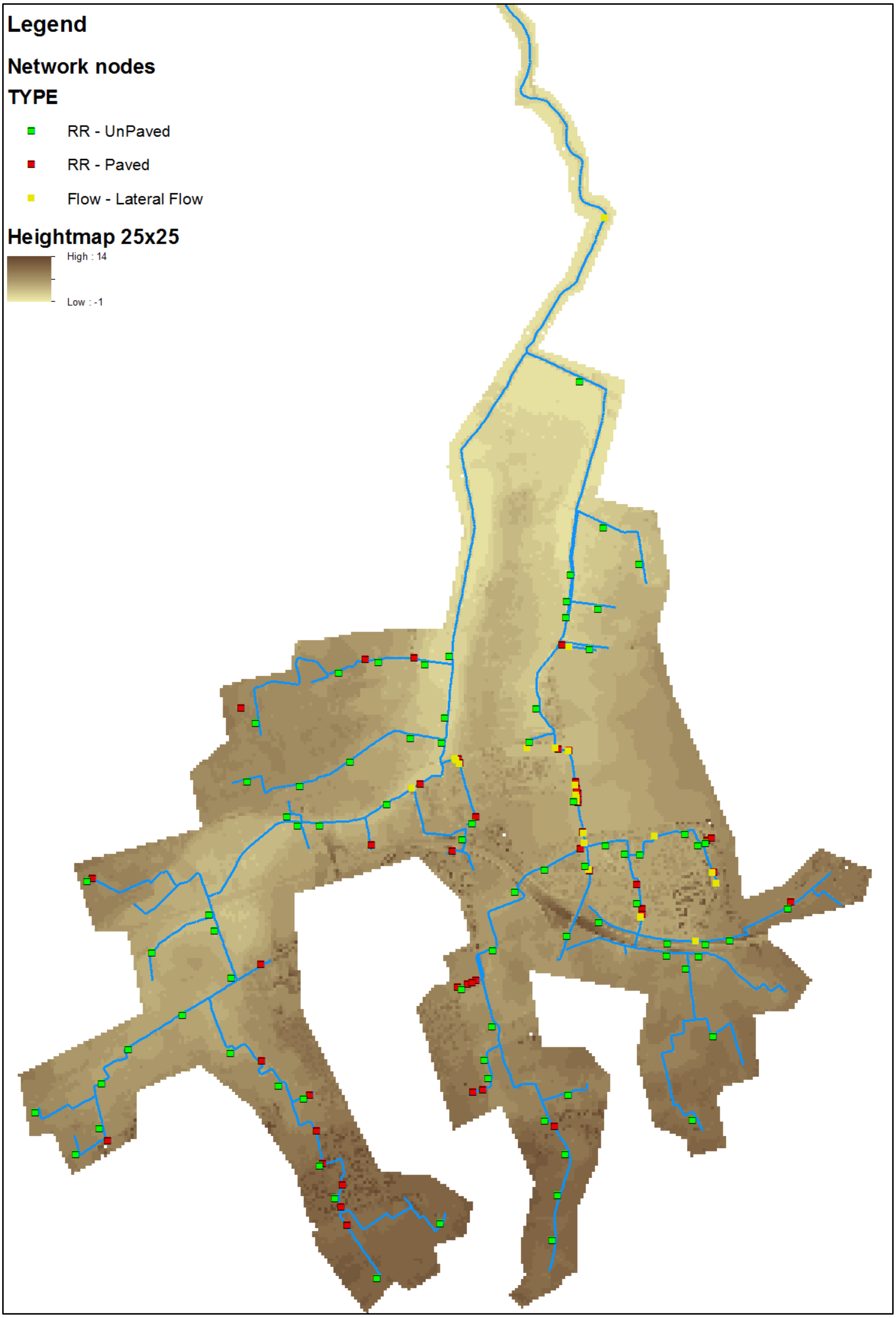

Figure III-I SOBEK model with channels, rainfall runoff and 1D-2D overland flow module

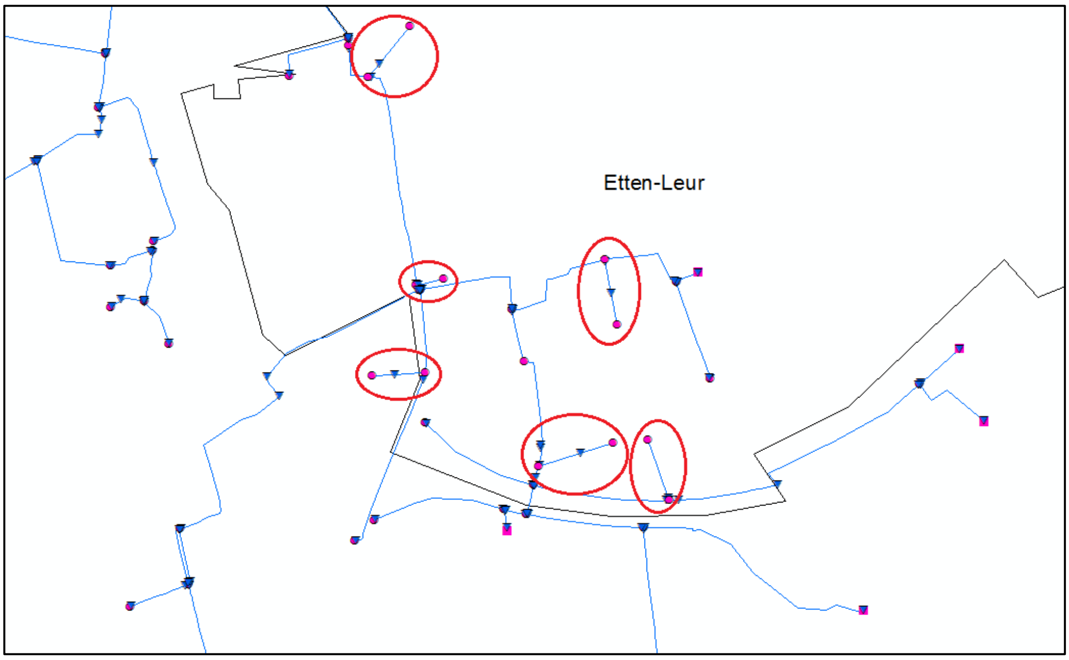

Figure III-II Locations of modelled retention areas

The geographic locations of the overflow location are shown in Figure III-III. At all of these locations the results of the recalibration will be presented below.

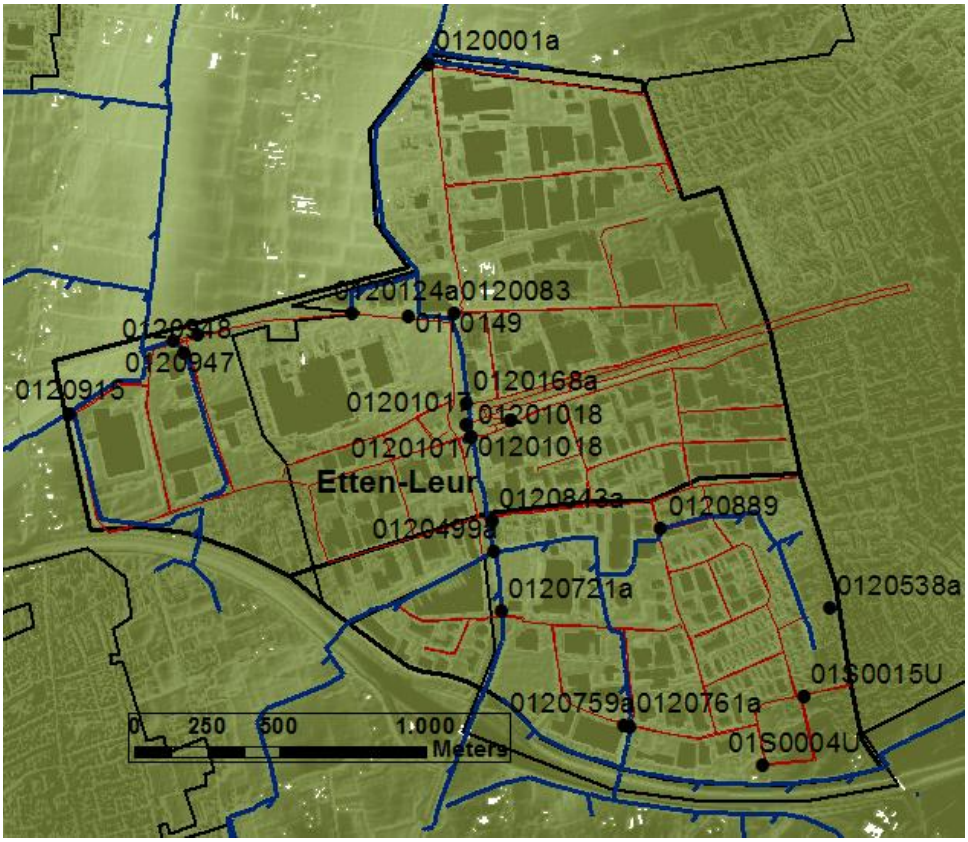

Figure III-III Overview of the overflow locations in and around the Vosdonk

The root mean square error (RMSE) was used to determine whether the calibration of the model of the receiving water body was good enough. As can be seen in Figure III-IV the RMSE is very low at locations in the Kibbelvaart, where the water levels are almost identical during the simulated period. The water levels at other locations show larger differences between the model with the 1D2D-overland flow module enabled and the model without this module. The peak water levels match relatively well between the models, the main differences are after the highest water levels. This is caused by the differences in storage around those locations and the remodelling can only compensate this partially.

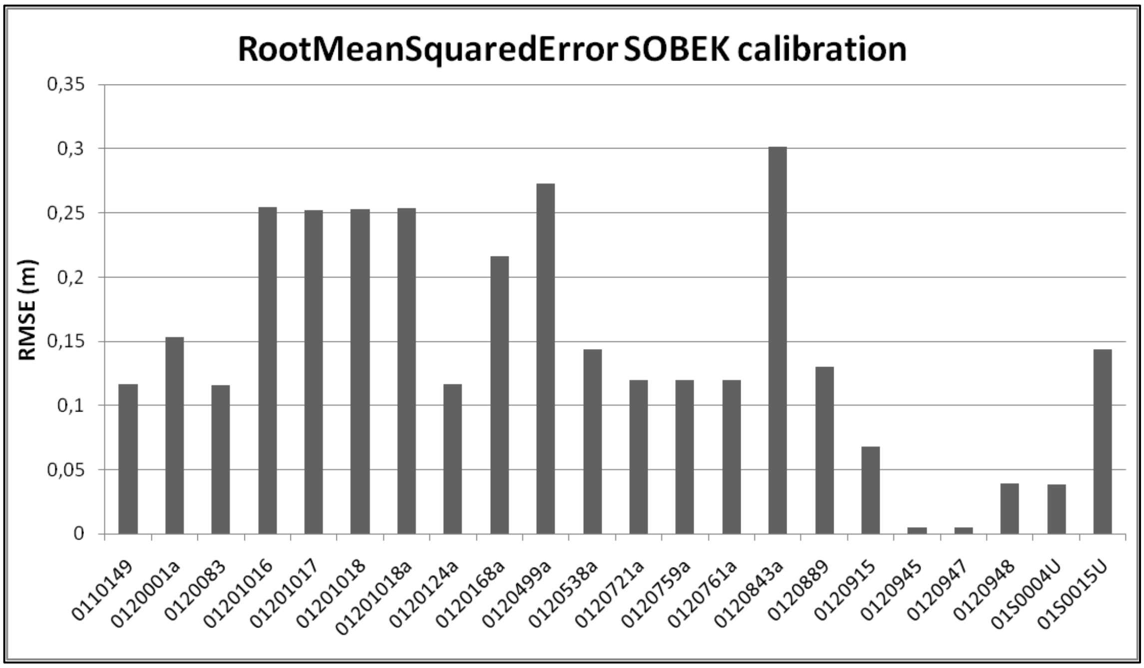

Figure III-IV RMSE calibration model of the receiving water body

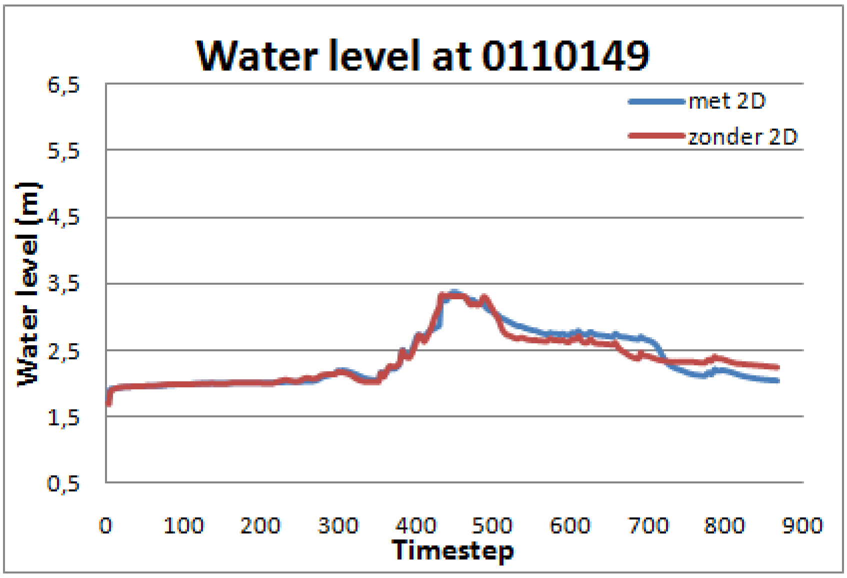

Figure III-V Water level at node 0110149

The water levels match in the model without the overland flow module matches the water levels compared to the model with that module. Peak water levels are nearly equal, while the main differences occur after the peak. This means that the model without the overland flow module has more storage, so the high water wave can be stored for a longer period of time. When the water is gone near the study area in the model with the overland flow module, there is still water in the storage that needs to be discharged, leading to higher water levels.

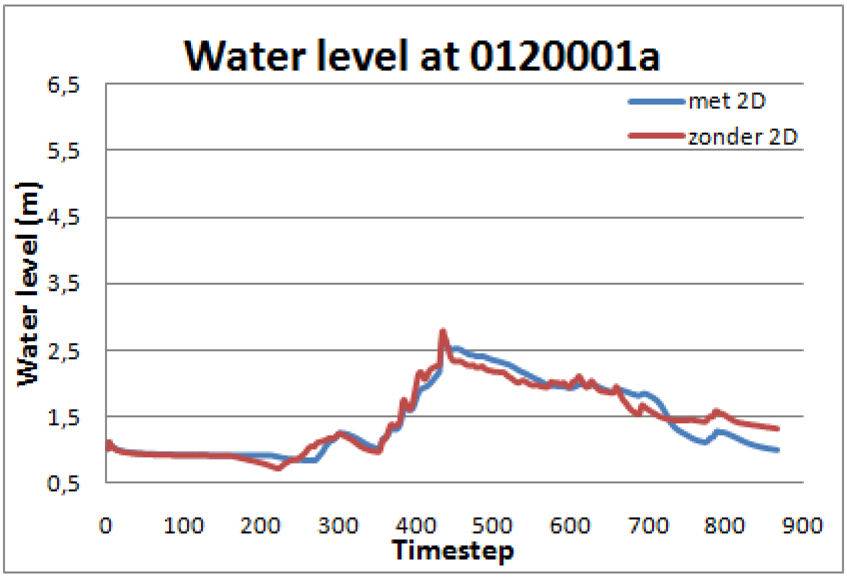

Figure III-VI Water level at node 0120001a

The same for node 0110149 applies to this node, but there are some deviations between the two in the rising limb of the high water wave.

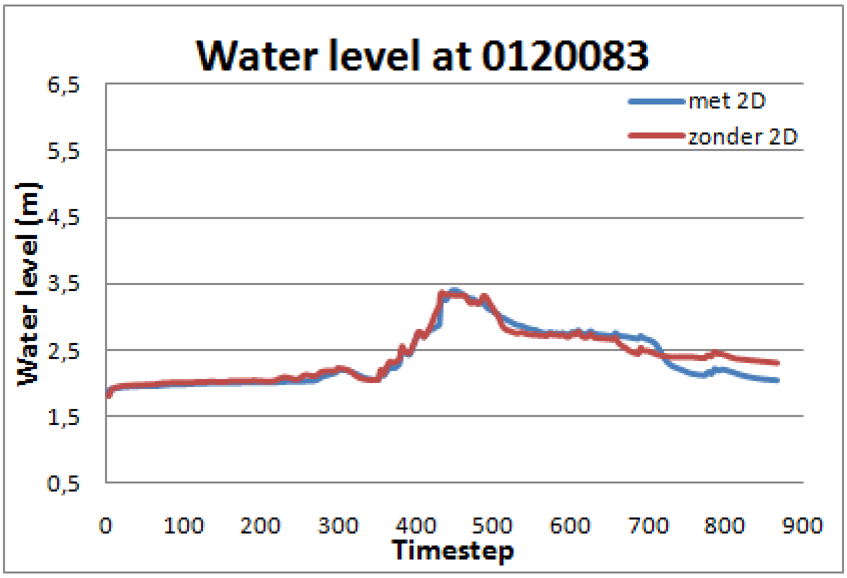

Figure III-VII Water level at node 0120083

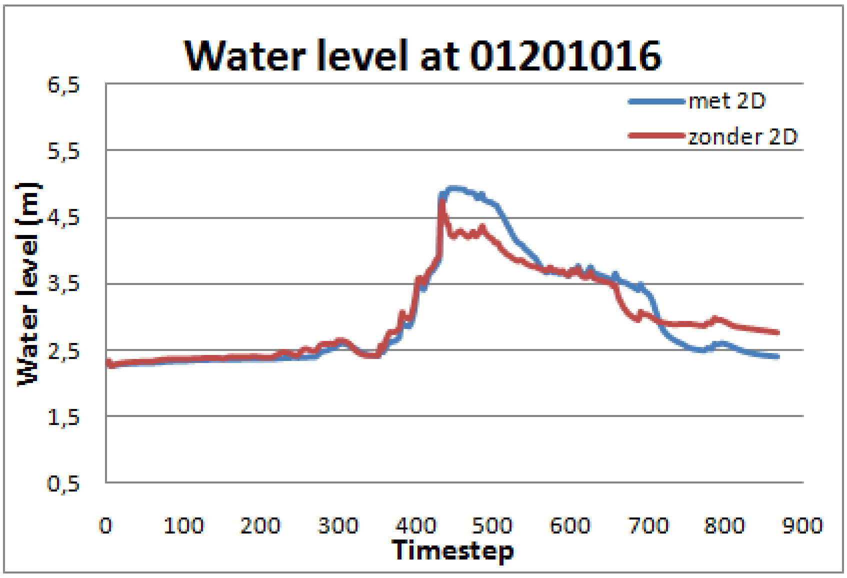

Figure III-VIII Water level at node 01201016

The water levels at this location and at the following locations are quite similar and show that although the maximum water levels match, the duration of the high water wave is much shorter for this node. This must be caused by storage further upstream and the simulation period was not long enough to show the discharge of this stored volume.

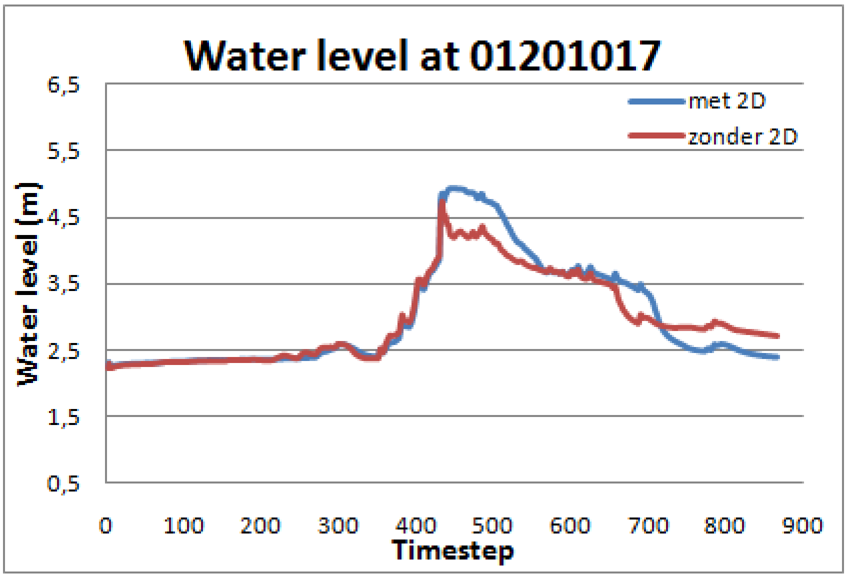

Figure III-IX Water level at node 01201017

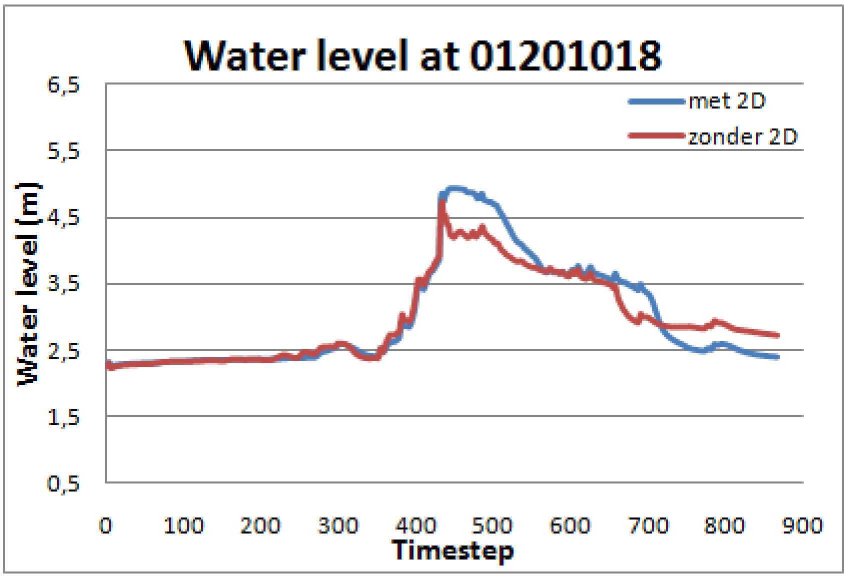

Figure III-X Water level at node 01201018

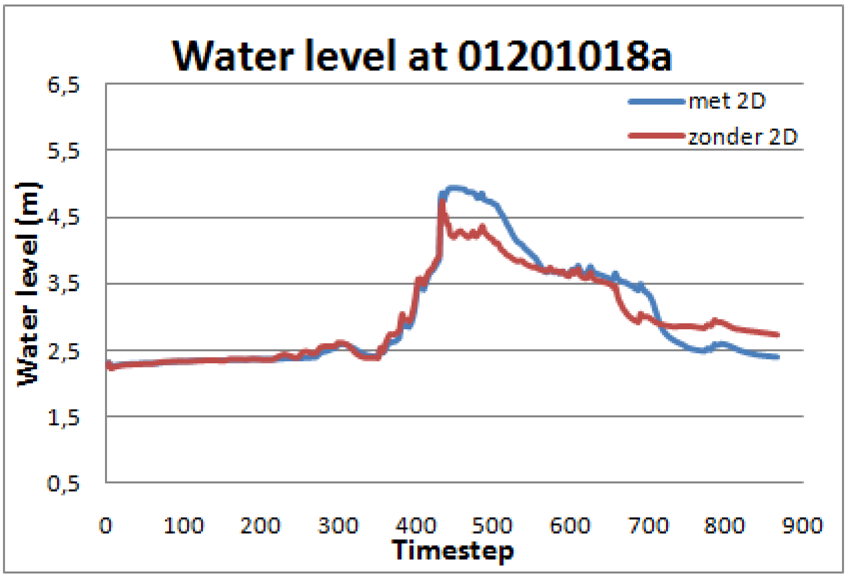

Figure III-XI Water level at node 01201018a

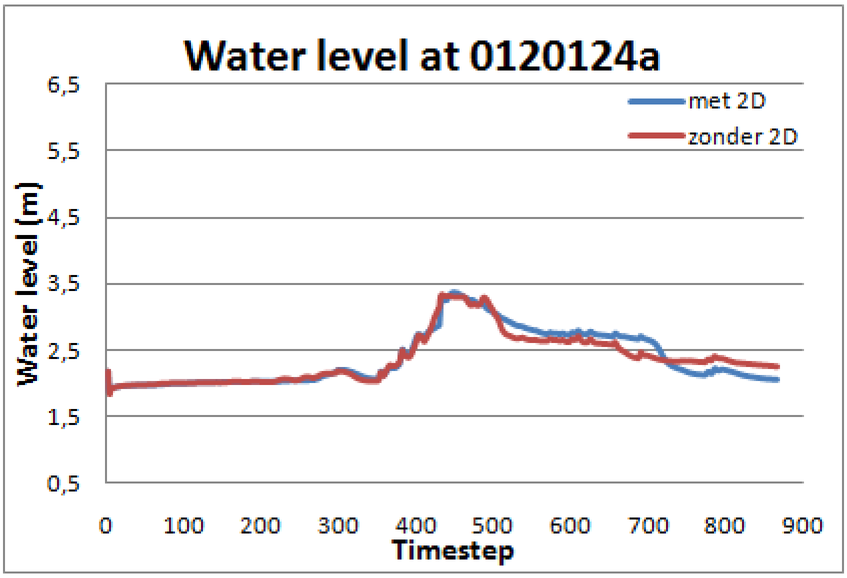

Figure III-XII Water level at node 0120124a

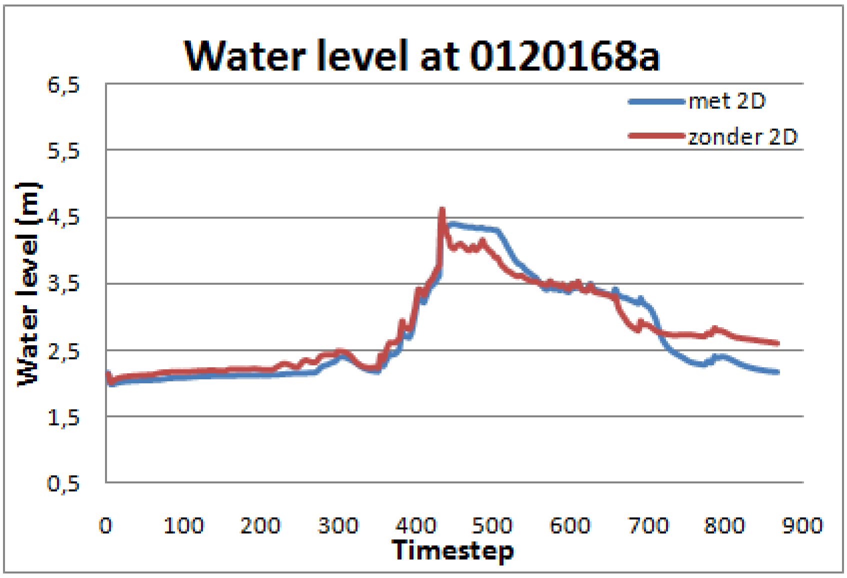

Figure III-XIII Water level at node 0120168a

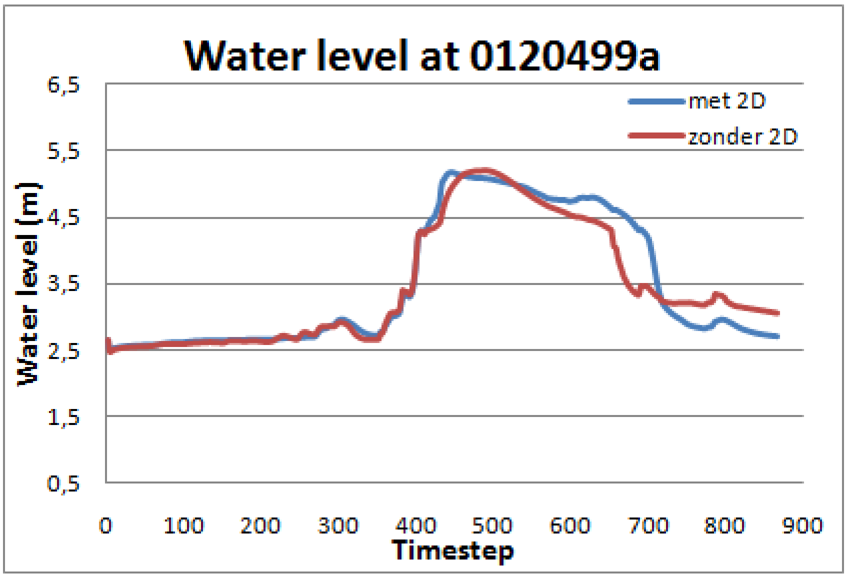

Figure III-XIV Water level at node 0120499a

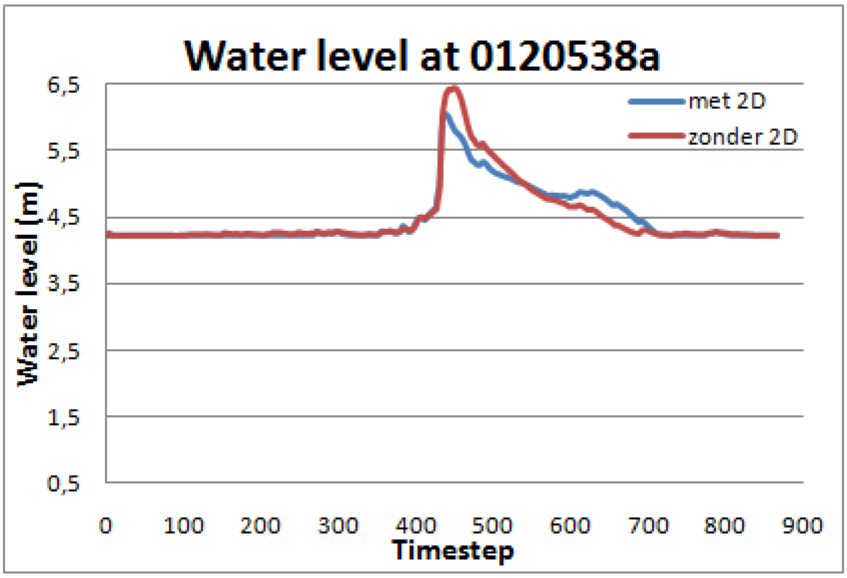

Figure III-XV Water level at node 0120538a

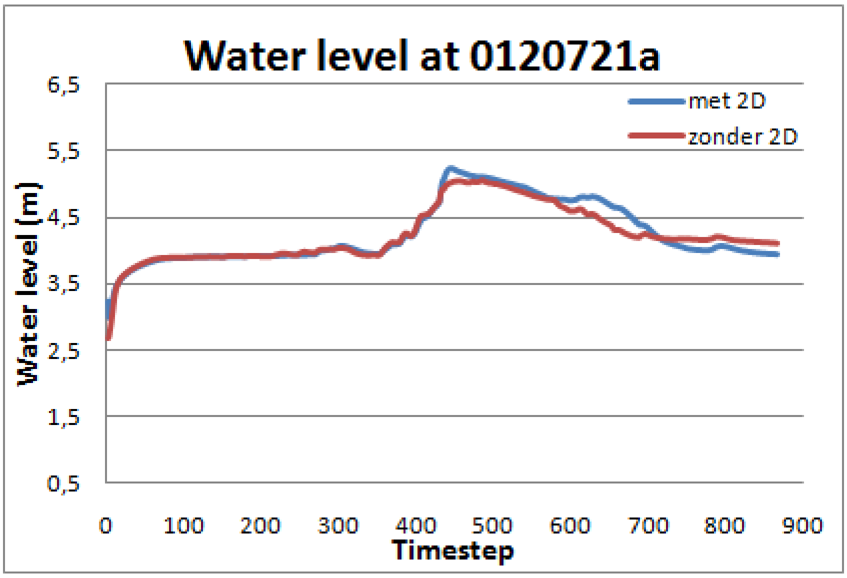

Figure III-XVI Water level at node 0120721a

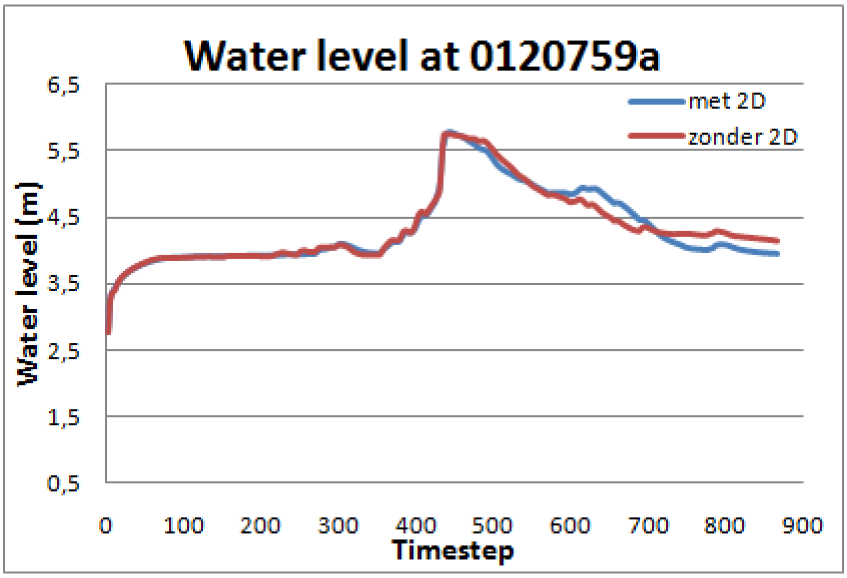

Figure III-XVII Water level at node 0120759a

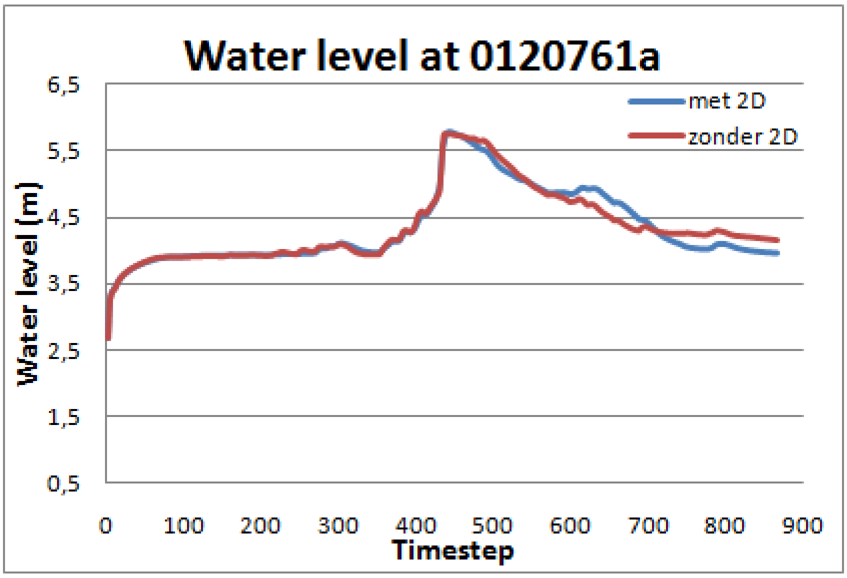

Figure III-XVIII Water level at node 0120761a

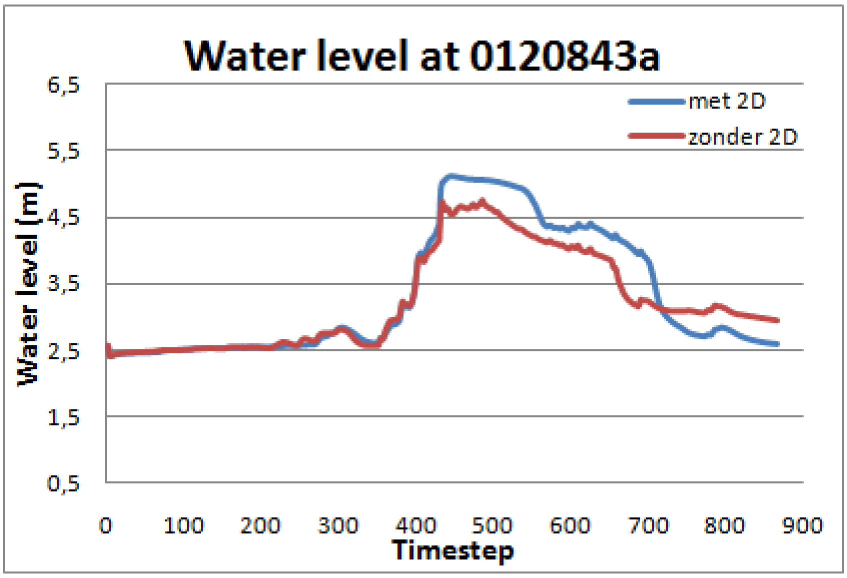

Figure III-XIX Water level at node 0120843a

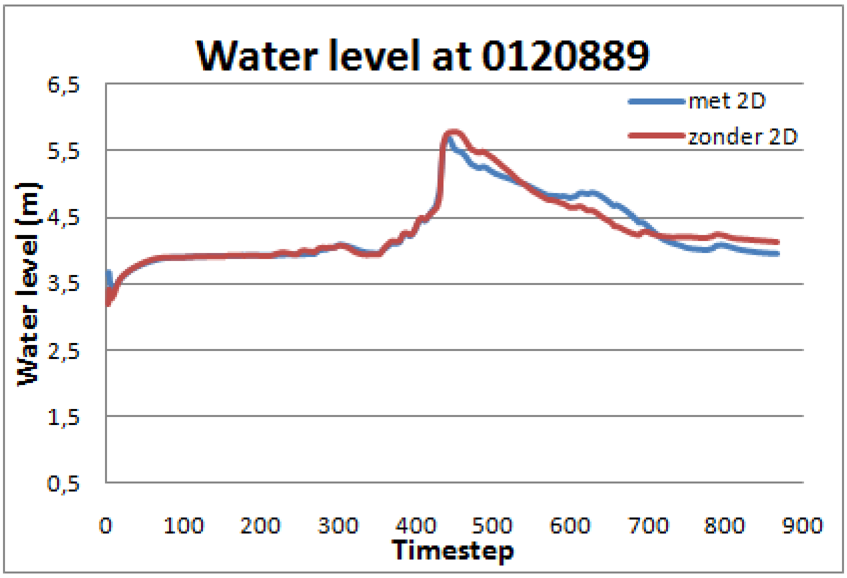

Figure III-XX Water level at node 0120889

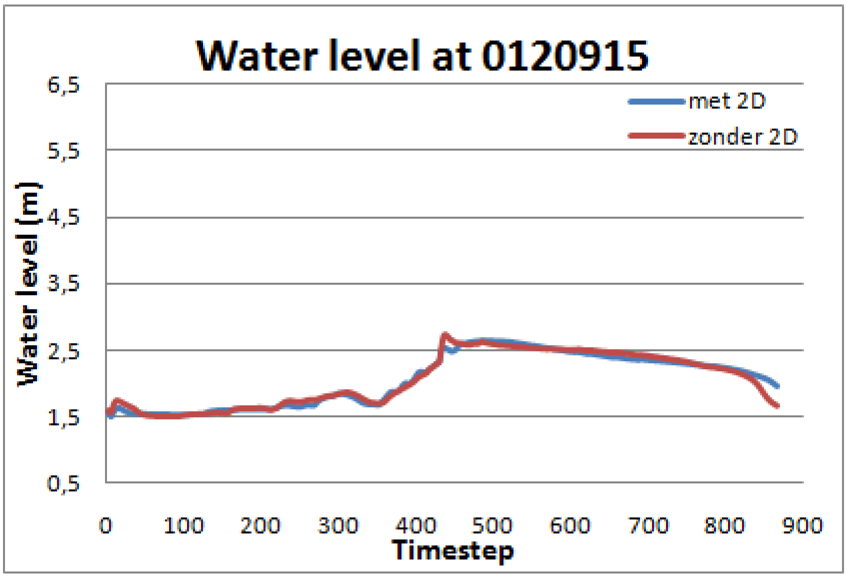

Figure III-XXI Water level at node 0120915

At this and the following locations, the water levels match closely with and without the overland flow module. These nodes are located in the basin of the *Kibbelvaart*, where there apparently is less storage which is influenced by disabling the overland flow module.

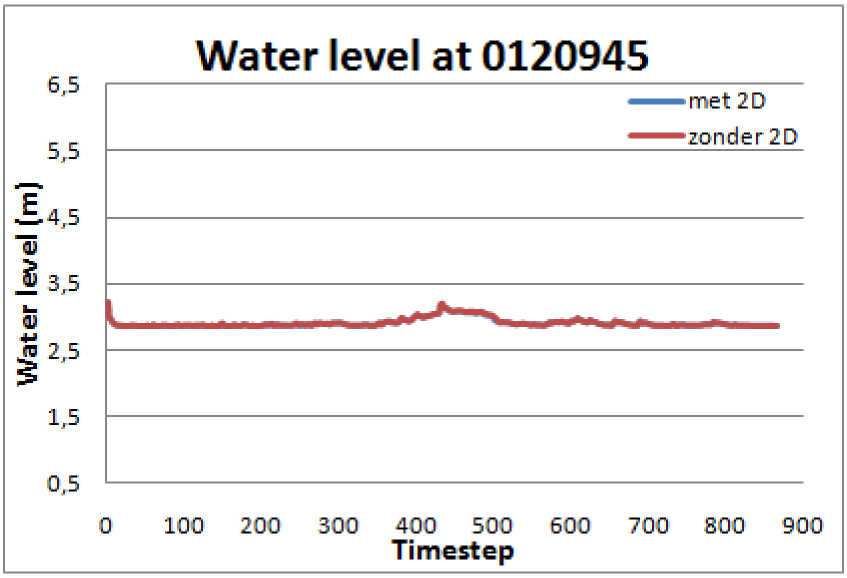

Figure III-XXII Water level at node 0120945

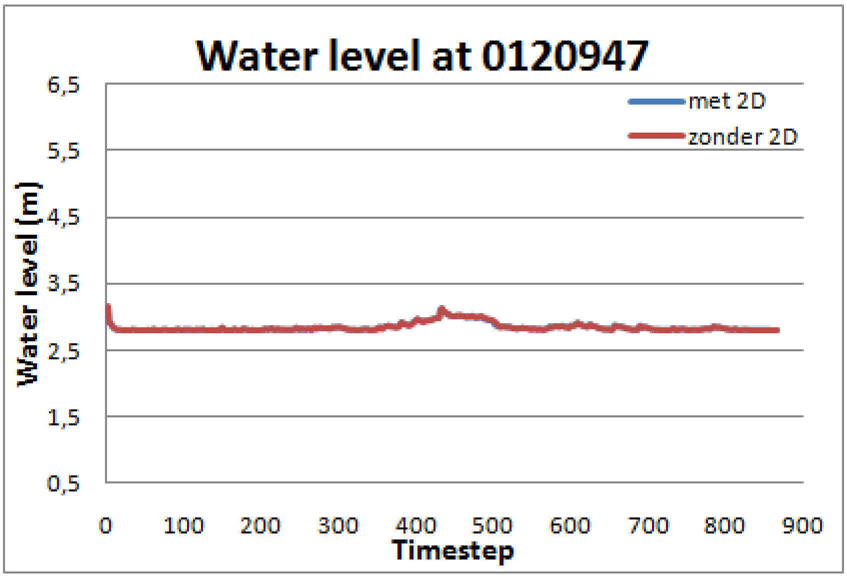

Figure III-XXIII Water level at node 0120947

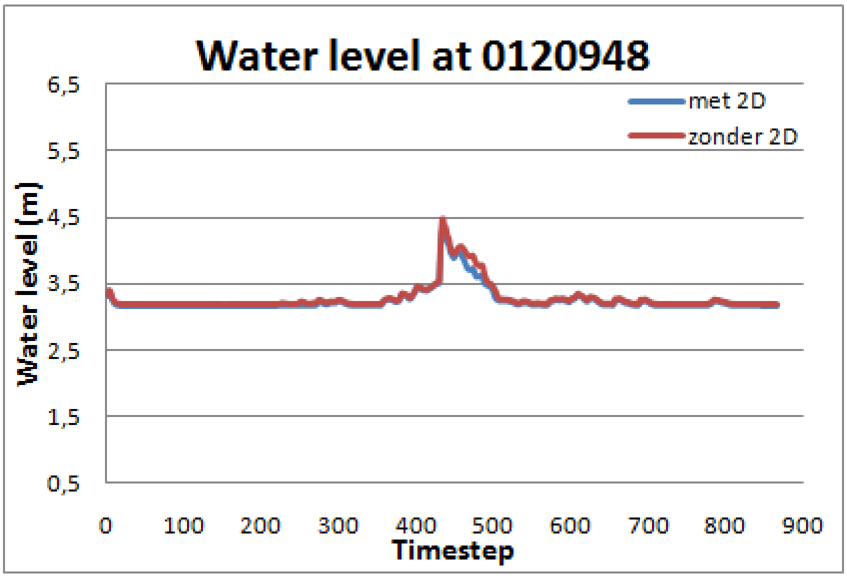

Figure III-XXIV Water level at node 0120948

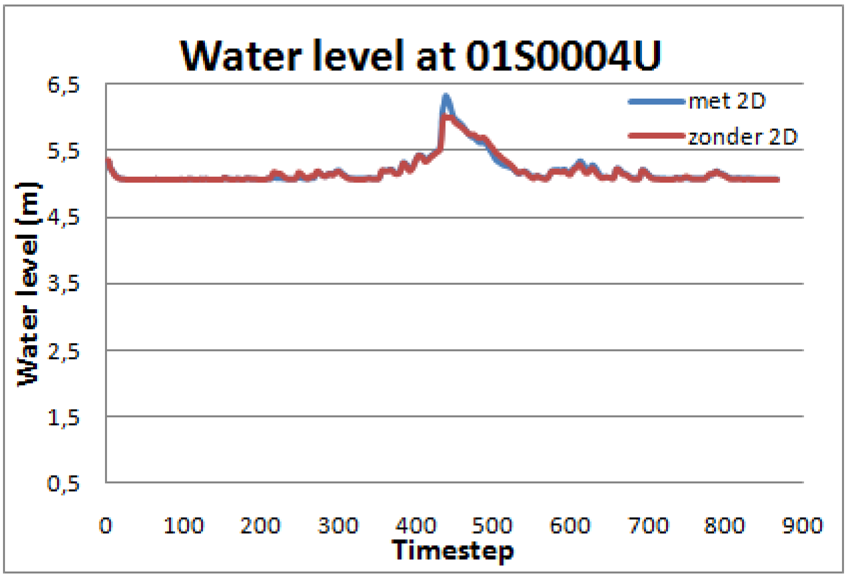

Figure III-XXV Water level at node 01S0004U

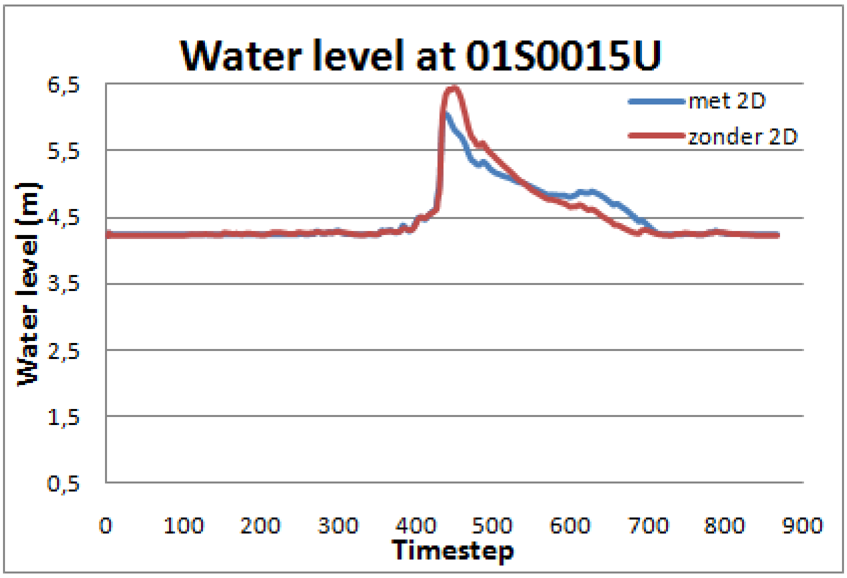

Figure III-XXVI Water level at node 01S0015U

Appendix IV Integrated modelling

This appendix described the different methods of integrated modelling used in this study. First the simplest method, level hydrographs, is explained, followed by the setup and validation of OpenMI. Finally the fully integrated model is described.

IV.I Level hydrographs

It is not very complicated to create an integrated model using level hydrographs. First the model of the sewer system is run without any water levels at the overflow locations. The discharges at the overflow locations are then used as a lateral inflow in the model of the receiving water body. With these lateral flows the model of the receiving water body is run and the resulting water levels at the overflow locations are used as boundary conditions for the model of the sewer system. This process is repeated a number of times until the exchanged water levels and discharges vary little between iterations. The process is schematically shown in Figure IV-I.

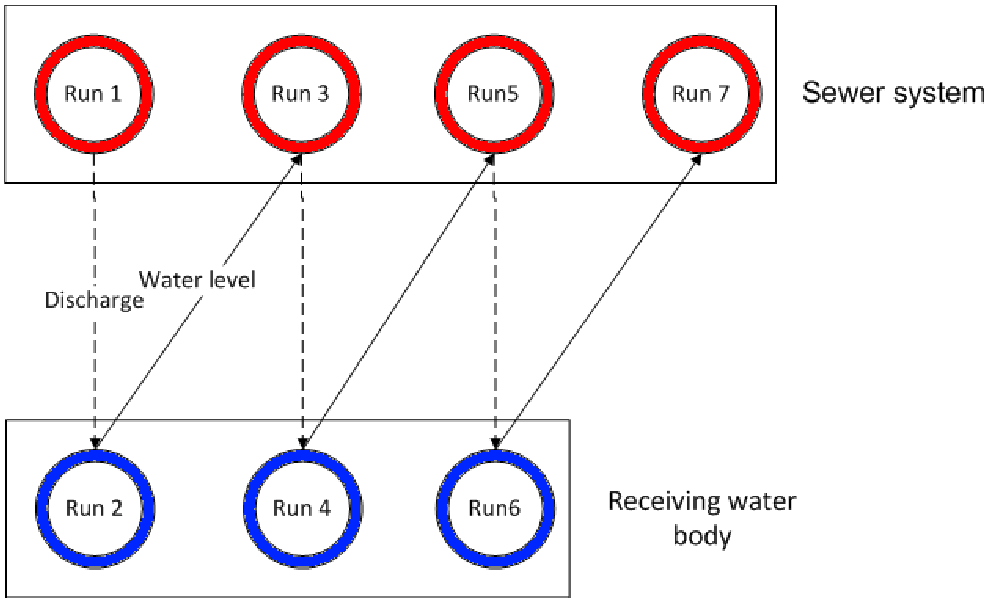

Figure IV-I Flow scheme of coupling using level hydrographs

In the previous study in this area, the sewer system and the receiving water body were linked using level hydrographs. The number of iterations in that study was limited to two, because it was assumed that additional runs would have no significant effect on the calculation results.

IV.II OpenMI

The models can be integrated in OpenMI using the OpenMI Configuration Editor.

IV.II.i OpenMI test-cases

To test whether integrated modelling in OpenMI would influence the calculation results, three test-cases were defined. The results of these test-cases are described in this paragraph.

Case 1: Effects of the integrated model in OpenMI on the water levels in SOBEK

To determine whether there would be an effect of integrated modelling in OpenMI on the water levels in the receiving water body, a calculation was done with very little precipitation in SOBEK and a dry period in Infoworks CS. The results of this calculation showed that there were no differences between the stand-alone SOBEK calculations and the integrated model.

Case 2: Effects of the integrated model in OpenMI on the water levels in Infoworks CS

Case 2 is in principle equal to Case 1, but the precipitation events are swapped. So the model of the receiving water body will receive no precipitation and the model of the sewer system will use a low intensity rainfall event. The resulting water levels in the sewer system are at most locations equal to the stand-alone calculations in Infoworks CS. However, at a number of locations, the integrated model calculates different water levels, see Figure IV-II. As can be seen in Figure IV-II, the locations where differences occur are all near an outflow location. The bottom levels of these outflow locations are below the bottom level of the connected branch in the receiving water body. This means that the conduits near the outflow locations are always (partially) filled. In the stand-alone calculations there are no water levels applied to these outflow locations, causing the differences in model results.

Figure IV-II Locations with different water levels (red dots) in the integrated model

Case 3: Exchange of water levels and discharges using OpenMI

To test whether OpenMI correctly exchanges water levels and discharges between SOBEK and Infoworks CS both models are loaded into OpenMI. The Infoworks CS model uses an event with a duration of one day and a constant intensity of 40 mm/hr. The SOBEK model was using a low intensity event, to allow discharges from Infoworks CS into the SOBEK model. When the discharges are compared more closely, it is clear that there is a lag of one time step between Infoworks CS and SOBEK. This is the effect of the explicit connection of the models through OpenMI. When comparing the water levels, this lag can also be seen at moments when there are large deviations compared to the previous time step.

IV.III Fully integrated model

To create a fully integrated model in SOBEK, the model of the sewer system in Infoworks CS must be exported in a format that is readable by SOBEK. The only format that both software packages have in common is the import and export to shape-files. These shape files contain the locations of nodes and links. The properties of the nodes and links are stored in additional database files. The results of the export to shape-files in Infoworks CS are different files for each of the properties in the sewer system. There are files for all sewer types, pumps, weirs and catchment areas. To import the model of the sewer system in SOBEK, the shape files of each of the model components must be loaded separately. The result of the import in SOBEK is the locations of the manholes and the conduits between them. Unfortunately the properties of all the model components are lost during this process. To correct this, all properties must be added manually. Using a spreadsheet, the information for all the nodes and conduits was extracted and imported in SOBEK. This resulted in a model of the sewer system, which calculated more or less the same water levels as Infoworks CS. When water levels were different when compared with Infoworks CS, this was mainly caused by the differences in the rainfall-runoff and runoff-routing methods. Another aspect that can cause these small deviations is the way the flood cones are schematized. In Infoworks CS they are a cone that is expanding with rising water levels, while in SOBEK Urban the size of the flood cones remains constant. This difference in schematization causes differences in water levels in the order of 2 or 3 centimetres.

A comparison of the water levels between Infoworks CS and SOBEK for a random node is shown in Figure IV-III. In Figure IV-IV the Root Mean Square Error (RMSE) is shown for all modelled locations in the sewer system. As can be seen in this figure, the differences between these models are in the range of 5 to 10 centimetres. Only at a few locations the RMSE is higher than 10 centimetres. At these locations the water levels vary more, but this is due to pump characteristics in the foul water system. Since these locations are not important in estimating the flood risk, the error in calculated water levels at these locations can be ignored.

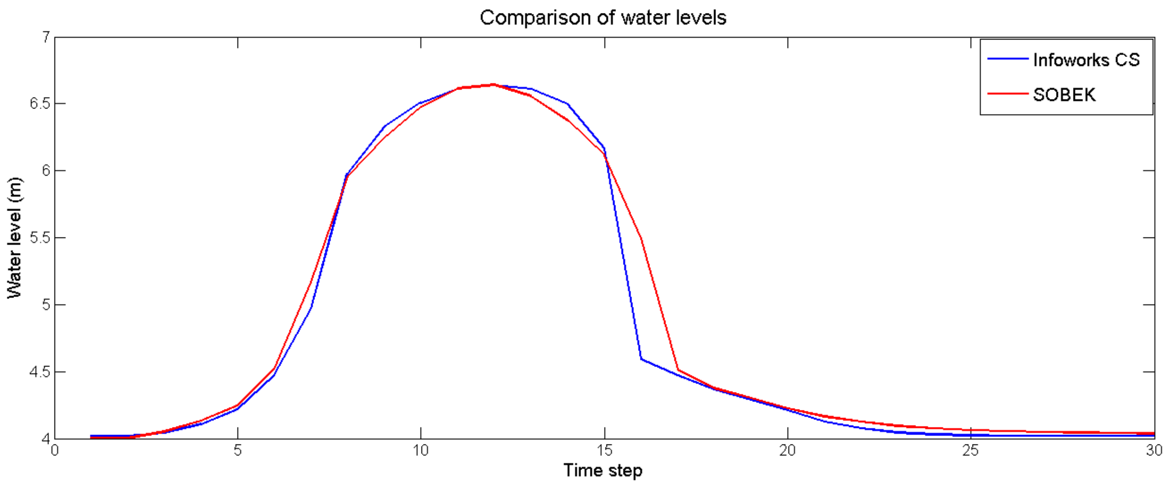

Figure IV-III Comparison of water levels in the sewer system between SOBEK and Infoworks CS (size of time step is 15 minutes)

As can be seen in Figure IV-III, SOBEK is able to calculate water levels which are similar to Infoworks CS using *Bui 8* as precipitation event. Water levels rise slightly faster and it takes more time steps after an event before the system returns to its initial levels. Although there are some small differences in model results, the integrated model in SOBEK can be compared against the integrated model in OpenMI. An overview of the fully integrated model in SOBEK is shown in Figure IV-V.

Figure IV-IV Root Mean Square Error when comparing water levels in SOBEK Urban and Infoworks CS

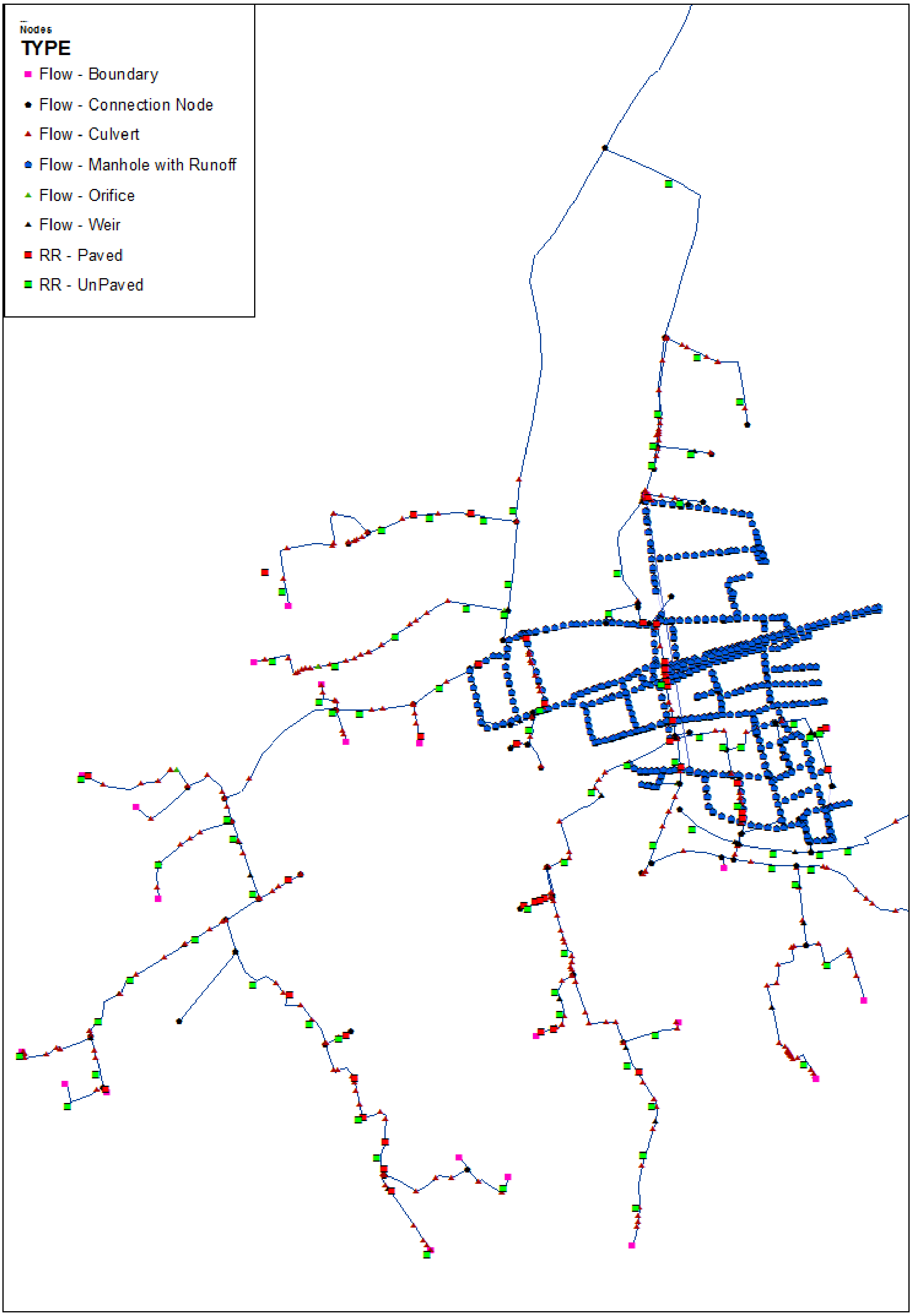

Figure IV-V Overview of the integrated model in SOBEK

Appendix V Results of the integrated models

In this appendix the results of the various integrated models are presented and shortly discussed. The graphs for all methods of integrated modelling are presented at the end of this appendix.

V.I Integrated model using level hydrographs

Flooding in the integrated model using level hydrographs shows the same pattern as for the integrated model using OpenMI, although the extent of the flooding is smaller. Especially during the first event the flood volume is much lower. During the runs the total flood volume changes only a little, showing the limitations of this method of integrated modelling. From the differences between the runs it is clear that flooding in the receiving water body decreases with the number of runs, while flooding in the sewer system tends to increase. This is due to the order in which the models were run. The first run shows an underestimation of the flood volume in the sewer system, because there are no limits on the outflow. This leads to an overestimation of the inflow to the receiving water body, which causes higher water levels.

Table V-I Results of the integrated model using level hydrographs - Run 1

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
# of flood locations	96	84	116	137	186	1	102	130	86	172	93
Total flood volume (m^3)	73	41	125	156	1335	1	96	181	50	254	53

Table V-II Results of the integrated model using level hydrographs – flood depth (m) - Run 2

Location	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
0110149	-	-	-	-	-	-	-	-	-	-	-
0120001a	-	-	-	-	2,03	-	0,19	0,13	-	0,25	-
0120083	-	-	-	-	-	-	-	-	-	-	-
01201016	-	-	-	-	-	-	-	-	-	-	-
01201017	-	-	-	-	-	-	-	-	-	-	-
01201018	-	-	-	-	-	-	-	-	-	-	-
01201018a	-	-	-	-	-	-	-	-	-	-	-
0120124a	-	-	-	-	-	-	-	-	-	-	-
0120168a	-	-	-	-	-	-	-	-	-	-	-
0120499a	-	-	-	-	-	-	-	-	-	-	-
0120538a	-	-	-	-	1,73	-	-	-	-	-	-
0120721a	-	-	-	-	-	-	-	-	-	-	-
0120759a	0,03	-	-	-	0,20	-	-	-	-	-	-
0120761a	0,05	-	-	-	0,22	-	-	-	-	-	-
0120843a	-	-	-	-	-	-	-	-	-	-	-
0120889	0,15	-	-	-	0,83	-	-	-	-	-	-
0120915	0,14	-	-	-	0,51	-	-	-	-	-	-
0120945	-	-	-	-	-	-	-	-	-	-	-
0120947	-	-	-	-	-	-	-	-	-	-	-
0120948	-	-	-	-	-	-	-	-	-	-	-
01S0004U	-	-	-	-	0,22	-	-	-	-	-	-
01S0015U	-	-	-	-	1,09	-	-	-	-	-	-

Table V-III Results of the integrated model using level hydrographs - Run 3

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
# of flood locations	109	84	117	138	186	1	106	133	86	172	93
Total flood volume (m^3)	80	42	126	157	1623	1	98	184	49	259	53

Table V-IV Results of the integrated model using level hydrographs – flood depth (m) - Run 4

Location	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
0110149	-	-	-	-	-	-	-	-	-	-	-
0120001a	-	-	-	-	1,61	-	0,12	0,07	-	0,16	-
0120083	-	-	-	-	-	-	-	-	-	-	-
01201016	-	-	-	-	-	-	-	-	-	-	-
01201017	-	-	-	-	-	-	-	-	-	-	-
01201018	-	-	-	-	-	-	-	-	-	-	-
01201018a	-	-	-	-	-	-	-	-	-	-	-
0120124a	-	-	-	-	-	-	-	-	-	-	-
0120168a	-	-	-	-	-	-	-	-	-	-	-
0120499a	-	-	-	-	-	-	-	-	-	-	-
0120538a	-	-	-	-	1,40	-	-	-	-	-	-
0120721a	-	-	-	-	-	-	-	-	-	-	-
0120759a	-	-	-	-	0,18	-	-	-	-	-	-
0120761a	-	-	-	-	0,20	-	-	-	-	-	-
0120843a	-	-	-	-	-	-	-	-	-	-	-
0120889	0,10	-	-	-	0,73	-	-	-	-	-	-
0120915	0,14	-	-	-	0,51	-	-	-	-	-	-
0120945	-	-	-	-	-	-	-	-	-	-	-
0120947	-	-	-	-	-	-	-	-	-	-	-
0120948	-	-	-	-	-	-	-	-	-	-	-
01S0004U	-	-	-	-	0,21	-	-	-	-	-	-
01S0015U	-	-	-	-	0,76	-	-	-	-	-	-

Table V-V Results of the integrated model using level hydrographs - Run 5

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
# of flood locations	96	84	116	137	186	1	102	130	86	172	93
Total flood volume (m^3)	73	41	125	156	1395	1	96	181	50	254	54

Table V-VI Results of the integrated model using level hydrographs – flood depth (m) - Run 6

Location	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
0110149	-	-	-	-	-	-	-	-	-	-	-
0120001a	-	-	-	-	1,78	-	0,10	0,06	-	0,16	-
0120083	-	-	-	-	-	-	-	-	-	-	-
01201016	-	-	-	-	-	-	-	-	-	-	-
01201017	-	-	-	-	-	-	-	-	-	-	-
01201018	-	-	-	-	-	-	-	-	-	-	-
01201018a	-	-	-	-	-	-	-	-	-	-	-
0120124a	-	-	-	-	-	-	-	-	-	-	-
0120168a	-	-	-	-	-	-	-	-	-	-	-
0120499a	-	-	-	-	-	-	-	-	-	-	-
0120538a	-	-	-	-	1,63	-	-	-	-	-	-
0120721a	-	-	-	-	-	-	-	-	-	-	-
0120759a	0,03	-	-	-	0,19	-	-	-	-	-	-
0120761a	0,05	-	-	-	0,21	-	-	-	-	-	-
0120843a	-	-	-	-	-	-	-	-	-	-	-
0120889	0,14	-	-	-	0,76	-	-	-	-	-	-
0120915	0,14	-	-	-	0,50	-	-	-	-	-	-
0120945	-	-	-	-	-	-	-	-	-	-	-
0120947	-	-	-	-	-	-	-	-	-	-	-
0120948	-	-	-	-	-	-	-	-	-	-	-
01S0004U	-	-	-	-	0,22	-	-	-	-	-	-
01S0015U	-	-	-	-	0,99	-	-	-	-	-	-

Table V-VII Results of the integrated model using level hydrographs - Run 7

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
# of flood locations	109	84	118	138	186	1	106	133	86	172	93
Total flood volume (m^3)	80	42	127	157	1620	1	99	184	49	259	54

V.II Results of the integrated model in OpenMI

Event 1 causes the second largest flooding of the sewer system and a flooding of the Kibbelvaart. During Event 6, flooding occurs at all locations in the sewer system and at many locations in the receiving water body. Event 11 is a major flooding event in the sewer system, but with little impact in the receiving water body. An overview of the results is shown in Table V-VIII and Table V-IX.

Table V-VIII Number of locations where flooding occurs Infoworks CS

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
# of flood locations	112	84	125	143	186	1	112	138	86	172	93
Total flood volume (m^3)	71	42	134	166	1578	1	105	199	50	276	55

Table V-IX Flood depths (m) receiving water body SOBEK

Location	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
0110149	-	-	-	-	-	-	-	-	-	-	-
0120001a	-	-	0,02	0,07	1,74	-	0,33	0,26	-	0,43	-
0120083	-	-	-	-	-	-	-	-	-	-	-
01201016	-	-	-	-	-	-	-	-	-	-	-
01201017	-	-	-	-	-	-	-	-	-	-	-
01201018	-	-	-	-	-	-	-	-	-	-	-
01201018a	-	-	-	-	-	-	-	-	-	-	-
0120124a	-	-	-	-	-	-	-	-	-	-	-
0120168a	-	-	-	-	-	-	-	-	-	-	-
0120499a	-	-	-	-	-	-	-	-	-	-	-
0120538a	-	-	-	-	1,22	-	-	-	-	-	-
0120721a	-	-	-	-	-	-	-	-	-	-	-
0120759a	-	-	-	-	0,13	-	-	-	-	-	-
0120761a	-	-	-	-	0,16	-	-	-	-	-	-
0120843a	-	-	-	-	-	-	-	-	-	-	-
0120889	0,05	-	-	-	0,63	-	-	-	-	-	-
0120915	-	-	-	-	0,82	-	-	-	-	-	-
0120945	-	-	-	-	-	-	-	-	-	-	-
0120947	-	-	-	-	-	-	-	-	-	-	-
0120948	-	-	-	-	-	-	-	-	-	-	-
01S0004U	0,03	-	-	-	0,23	-	-	-	-	-	-
01S0015U	-	-	-	-	0,59	-	-	-	-	-	-

V.III Results of the fully integrated model

The results for the fully integrated model deviate slightly from the other two methods of integrated modelling. This is partly due to the different modelling technique and for the other part to differences in the schematization. The effects of the differences in schematization were discussed in Appendix IV.

Table V-X Results of the fully integrated model in SOBEK – sewer system

	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
# of flood locations	107	83	128	143	186	1	105	141	86	171	93
Total flood volume (m^3)	72	42	130	173	1604	2	99	184	50	277	52

Table V-XI Flood depths (m) using the fully integrated model in SOBEK – receiving water body

Location	Event 1	Event 2	Event 3	Event 4	Event 5	Event 6	Event 7	Event 8	Event 9	Event 10	Event 11
0110149	-	-	-	-	-	-	-	-	-	-	-
0120001a	-	-	-	-	1,72	-	0,13	0,05	-	0,02	-
0120083	-	-	-	-	-	-	-	-	-	-	-
01201016	-	-	-	-	-	-	-	-	-	-	-
01201017	-	-	-	-	-	-	-	-	-	-	-
01201018	-	-	-	-	-	-	-	-	-	-	-
01201018a	-	-	-	-	-	-	-	-	-	-	-
0120124a	-	-	-	-	-	-	-	-	-	-	-
0120168a	-	-	-	-	-	-	-	-	-	-	-
0120499a	-	-	-	-	-	-	-	-	-	-	-
0120538a	-	-	-	-	1,50	-	-	-	-	-	-
0120721a	-	-	-	-	-	-	-	-	-	-	-
0120759a	-	-	-	-	0,15	-	-	-	-	-	-
0120761a	-	-	-	-	0,17	-	-	-	-	-	-
0120843a	-	-	-	-	-	-	-	-	-	-	-
0120889	0,12	-	-	-	0,65	-	-	-	-	-	-
0120915	0,14	-	-	-	0,50	-	-	-	-	-	-
0120945	-	-	-	-	-	-	-	-	-	-	-
0120947	-	-	-	-	-	-	-	-	-	-	-
0120948	-	-	-	-	-	-	-	-	-	-	-
01S0004U	-	-	-	-	0,22	-	-	-	-	-	-
01S0015U	-	-	-	-	0,87	-	-	-	-	-	-

V.IV Water levels in the integrated models

The water levels at the selected nodes are presented in the figures below. First shown are the nodes in the receiving water body. The geographic location of each of the nodes is shown in Figure V-I.

Figure V-I Selected nodes for the sewer system

The graphs for the nodes are shown for Event 5, which causes the largest floods in the sewer system. Although this means that the water levels are not shown for the remaining events, the results are the clearest during Event 5. The figures are shown below in Figure V-II to Figure V-VI.

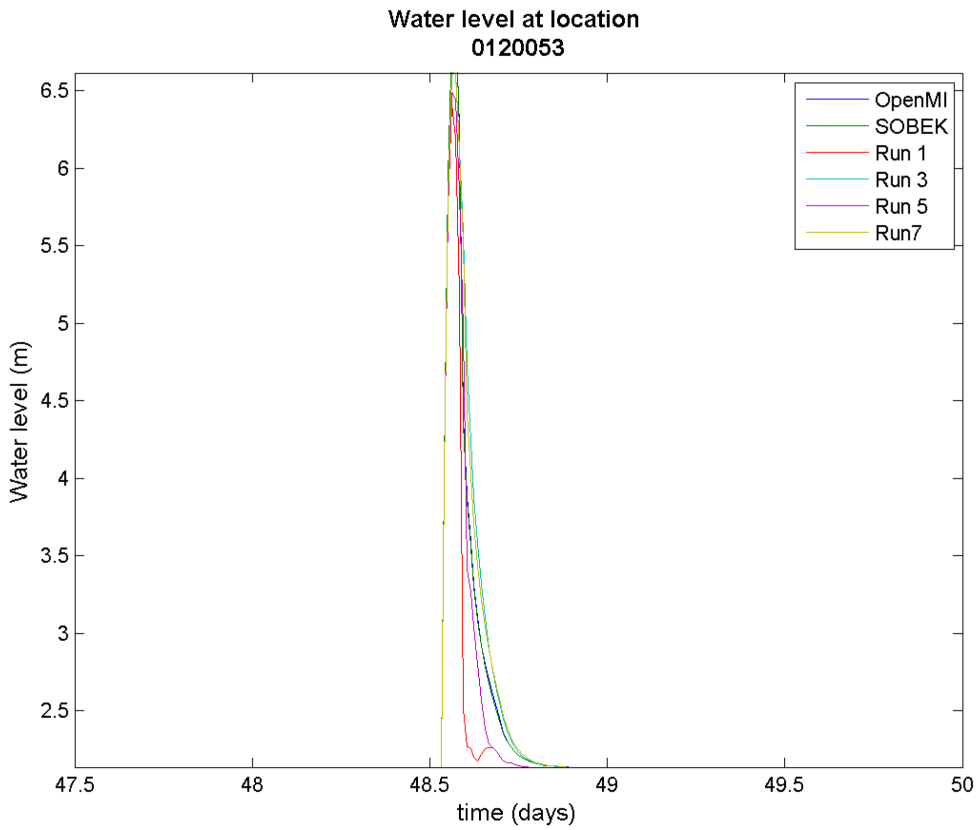

Figure V-II Water levels at node '0120053'

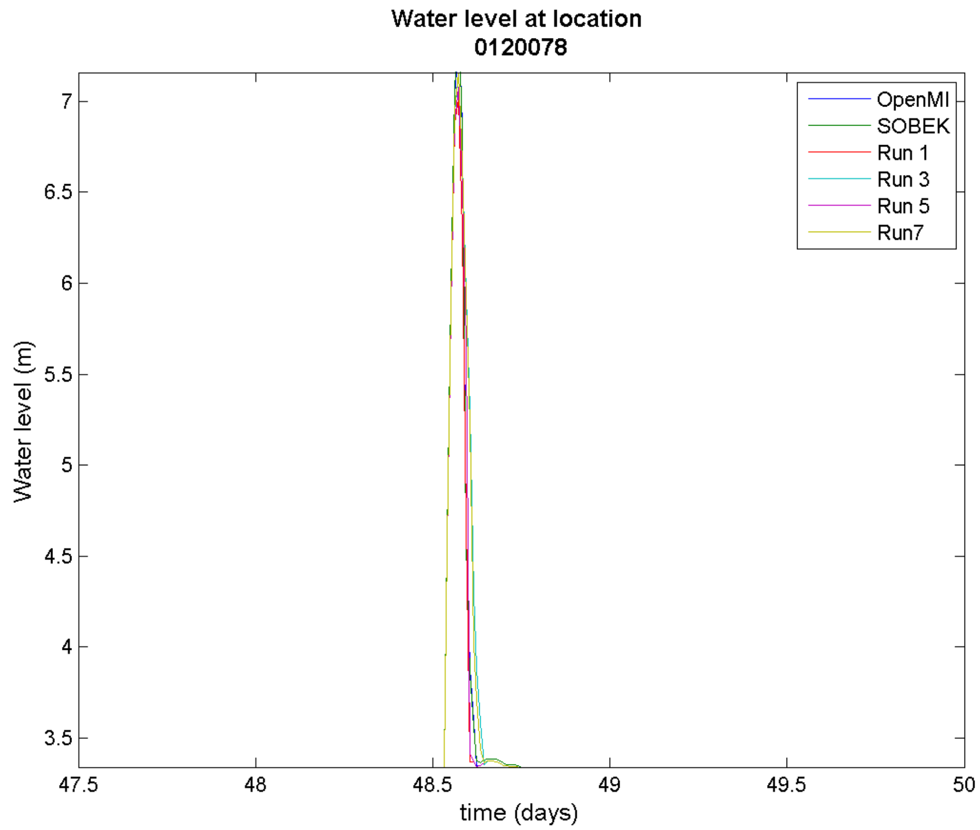

Figure V-III Water levels at node '0120078'

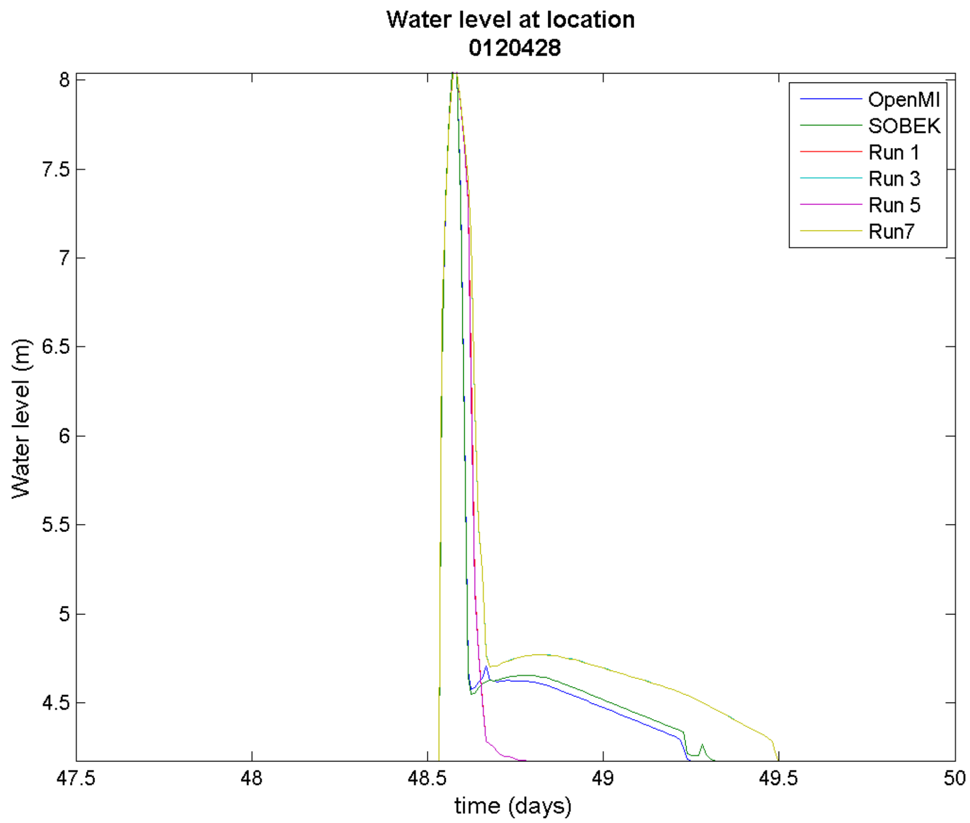

Figure V-IV Water levels at node '0120428'

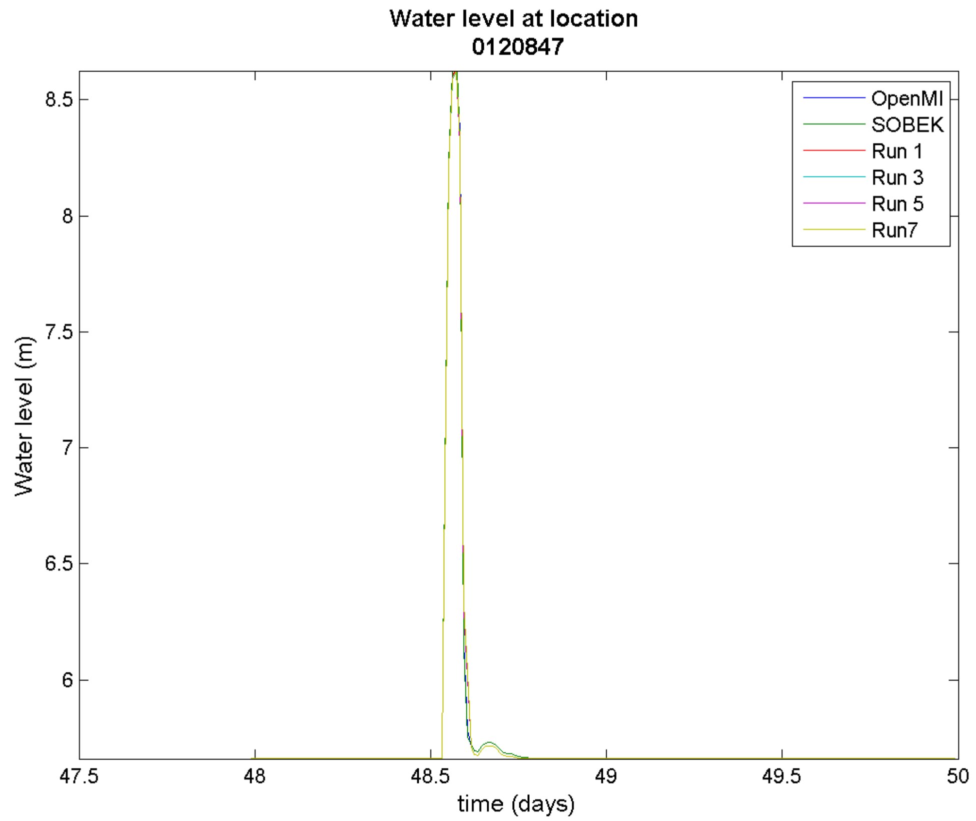

Figure V-V Water levels at node '0120847'

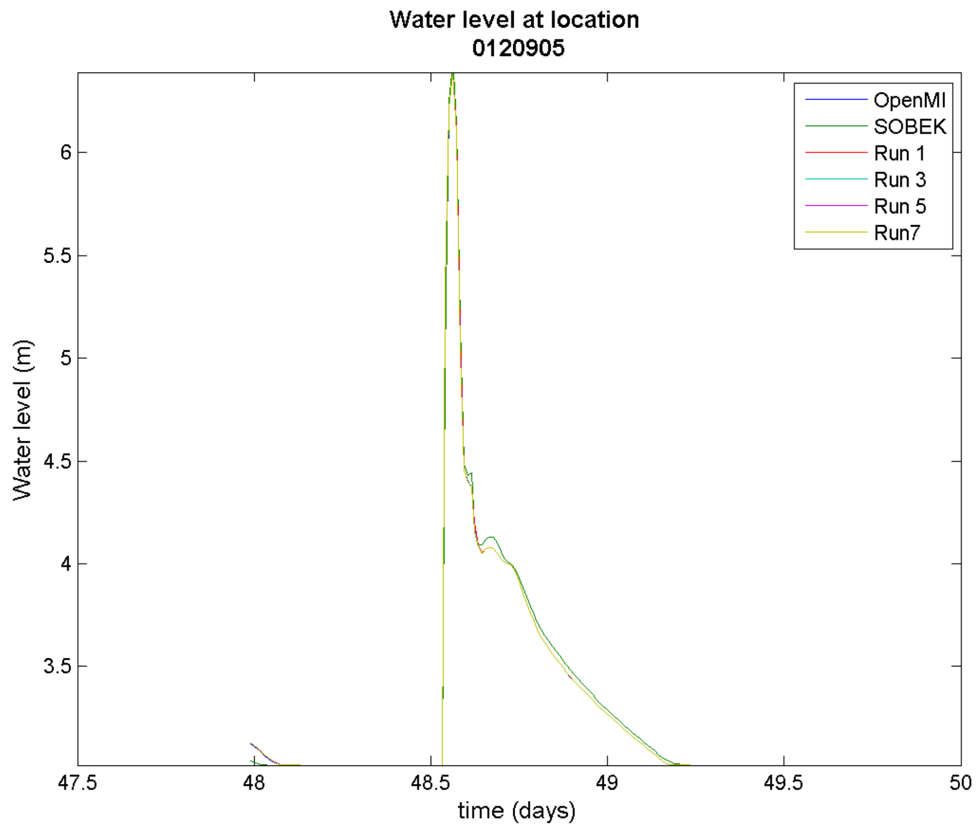

Figure V-VI Water levels at node '0120905'

The water levels in the sewer system are quite similar between the different modeling techniques. Although there are some big differences at some nodes, the water levels show the same pattern most of the time. The water levels in the fully integrated model in SOBEK are slightly higher, this is most likely caused by a small difference in the size of the virtual basin, but the overall effect of this are only a few centimeters. Between the various runs in the method using level hydrographs the results can vary. What causes the non-convergence in them did not become clear in this study.

V.V Receiving water body

The results for the nodes in the receiving water body are presented below. Figure V-VII shows the geographic locations of the nodes in the water system.

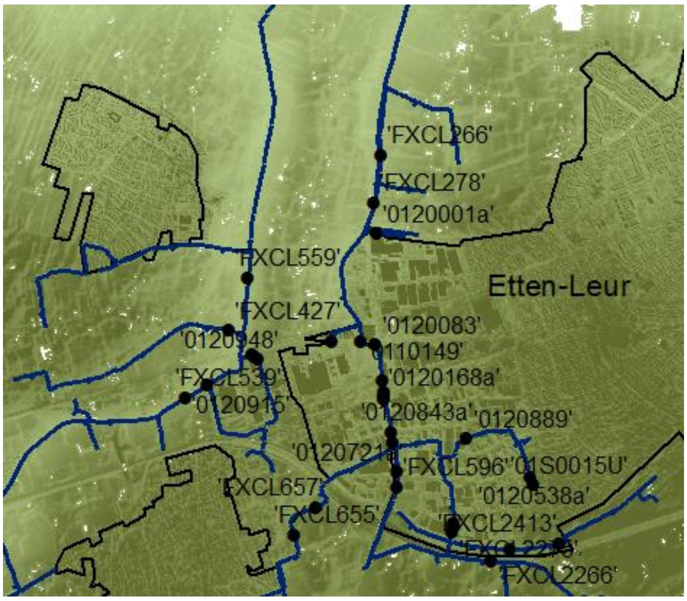

Figure V-VII Selected nodes for the receiving water body

The graphs show the water levels for all the model runs which are done for the receiving water body in one figure. This is done to make the results more comparable. Although it may be difficult to show much detail in the following graphs it gives an overview on the number of floods in the system and which events causes them.

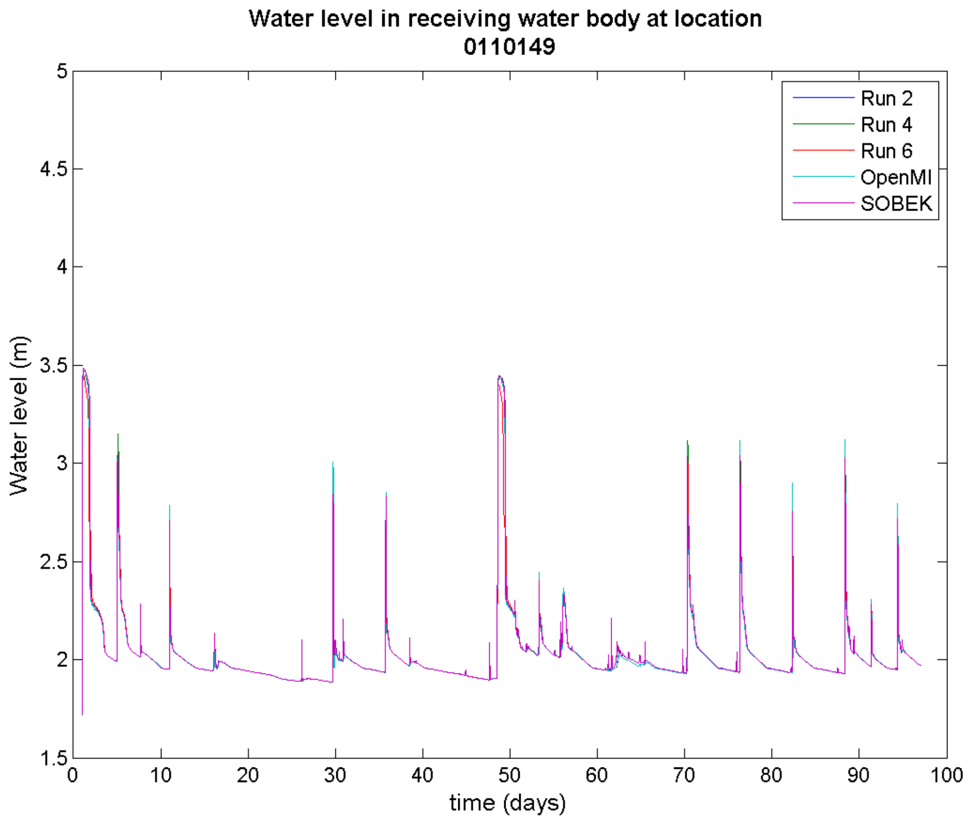

Figure V-VIII Results at a node in the centre

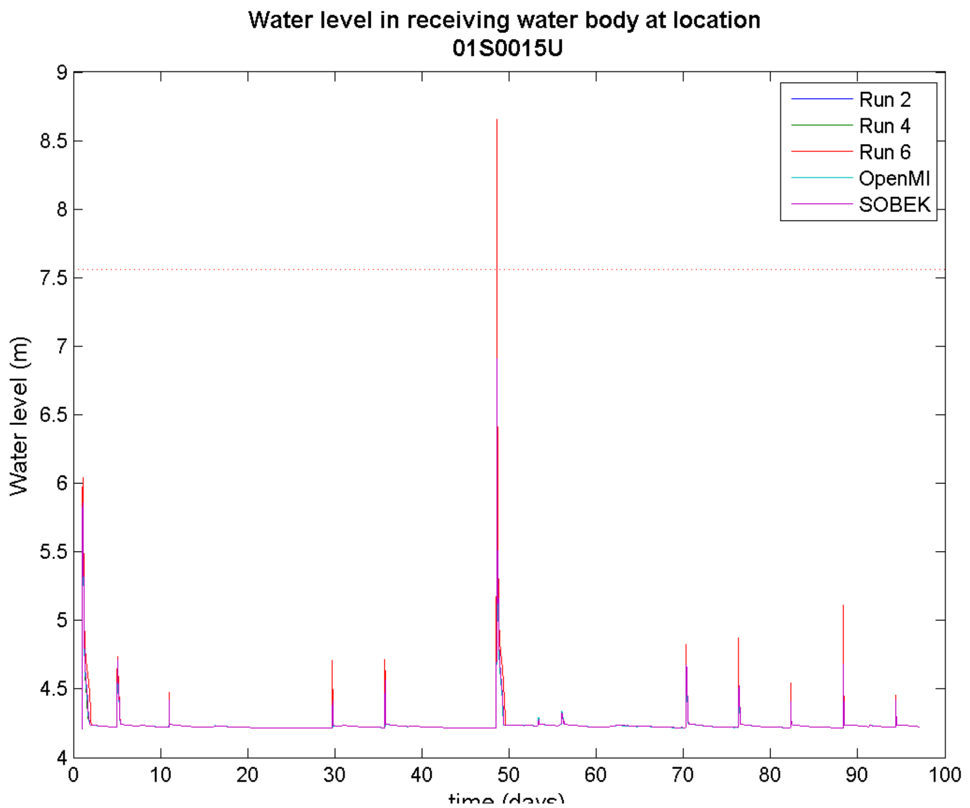

Figure V-IX Results at a node in the south-east

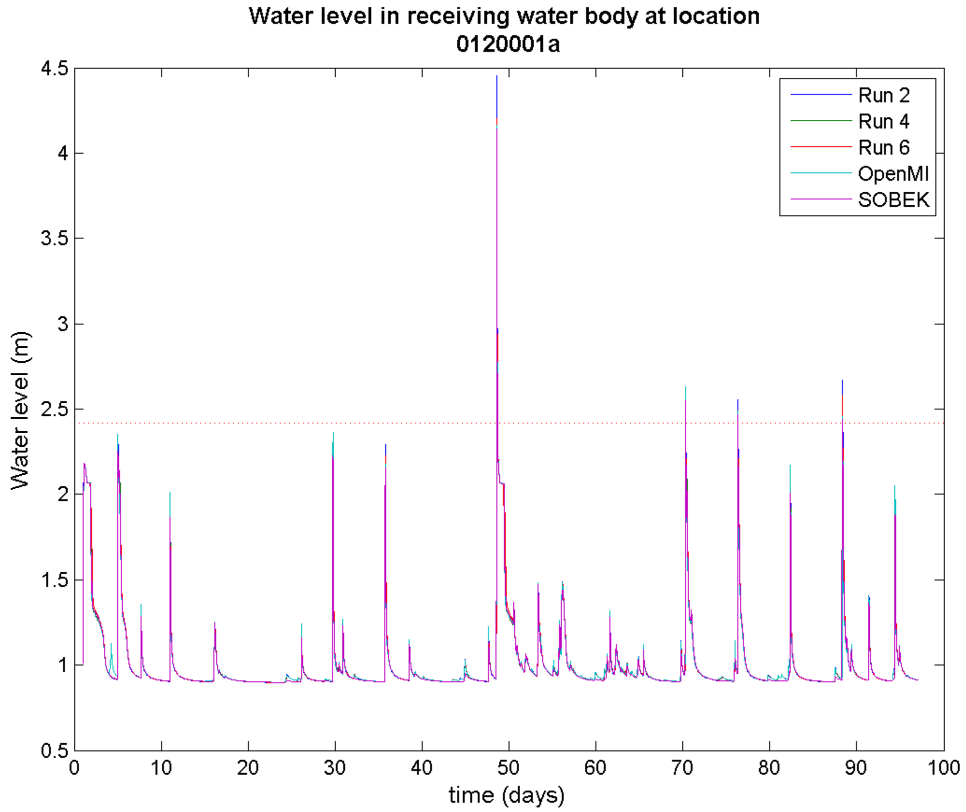

Figure V-X Results at a node north

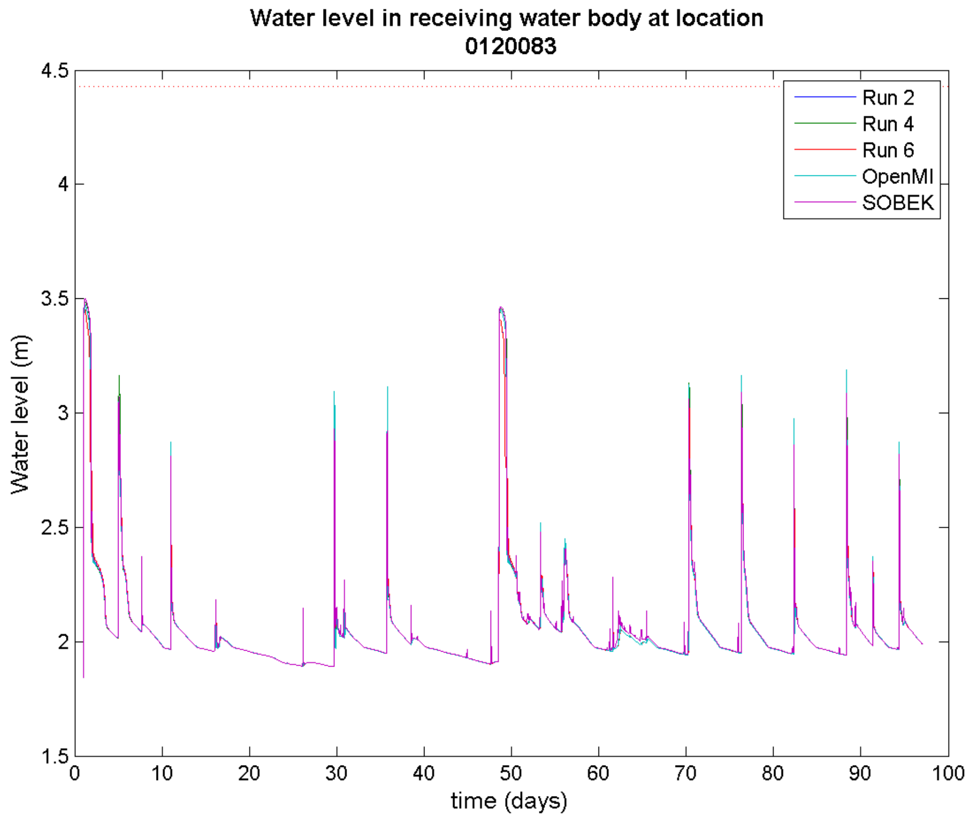

Figure V-XI Results at a node in the centre

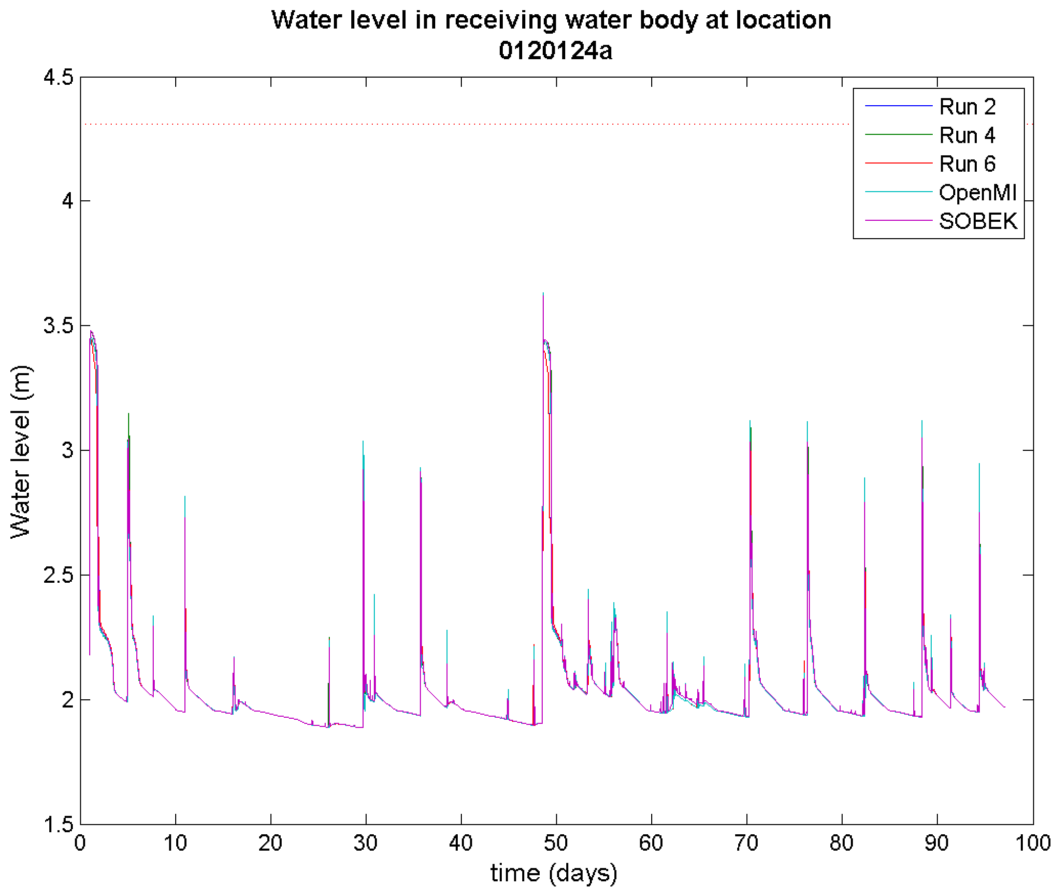

Figure V-XII Results at a node in the centre

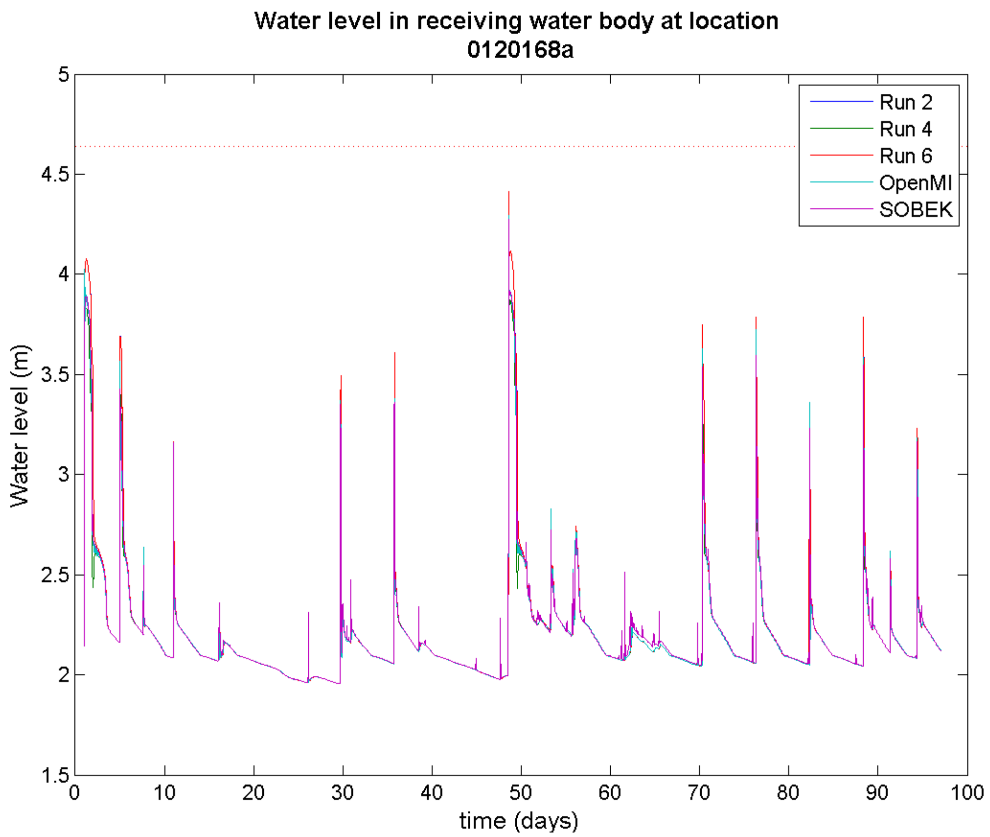

Figure V-XIII Results at a node in the centre

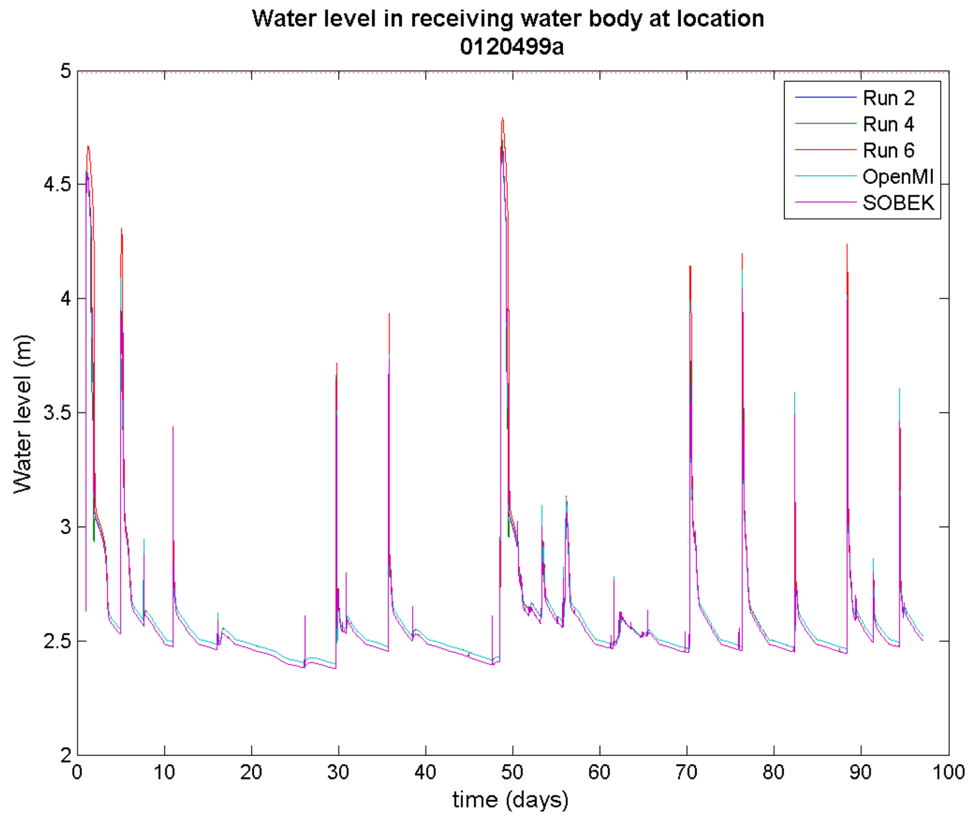

Figure V-XIV Results at a node in the south

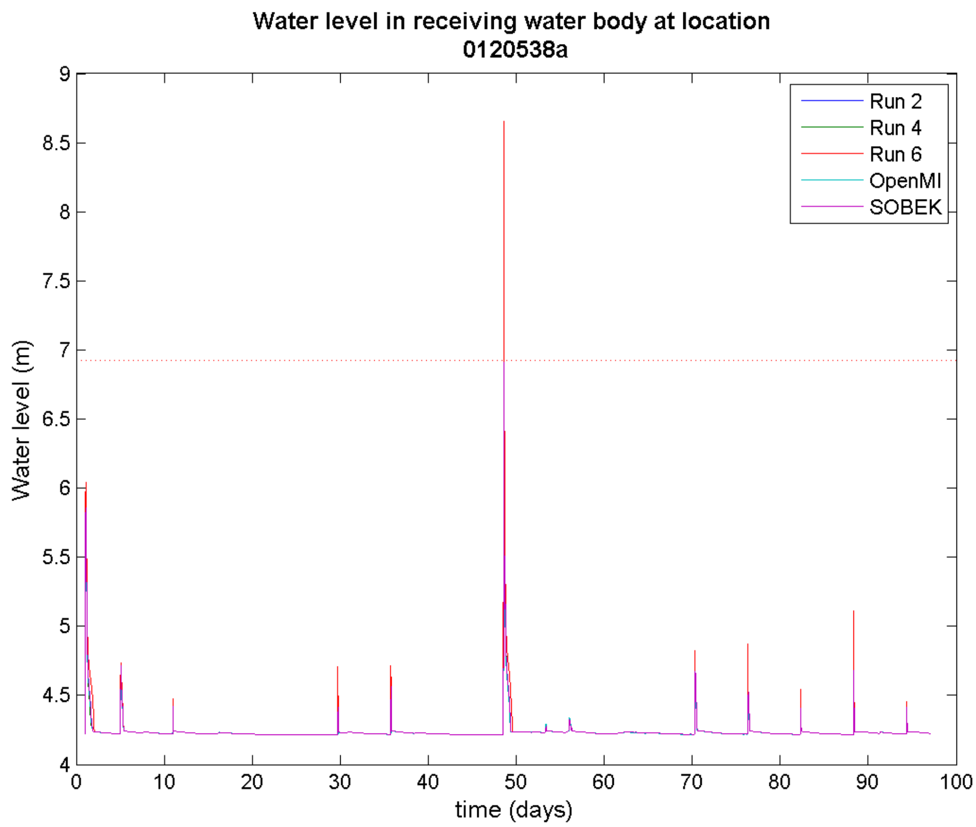

Figure V-XV Results at a node in the south-east

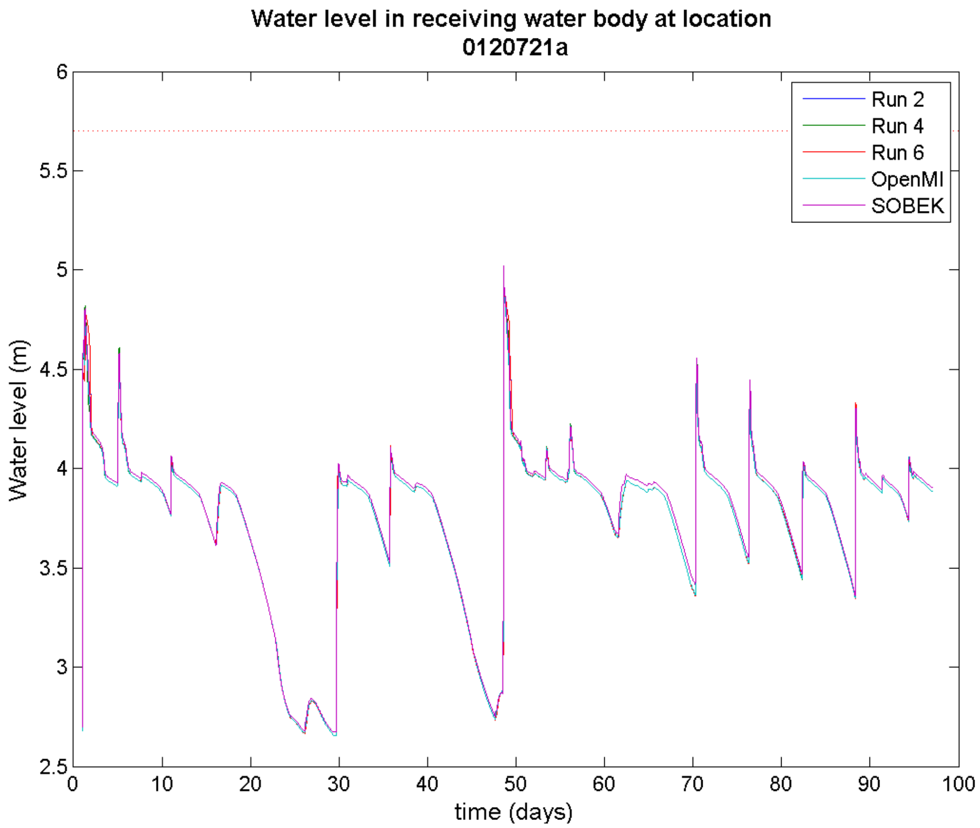

Figure V-XVI Results at a node in the centre

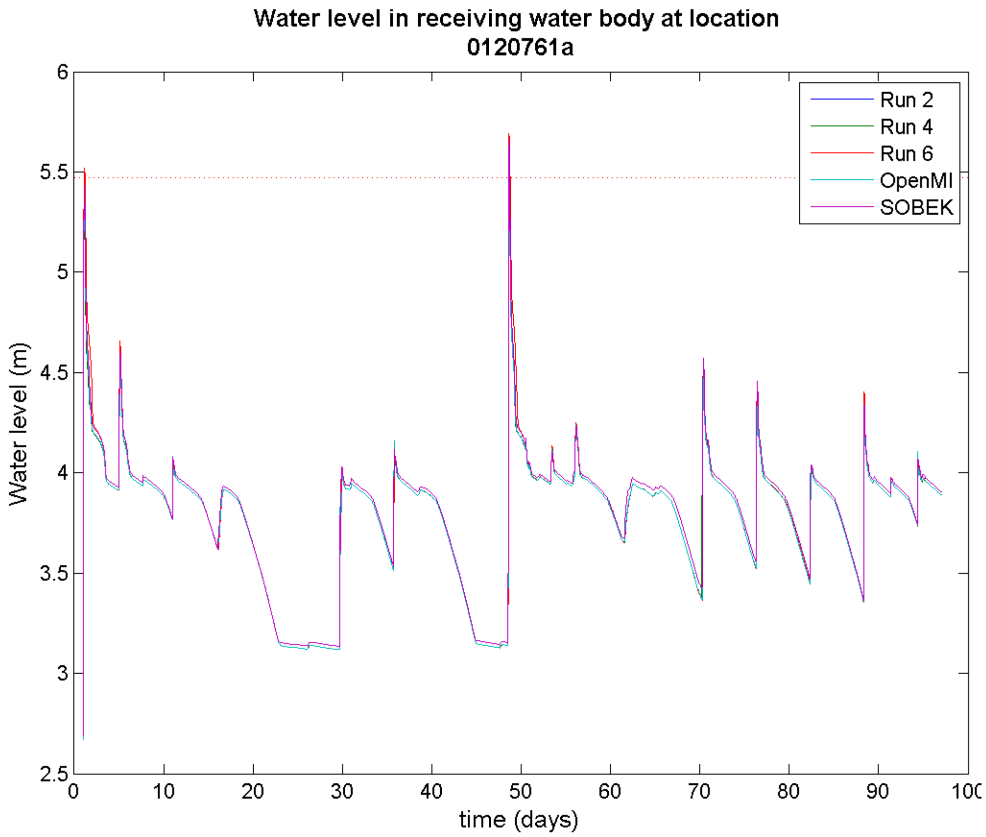

Figure V-XVII Results at a node in the south

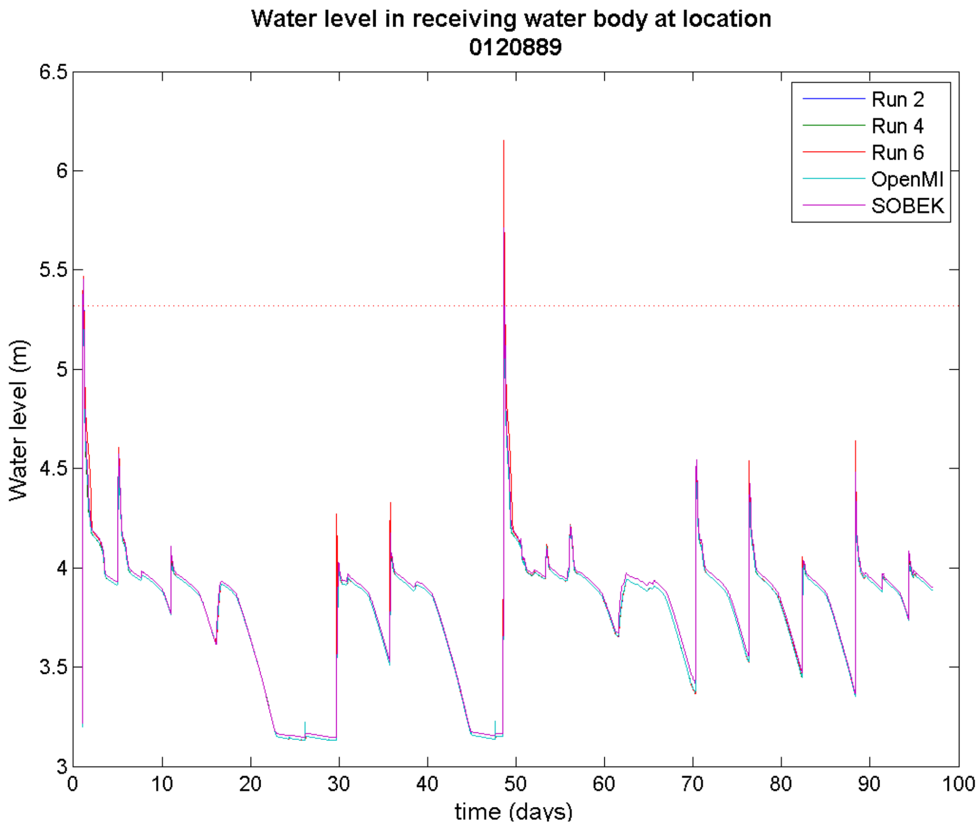

Figure V-XVIII Results at a node east

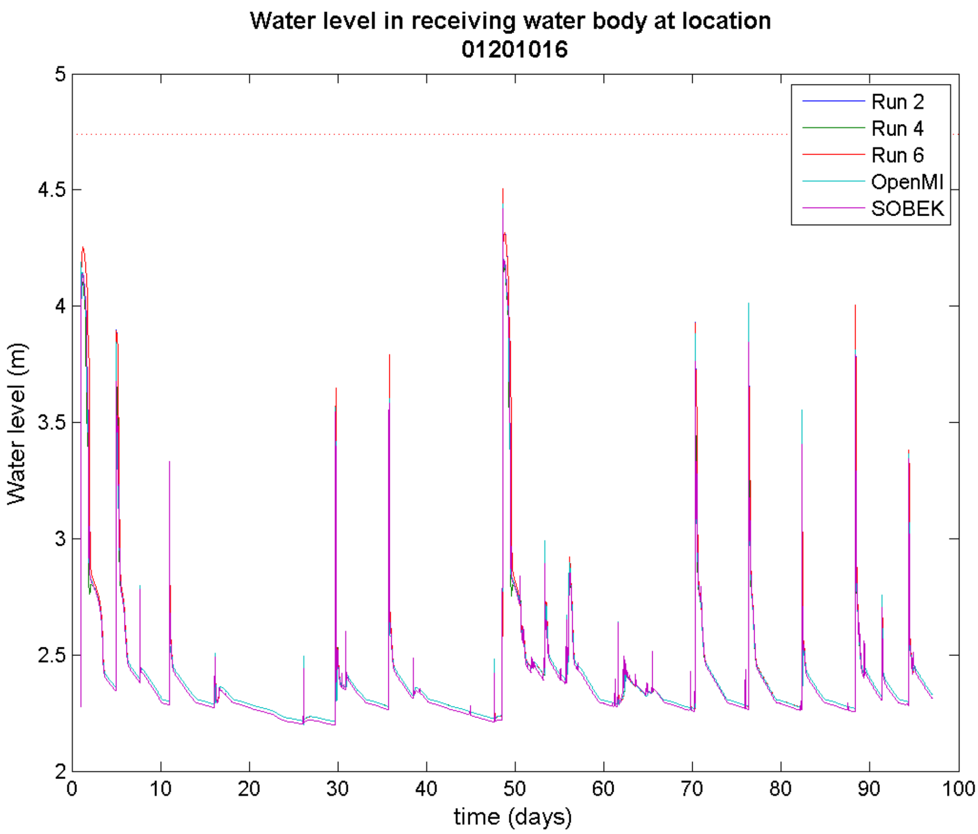

Figure V-XIX Results at a node in the centre

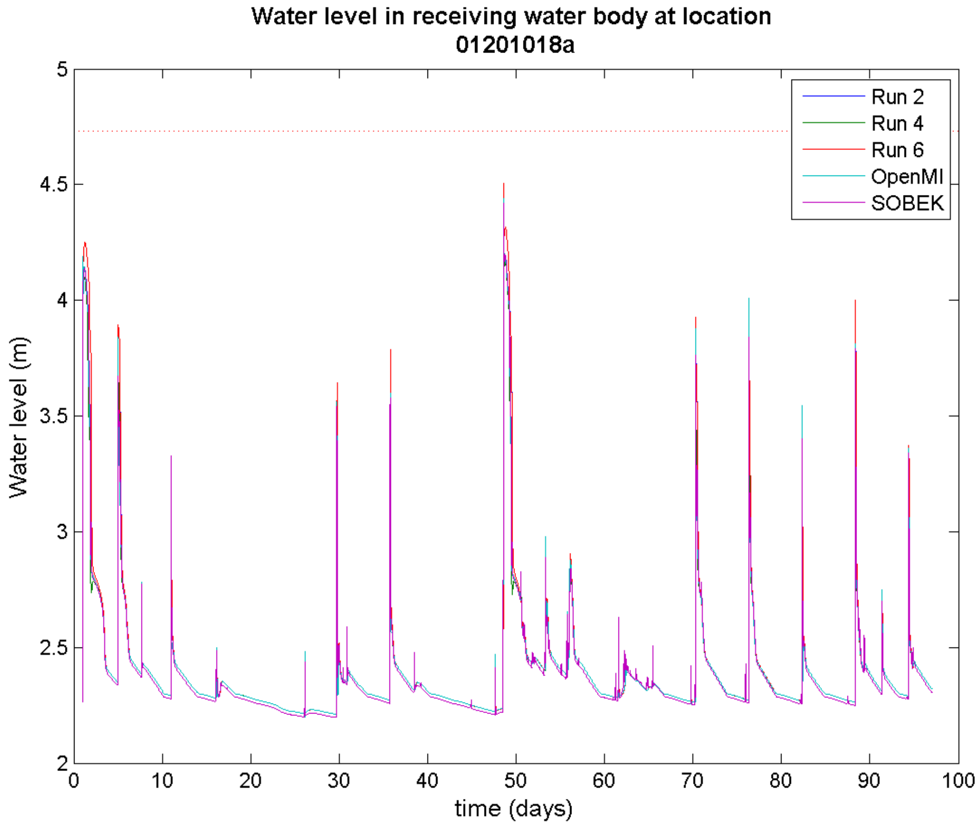

Figure V-XX Results at a node in the centre

As can be seen in the figures above, flooding mostly occurs during event 5, which is the large peak around day 50. Also event 1 causes some flooding in the receiving water body, but only on a smaller scale, both in volume and number of locations. Although there are some differences in the calculated water levels, mostly in the order of a few centimetres, this causes no extra flooding events in the receiving water body.

Appendix VI References

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