Water quality modelling with SOBEK in Dutch polders

Subject to salinization and river water flushing
Case study in Anna Paulownapolder

Yasmin Faraji, January 2015

Master's thesis by: Yasmin Faraji
Student number: 3853349

Supervisor Utrecht University: prof. dr. ir. Marc Bierkens
Supervisor Nelen & Schuurmans: Jorik Chen MSc.

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Faculty of Geosciences
Department of Innovation, Environmental and Energy Sciences

Universiteit Utrecht

Nelen & Schuurmans

Abstract

Anna Paulownapolder in the province of North Holland is characterized by high quality agriculture and valuable crops (tulip bulbs) which are salt sensitive. The polder is situated in the northern part of the Schermerboezem, near the Helsdeur at Den Helder. Salinization of the polder waters at the water inlet points is caused by opening the Helsdeur for navigation in the Schermerboezem causing water with high salt content to leak into the canal. The problem is of larger importance during summer when there are more ships and there is not enough rainfall to dilute the added salt. Therefore, the polder is flushed with IJsselmeer water during dry periods in order to replace the saline water with the fresh water.

To better understand the origin of the salinity and Chloride concentration in the Anna Paulownapolder, SOBEK RR-CF-WQ was used to simulate the salinity transport in this area. SOBEK was applied both as a fine-scale (more detailed) model and as a coarse-scale (less detailed) model to see if the details of a SOBEK model can affect the simulation of the salinity transport in the area and represent more reliable outcomes. Both models were evaluated for wet and dry periods. Different variables such as water depth, water level and the water balance were checked to see whether the polder system was simulated properly.

Next, a fraction analysis was performed to identify the origin of the salt in the area. Although, previous studies have shown that boil seepage is the most dominant cause of the salinity in low-land areas such as polders, boundary flow (i.e. Boezem inlet water) is the most dominant origin of the salt in the Anna Paulownapolder. Actually, seepage does not play an important role in the salinity of the Anna Paulownapolder. Two different scenarios were investigated by applying both models: 1) scenario 1, simulation of salt transport in the watercourses before the flushing event by IJsselmeer; 2) scenario 2, simulation of salt transport in the watercourses after the flushing event by IJsselmeer. In both scenarios, comparison of the simulation results with observations confirmed that the fine model resulted in more reliable outcomes than the coarse model.

Key words: Hydrodynamic model, SOBEK, more detailed model, less detailed model, salinity, dry period.

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1 Introduction

1.1 Background

Surface and groundwater salinization owing to the combined effects of seawater intrusion and marine encroachment is known as a common process in coastal and deltaic areas (Custodio and Bruggeman, 1987; Post and Abarca, 2010). In the Netherlands, saline groundwater a.o. originates from Holocene transgressions producing wide-ranging salinity distributions (Oude Essink, 1996; Post, 2004; Vos and Zeiler, 2008). Saline groundwater can reach the surface through upward flow in areas that lie below mean sea level (MSL).

Nearly 25% of the Netherlands lies below mean sea level (MSL). In many of these low-lying areas, upward seepage of saline and nutrient-rich groundwater causes salinization and eutrophication of surface waters (van Rees Vellinga et al., 1981; van Puijenbroek et al., 2004; van der Eertwegh et al., 2006). In turn, the salinization of surface water has a negative impact on agriculture and unfavourably disturbs aquatic ecosystems (e.g. Van Rees Vellinga et al., 1981; Van der Eertwegh et al., 2006; Oude Essink et al., 2010).

In The Netherlands, the major seepage fluxes are seen in deep polders. In these systems, surface waters are kept at levels as low as 4-7 meter below mean sea level (MSL), triggering large upward and lateral hydraulic gradients in the underlying aquifers (e.g. Van Rees Vellinga et al., 1981; Oude Essink et al., 2010). As salinization by groundwater seepage has been a main water quality problem for a long time in the Netherlands, the water and chloride balances of deep polders in the Netherlands have been investigated in many studies (ICW, 1976; Wit, 1974; Van Rees Vellinga et al., 1981; Pomper and Wesseling, 1978; Griffioen et al., 2002).

Seepage through the confining top layer of clay and peat, with its low permeability, has been assumed spatially uniform in most of these former studies. This however, makes it impossible to give details on the high levels of salt load that was observed (e.g. ICW, 1976; Van Rees Vellinga et al., 1981). De Louw et al. (2010) showed that preferential seepage through boils is the dominant salinization source in deep polders in the Netherlands by determining three types of seepage: "(1) diffuse seepage through the Holocene confining layer, (2) seepage through paleochannel belts in the Holocene layer, and (3) intense seepage via localized boils". They indicated that seepage through boils is indeed the predominant salinization source in deep polders in The Netherlands (see figure 1.1) and contributes to more than 50% of the total chloride concentration in Noordplas Polder surface water. This study also assessed the variation in seepage flux, and chloride concentration between boils as well as their location in the polder, and accordingly, their contributions to surface water salinization.

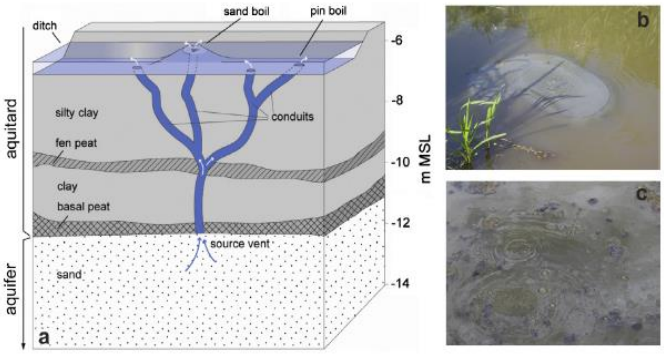


Figure 1.1 Boils in deep polders: (a) diagram of boils with several conduits in aquitard (adapted from De Louw et al. (2010)), (b) sand boil, (c) a boil emitting methane.

1.2 Statement of the problem

The role of surface water quality is particularly high during the warm and dry summer season, when the demand for fresh water is high, while at the same time salinization of surface water is largest due to the lack of dilution by rainfall. In the near future, land subsidence and sea-level rise are believed to result in an increase in seepage fluxes, while climate change will lead to drier summers. These factors together will likely result in a serious decline in fresh surface water (e.g. Sherif and Singh, 1999; Ranjan et al., 2006; Vandenbohede et al., 2008), specifically in the deep polders (Oude Essink et al., 2010).

A current remedy against salinization of surface water during the summer is flushing the surface water system with river water. River water is let in on one side of the polder and pumped out at the other side. Through this procedure one hopes to replace the brackish surface water by fresh river water. However, a disadvantage of this practice is that the quality (nutrient content) of the river water is often very different from the natural water quality in the polder with detrimental effects on aquatic ecosystems and terrestrial plants in the polder area. Moreover, it is often experienced that flushing is not effective in the smaller canals and ditches of the polder.

To predict, understand and optimize the effects of groundwater-induced salinization and flushing on the surface quality in polders, surface water quality models are used (e.g. De Louw et al., 2013). Most of these models consist of a hydrodynamic component and a water quality (transport plus hydrogeochemistry) module. However, up to now these models have not been very successful in reproducing observations of surface water salinity and nutrient content. It is hypothesized that this is due to the fact that the hydrodynamic modelling component used in water quality models is too simple: 1) it only considers 1D-flow in watercourses; 2) only the largest watercourses are included to computational constrains (Beck, 1987; Van Straten, 1998). Where the scientific knowledge and existing data are not sufficient to set up a more detailed model, simple and less detailed models are preferred for which the amount of needed data is less and time of computation is also shorter, (Anastasiadis et al., 2013).

There is abundant literature about water quality models, modelling methods and techniques. See for instance example by James (1993), Wurbs (1994), Chapra (1997), Cox (2003a, b), Ji (2008), Ambrose et al., (2009) and Kannel et al. (2010), which provide the principles and norms on water quality modelling for various water quality variables and under diverse circumstances. However, despite the massive literature available on water quality modelling and the expansion and progress of the models, only a few case studies with real applications are accessible worldwide. One of the plausible explanations for such a paradox is the mismatch and gap between the data being monitored by water quality observation stations and the data required as inputs to water quality models. As is argued by Sharma and Kansal (2013), the extent, amount, regularity and detail of the data usually monitored do not match with the massive data requirements of most models.

The research presented in this thesis focuses on the improvement of water quality modelling by using modelling approaches providing more detailed and more specific water quality information even in very fine watercourses. To do this, the SOBEK model is used. SOBEK is a modelling suite for different fields of water resources including water quality which is capable of simulating the complex flows and the water linked processes in nearly any system. Different water quality variables and processes can be modelled by SOBEK such as salt transport in a watershed. Also, the origin of pollutants in any water system can be easily analysed by fraction computations. Fraction calculation needs no extra input data which makes it easy to trace water from to its source throughout the network (Deltares, 2013).

1.3 Objective

The aim of this research is using SOBEK to model the surface water quality in a polder subject to salinization and flushing in order to assess whether water quality predictions are improved if a more detailed model is used.

To do this, Anna Paulownapolder is selected as a case study. Two water quality SOBEK models in this area will be set up: a very detailed water quality model with both large and fine watercourses containing all different structures in the study area and a regular water quality model with only the largest watercourses. Chloride is used as a conservative tracer for this study and simulation results of the two models will be compared with observations before and after a flushing event. Models results will be compared with the field measurements.

The main research question therefore is:

How do details of a SOBEK model affect the quality of simulation of salinity transport in the Anna Paulownapolder, especially during the dry period?

To answer the main research question, the following sub questions are formulated:

1. *How does the salinity transport happen in the study area and what is its origin?*
2. *What are the differences of a more detailed (fine) SOBEK model to represent and simulate the transport of salinity in comparison with a less detailed (coarse) model?*
3. *Would the results of a more detailed (fine) model be more reliable than less detailed (coarse) model when compared to observations from the Anna Paulownapolder?*

1.4 Outline of the report

Chapter 2 outlines the study area and the pre-existing data that is used for the input and schematization. In chapter 3 the methodology is explained. Then, the validation of the models is discussed in chapter 4. The results of the simulation for different scenarios with the two models are presented in chapter 5. Chapter 6 contains the discussion, chapter 7 the main conclusions. Finally, Chapter 8 ends with the recommendations.

2 Site description and input data

2.1 Description of the polder system

A polder is a low-lying area that includes number of areas with similar water levels (sub-polder systems), which is artificially detached from the hydrological regime of its surrounding areas. In a polder, with the use of hydraulic structures and dikes, the surface water levels, and as a result the groundwater levels, are maintained within ranges appropriate for the land use in the area (Segeren, 1983). Drainage systems are the principal water management systems in the polders of the Netherlands, with a different system setup for agriculture, urban areas, nature reserves and forests (Schultz, 2008).

The functioning of the whole system is characterized by a number of major settings depending on the required surface water and groundwater level regime and magnitude and variability of rainfall and evaporation. The major settings for agriculture contain the distance between the subsurface pipe drains or open field drains and their depth, the ideal water level, the pumping capacity and the proportion of open water (see figure 2.1) (Schultz and Wandee, 2003).

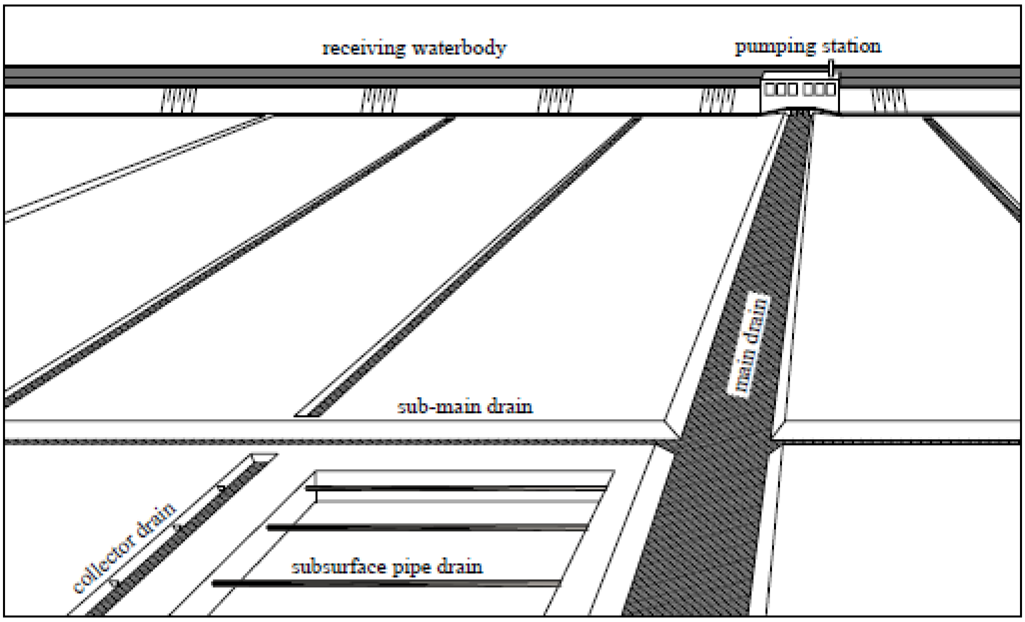


Figure 2.1. Schematic layout of the drainage system in a polder (Schultz, 2008)

Since the specific water level in a polder system is essential; in winter, excess rainfall should be drained out of the polder by the means of a compound system of surface water bodies increasing from small ditches to larger canals. In this system the dimensions of channels, pumps and other structure are determined by the amount of rainfall on the area. This system also has to get rid of excess rainfall during winter and the seepage water if it is applicable. The most important water system of a polder is called the 'Boezem' (a polder inlet/outlet), which forms the highest water level of the polder system. During periods of excess rainfall water is pumped from the smaller canals into the Boezem system and eventually pumped into the main Dutch water system (see figure 2.2). In hot dry periods, conversely, the whole system works the other way around; depending on the amount of seepage, water will be pumped into the polder system from the main Dutch water (inlet water) with the aim of maintain constant the groundwater levels to avoid decline of grass and crops growing and peat soils mineralization (RIVM, 2000).

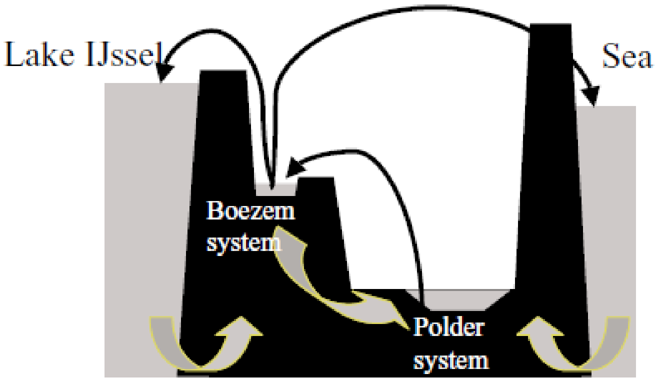


Figure 2.2. Ground water fluxes (grey arrows) caused by different water levels, and pumping routes (black arrows) from deep polders to intermediate polders (the Boezem system), and to the main water body for inlet water or the sea (van Puijenbroek et al., 2004).

2.2 Site description

As a case study, Anna Paulownapolder is chosen. Anna Paulowna is located in the province of North Holland. The area is shown in Figure 5. The study area (5050 ha) consists of three polders:

- Anna Paulowna Hoog (1734 ha);
- Anna Paulowna Laag (2616 ha);
- Oostpolder (700 ha).

Anna Paulownapolder is characterized by high quality agriculture and valuable crops (tulip bulbs) which are salt sensitive. The polder is situated in the northern part of the Schermerboezem, near the Helsdeur at Den Helder. The Amstelmeerboezem forms the northern boundary of the polder. Salinization of the polder waters at the water inlet points is caused by opening the Helsdeur for navigation in the Schermerboezem causing water with high salt content to leak into the canal. The problem is of larger importance during summer when there are more ships and there is not enough rainfall to dilute the added salt. Therefore, the polder is flushed with IJsselmeer water during dry periods in order to replace the saline water with the fresh water (Hermans, 2014).

Furthermore, in the centre of the polder brackish open water can be found due to salt water seepage which occurs particularly at high tide as a result of salt water intrusion from the sea (Hermans, 2014).

There are three water inlets in the study area. Anna Paulowna Hoog has two inlets on the west side from Schermerboezem: Westeinde inlet which is the main one (inlet 1) and Kooy Hoek (inlet 2). Anna Paulowna Laag receives water from Anna Paulowna Hoog. The lowest and highest level areas in Anna Paulowna Laag receive water from the Schermerboezem through Oude Sluis (inlet 3). Oostpolder only gets water from Anna Paulowna Laag (see figure 2.3) (Nelen & Schuurmans, 2012).

2.2.1 Drainage systems

The area contains three main pumping stations used to pump out excess rain and seepage water from the system (figure 2.3). Anna Paulowna Hoog is drained by the Balgdijk pumping station. Anna Paulowna Laag is drained by Wijdenes Spaans pumping station and the Oostpolder is drained by Oosthoek pumping station (Nelen & Schuurmans, 2012).

2.2.2 Surface water management

Anna Paulowna Hoog consists of nine surface water level areas with sizes varying between 0.4 and 875 hectares and the surface water level is between -1.2 m NAP and -0.4 m NAP. There are 42 water management areas in Anna Paulowna Laag. The size of these differ between 0.4 and 1018 hectares and the surface water level is between -4 m NAP and -0.6 m NAP. Oostpolder includes of two level areas. The size of these areas are 322 and 375 hectares respectively and the surface water level is between -4 m NAP and -3.4 m NAP (Nelen & Schuurmans, 2012).

2.2.3 Soil type

Different soil types can be found in these three polders. Anna Paulowna Hoog is mainly covered by drift-sand and Oostpolder has a sandy clay soil. The soils in Anna Paulowna Laag are more diverse. The largest part is sandy, but there is also a lot of clay and drift-sand (Nelen & Schuurmans, 2012).

2.2.4 Land use

As it mentioned before, land use in Anna Paulowna is characterized by high quality agriculture, mainly tulip bulbs. Also, the western part of Anna Paulowna Laag characterized by bulbs. The eastern part of Anna Paulowna Laag and Oostpolder contain mostly arable land (Nelen & Schuurmans, 2012).

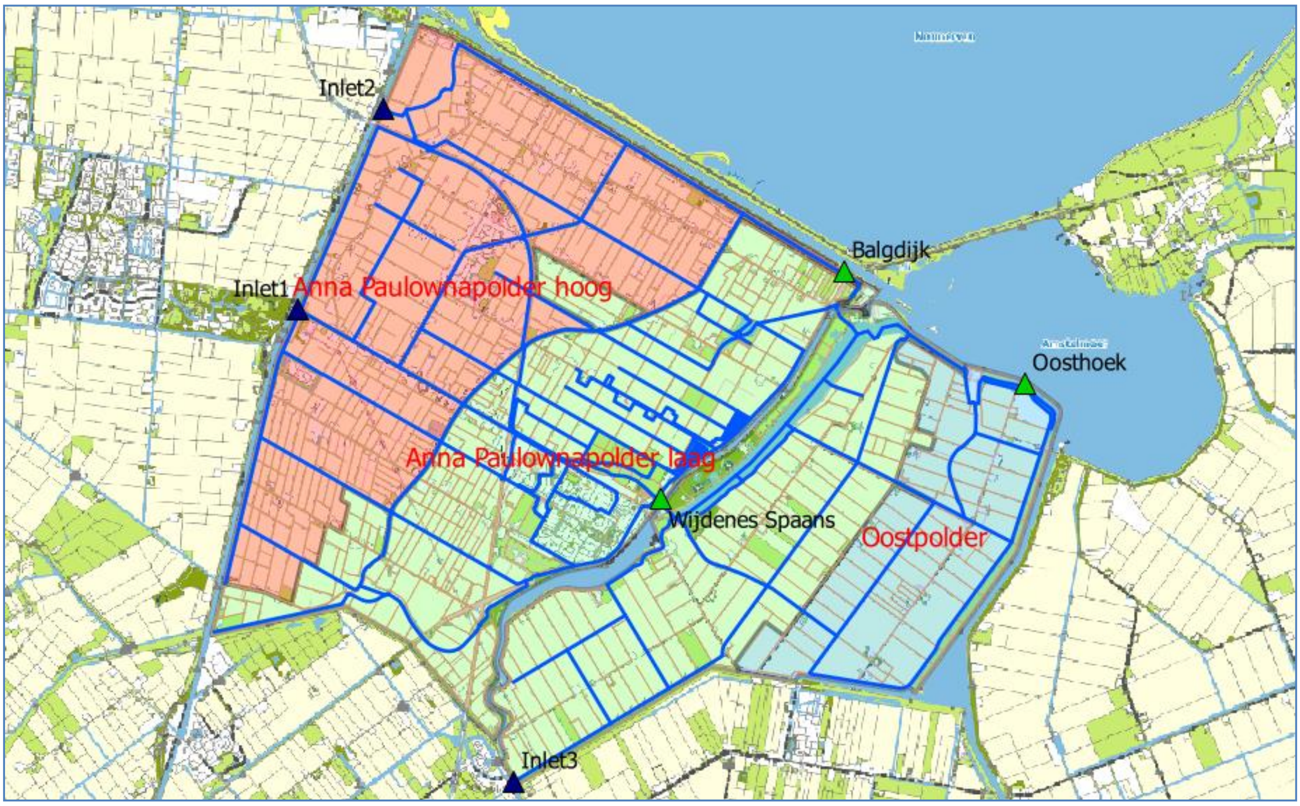


Figure 2.3. Overview map of Anna Paulowna and the main water system in the polder area. Dark blue triangles represent inlets, green triangles represent main pumps and blue lines depict main watercourses.

2.3 Overview of input data

Several different data types are required to set up a model in SOBEK which include:

2.3.1 Information about the surface water system

- Watercourses (including profile and depth of waterways) and structures (culverts, dams, pumping stations, bridges and locks);
- Barriers and sections;

- Surface water levels, which are regulated strictly in polders system (Van Rees Vellinga et al., 1981; Oude Essink et al., 2010). Surface water levels have been implemented as summer and winter target levels for each catchment area;
- Boundary conditions include the location of inlets (where water pumps into the polder) and location of the main pumps (where water pumps out of the polder).

2.3.2 Soil Type

The type of soil per catchment area is based on the Stiboka soil map of Alterra, which has been simplified according to the Altera’s conversion list in order to use in SOBEK. In SOBEK package 21 different soil types can been distinguished, but each catchment area can be characterized by only one soil type. So, the most dominant soil type was assigned to each catchment area.

2.3.3 Roughness of the land surface

Another input parameter is the surface roughness of the study area. I used the Strickler formula, which is one of the methods to define the bed roughness as expressed by a Chézy coefficient.

2.3.4 Land Use

The land use is used to compose this friction grid. Data of the type of land use is based on the LGN5 (Landelijk Grondsgebruikbestand Nederland).

2.3.5 Seepage

The provincial seepage map has been used to determine the amount of groundwater seepage. This value is average summer seepage per catchment area.

2.3.6 Precipitation and evaporation (mm/day)

The daily precipitation at Anna Paulownapolder and daily evaporation at De kooy station were used as inputs to SOBEK. Since the focus of this study is on Chloride and salinity is a significant problem in the dry periods, rainfall from 2003, which was identified as a dry period, was used as input.

2.3.7 Chloride concentration

To determine the chloride concentration at the inlets, surface water concentration data were used. They were measured on a monthly basis by HHNK http://hnk-water.nl/. These data includes the chloride concentration before and after flushing the polder by IJsselmeer water.

3 Materials and methods

3.1 Model description

Two different water quality models were schematized to simulate surface water quality in the study area. These schematizations (fine and course) were used in order to answer the research question of this thesis. To model the Anna Paulownapolder, SOBEK version 2.12 was applied. The SOBEK-Rural 1DFLOW module is an advanced component that can be used for the simulation of one-dimensional flow in irrigation and drainage systems. This module can be used stand-alone or in combination with other modules. In this study the rainfall-runoff, channel-flow and water quality module were used and the two following models implemented:

- A model which calculates the flow in all (primary and secondary) watercourses (fine model).
- A model which only calculates the flow in the main watercourses (coarse model).

3.2 Rainfall-Runoff module (SOBEK RR)

The runoff and groundwater drainage into the watercourses are simulated by rainfall-runoff modules based on a simple water balance for separate elements. For the rainfall-runoff module daily data of rainfall at Anna Paulownapolder and daily potential evaporation at De kooy station were used as an input (see figure 3.1)

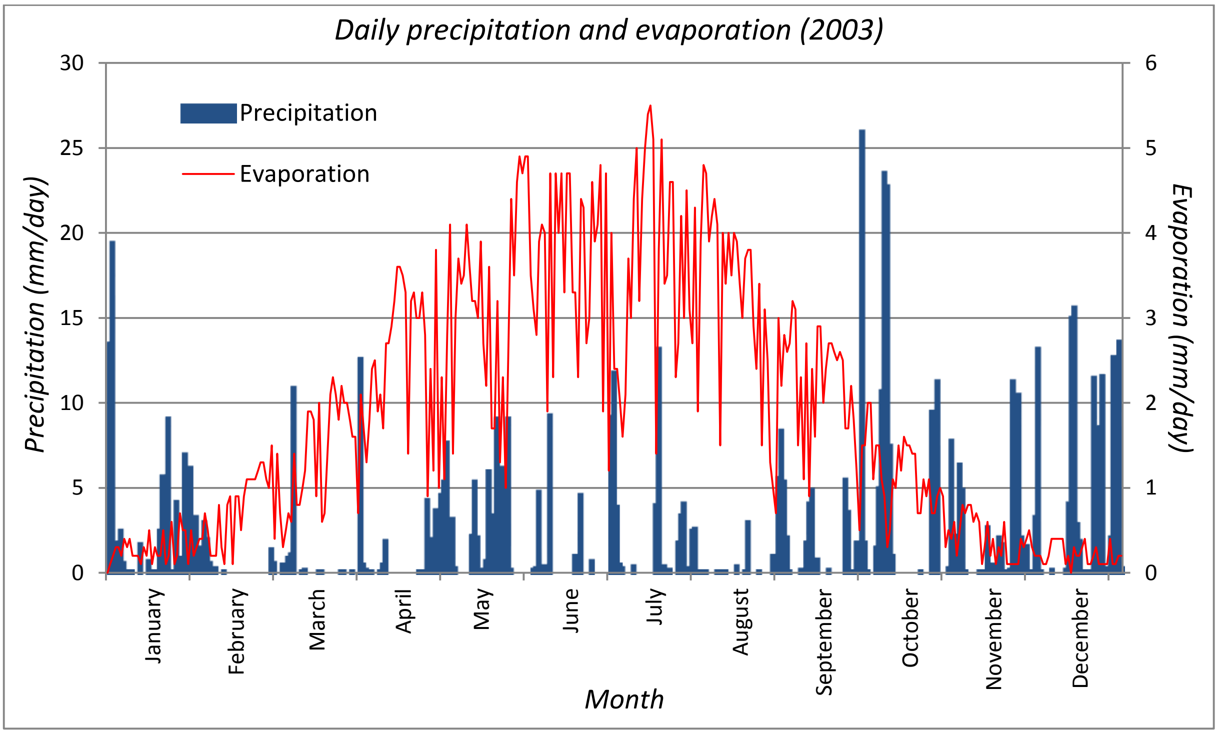


Figure 3.1. Daily rainfall and potential evaporation in the study area

In SOBEK RR module the following fluxes are processed:

1. precipitation;
2. evapo(transpiration);
3. surface runoff;
4. infiltration into the soil;

5. drainage (of groundwater) to surface water;
6. seepage of regional groundwater to surface water;
7. percolation from the soil to the groundwater.

In SOBEK RR two types of surfaces are distinguished and separately modelled:

3.2.1 Paved area

Paved area refers to the paved surfaces in urban, industrial and rural areas, such as roofs, roads and parking spaces. Apart from modelling surface runoff, runoff is routed through two different types of sewage systems: *mixed sewer system* (in a mixed system domestic sewage and rainfall flow into the same system) and *separated sewer system* (In a separated system there are separate sewage systems for rainfall and dry weather flow). In the model, all sewer outflows flow toward a wastewater treatment plant. To determine the surface elevation of paved area, the median of all the catchment areas' elevation is used.

3.2.2 Unpaved area

There are two different types of unpaved area (nodes) in this model include: unpaved rural and unpaved urban. The surface elevation of unpaved area is important for the discharge processes. By default, the unpaved area is schematized with a single surface elevation, which is equal to the median of all the surface level heights in the drainage area. For the schematization of the drainage process from unpaved area towards open water the formula of Ernst (Ernst, 1978) was used.

$q = dH/\gamma$ *Ernst formula*

3.3 Channel flow module (SOBEK CF)

The channel-flow module calculates flow velocities, water level and water depths by solving the De Saint-Venant equations for 1D flow, with the continuity equation and the momentum equation (see appendix A) (Deltares, 2014).

Continuity equation

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (u\hbar)}{\partial x} = 0$$

Momentum equation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + g\frac{u|u|}{C^2\hbar} = 0$$

The SOBEK channel flow module contains the following components:

- Watercourses: supply and drainage and water storage
- Structures: culverts, bridges and siphons
- Separating level structures: weirs and pumping stations
- Laterals: seepage / infiltration, rainfall and evaporation from open water

3.3.1 Watercourses

All the main watercourses and the secondary water systems in the study area are modelled in the fine schematization, and the secondary channels are omitted in the coarse schematization. SOBEK calculates the flow in watercourses through a cross-section. A cross-section is defined as an input element of SOBEK in which the shape and size of the river profiles perpendicular to the flow is described. The field data of cross section are the relations between the vertical, Z and the lateral, Y. Also, the roughness of the ditches as mentioned before, is determined by Stickler formula and a default value of 30 [-].

3.3.2 Structures

All structures that affecting the flow in watercourses module are schematized as follows:

- Culvert
- Bridge
- Siphon

The dimensions and characteristics of these structures are based on the management settings of HHNK.

3.3.3 Weirs and pumps

All weirs in the study area have a fixed crest level in which the discharge strongly depends on the crest width. Functioning of the weirs also depends on the management settings of HHNK. The major pumping stations including inlets and outlets have already been described in section 2.2.1 and 2.2.2. Also, there are many small pumps in the study area, which control the water level in ditches and catchment areas in order to maintain the water level at the desired amount. In both models of this study, the operation of the pumps is based on water level measurements at a location at which the water level can be measured during wet and dry periods. Moreover, it should be mentioned that in these models the water level controllers are defined for winter target level and summer target level for each catchment area.

3.4 Water quality module (SOBEK WQ)

Since, the aim and objective of this master thesis is to simulate the salinity in the Anna-Paulownapolder, Chloride is chosen as a conservative tracer which is only subject to transport (not to water quality processes) in Water Quality module of SOBEK (Deltares, 2013).

3.4.1 Transport equation for salinity

Salt transport is defined as transport of conservative particles in water which is characterized by the advection-diffusion equation or transport equation. Besides the transport equation, density differences should be taken into account for the momentum equation. Hence, the water flow module is extended with the salt intrusion module by the density and the flow field. The salinity concentration is expressed by *C* and the transport equation described as (Deltares, 2014):

$$\frac{\partial A_t\, C}{\partial t} + \frac{\partial}{\partial x}\left(QC - A_f D \frac{\partial C}{\partial x}\right) - S_s$$

3.5 Simulation and scenarios

To investigate the salinity transport in the Anna Paulownapolder, different cases will be studied. First of all, due to importance the origin of the salt in the study area, a fraction analysis will be used for both models to see what the dominant cause of the salinity in the area is. Thereafter, two scenarios will be performed and analysed for the spatial and temporal distribution of the salinity in the study area:

- Scenario 1: simulation of the salt transport before flushing the polder by IJsselmeer water
- Scenario 2: simulation of the salt transport after flushing the polder by IJsselmeer water

In fact, these two scenarios have been chosen based on the Anna Paulownapolder's situation. The study area is located in the Northern part of the Schermerboezem, near the Den Helder, Helsdeur. The sluice of Helsdeur is open for shipping navigation which results into salinization of the water in Schermerboezem. Due to the location of the inlets of the polder, salinization of this part could be a big threat for the study area especially during dry periods. Hence, polder is flushed by the IJsselmeer water during the dry period. Therefore, the two scenarios will analyse to see how the salinity distributions develops under a dry period and changes due to flushing throughout the study area. The two scenarios will be implemented for both fine and coarse models to evaluate the effect of resolution on the model results.

4 Validation of the models

To see if the models work properly, both fine and coarse models (see figures 4.1 and 4.2) were evaluated and validated under different conditions. Figures 4.1 and 4.2 represent the fine and coarse SOBEK models respectively, which were used in this study.

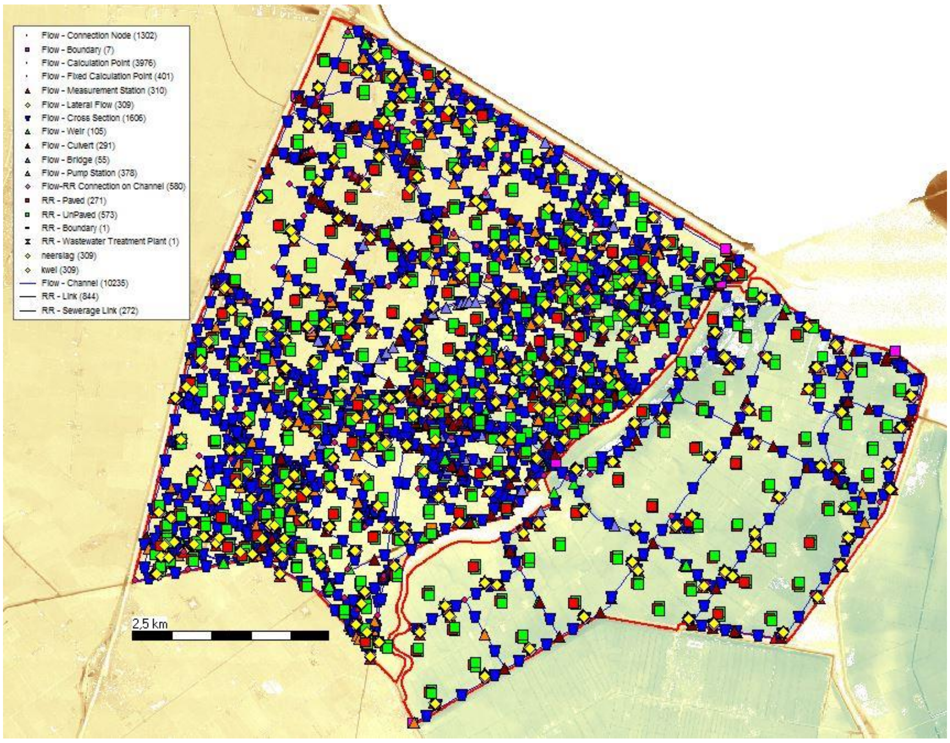


Figure 4.1. Fine (more detailed) schematization of the study area with all primary and secondary watercourses.

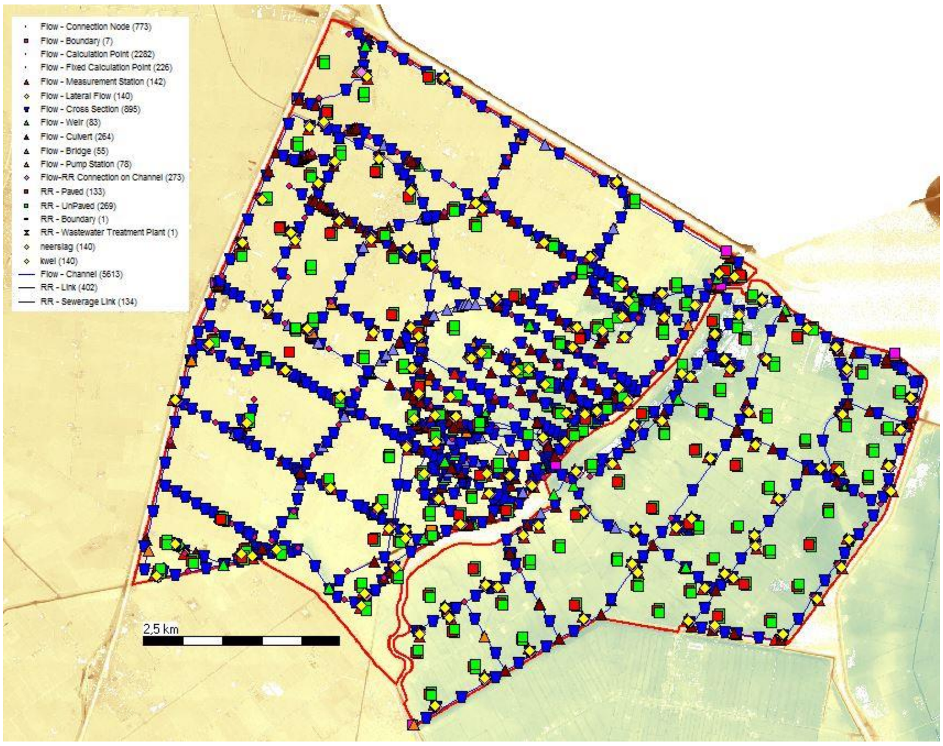


Figure 4.2. Coarse (less detailed) schematization of the study area with only primary watercourses.

4.1 Standard SOBEK evaluation

Integrity of the SOBEK Network was evaluated by the Tools, Validate, Flow / RR model in the menu bar of Netter (SOBEK). The following errors can be found in this control step:

- There is not a calculation point between the structures
- Two objects are overlapping
- There is an unidentified measurement station

4.2 Evaluation in dry period

It was crucial to know whether the Anna Paulownapolder water systems work properly under the dry condition in two models. In fact, in this system the watercourses are not allowed to be dry at all since, enough water should be supplied for agriculture in this area. It means that the inlets should pump the water into the system if the water levels drop under the target level during the summer. Hence, both fine and coarse models were tested for 0 mm rainfall during a month in summer. The results of these tests are shown in two following sections.

In this part the following three parameters were checked:

- *The minimum water depth*:
  This parameter is important in the study area because a dry channel is not acceptable. As a result, channels with 0 m water depth should not exist.
- *Water level*:
  The fluctuations of water level are important in the study area. This parameter was monitored to see if the water level variation is within acceptable range and there are no sudden changes over the time. The suitable surface water level in the Anna Paulowna Hoog should be between -1,2 and -0,4 m NAP. In Anna Paulowna Laag the appropriate water level is between -4 and -0,6 m NAP and in Oostpolder these values are -4 and -3,4 m NAP.
- *Maximum discharge*:
  The maximum discharge was checked to see if the pumps work properly. Actually, the amount of discharge should not be more than the pumps capacity.

4.2.1 Evaluation of the fine (more detailed) model during a dry period

After setting rainfall to 0 mm in the model, results showed that the pumps at inlets and outlets work properly. The minimum water depth in the watercourses was monitored (see figure 4.3). As can be seen, water depth in all channels is at the appropriate level and dry channels were not observed under this condition. Figure 4.4 shows the water levels for this period. All water levels are at the allowable and acceptable ranges that mentioned above.

Figure 4.5 represents the maximum discharge during the same period. As the shows, the maximum discharge happened at inlets which is according to expectation. Inlets pumped the water into the system in order to keep the water level at its suitable amount.

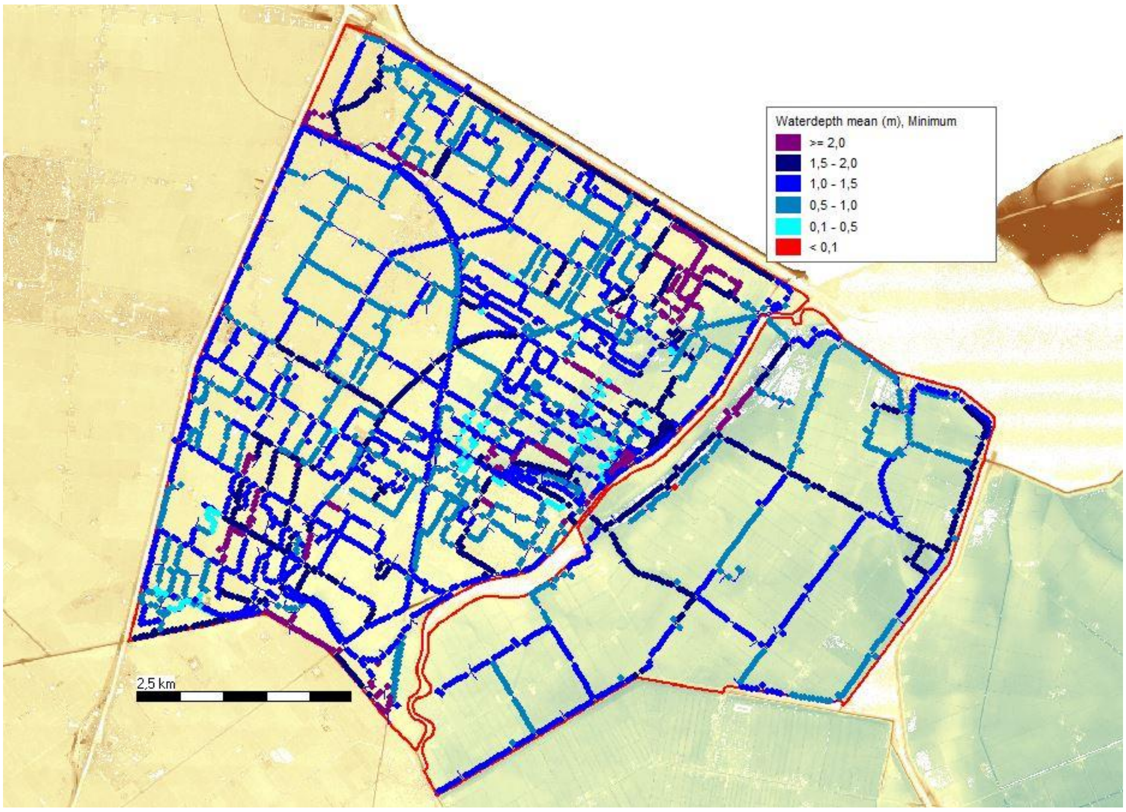


Figure 4.3. Minimum water depth in the watercourses during dry period in the fine schematization

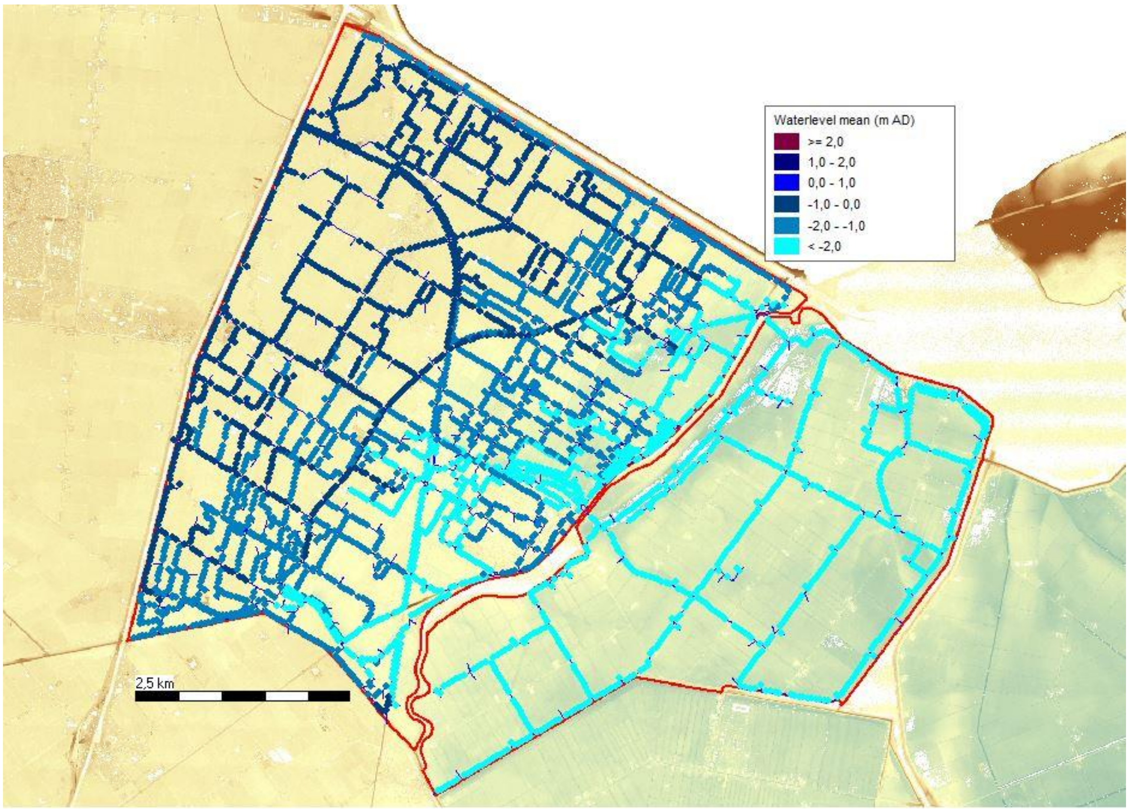


Figure 4.4. Water level in the watercourses during dry period in the fine schematization

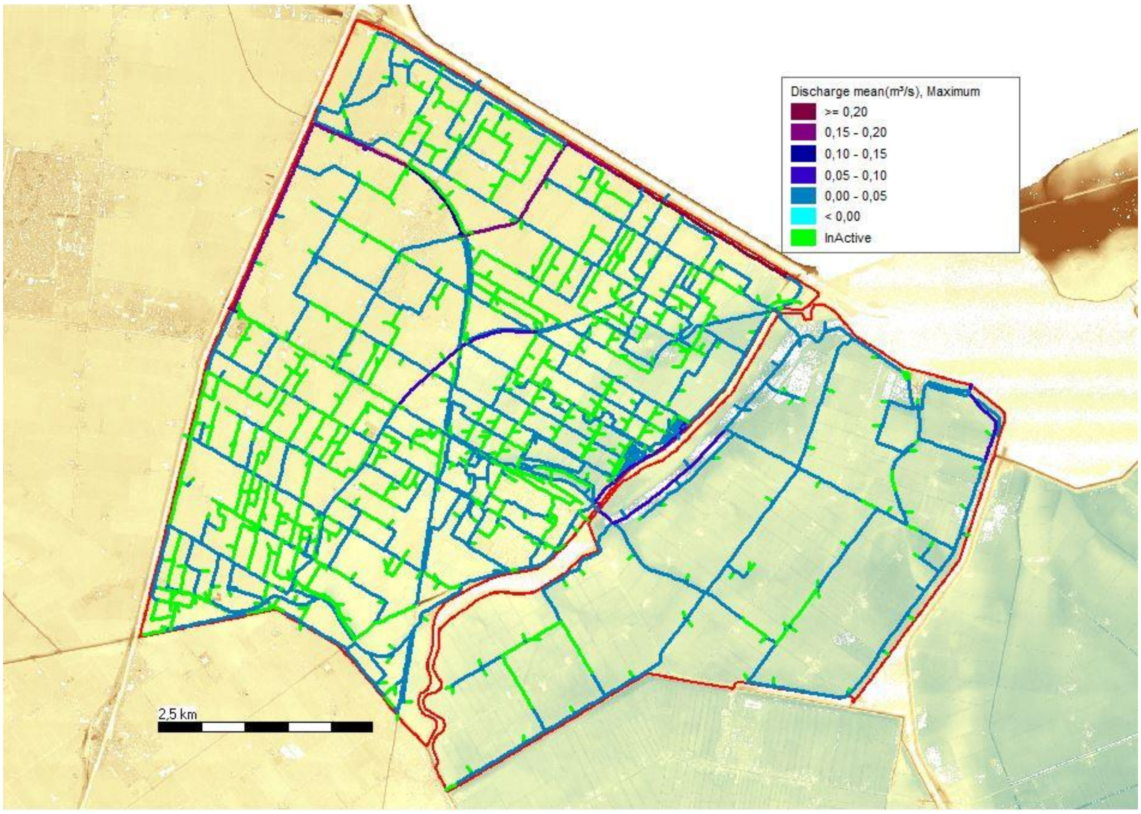


Figure 4.5. Maximum discharge in the area during dry period in the fine schematization

4.2.2 Evaluation of the coarse (less detailed) model during a dry period

Using 0 mm rainfall resulted in logical outcome as well. Water depth changes in channels showed correct results and the watercourses did not fall dry (see figure 4.6). Also, water levels in the polder are within acceptable ranges as shown in figure 4.7. The functioning of pumping stations at inlets and outlets was correct. Results of the maximum discharge for this simulation are illustrated in figure 4.8.

Although differences can be seen in the way how water flows in the watercourses in figure 4.5 (fine model) and 4.8 (coarse model), this difference can be explained by lack of secondary channels and some associated structures in the coarse model.

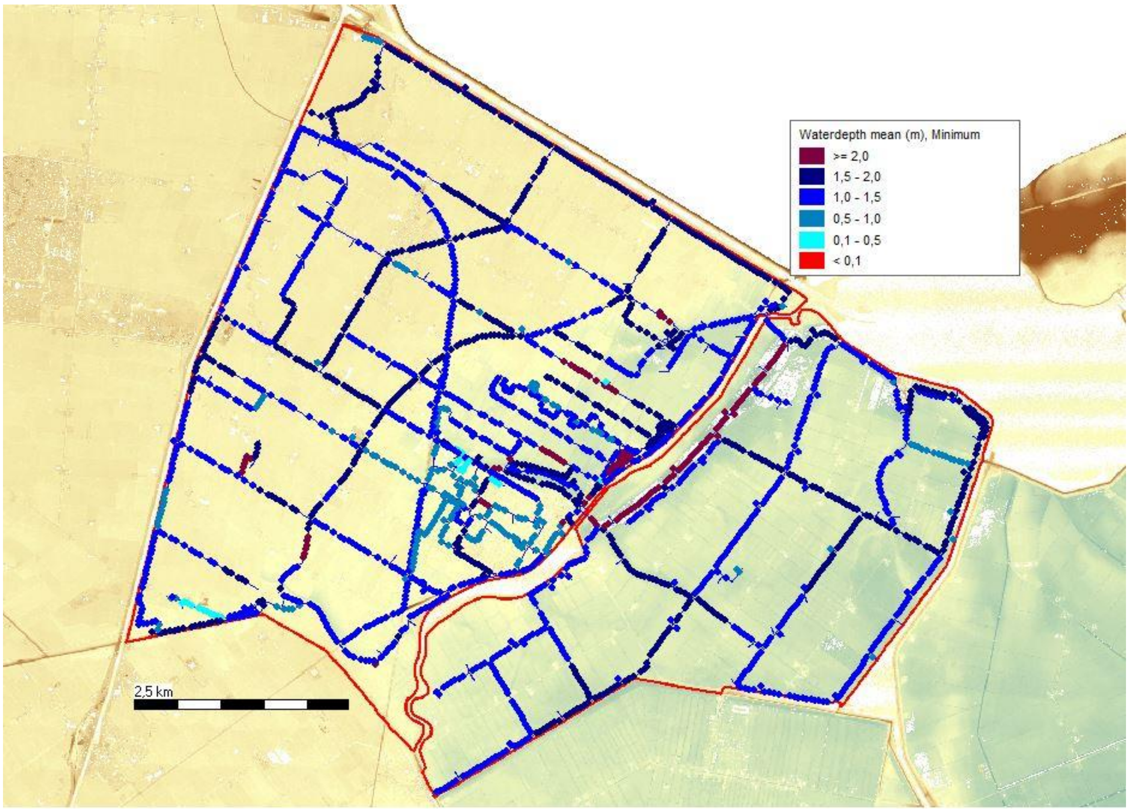


Figure 4.6. Minimum water depth in the watercourses during dry period in the coarse schematization

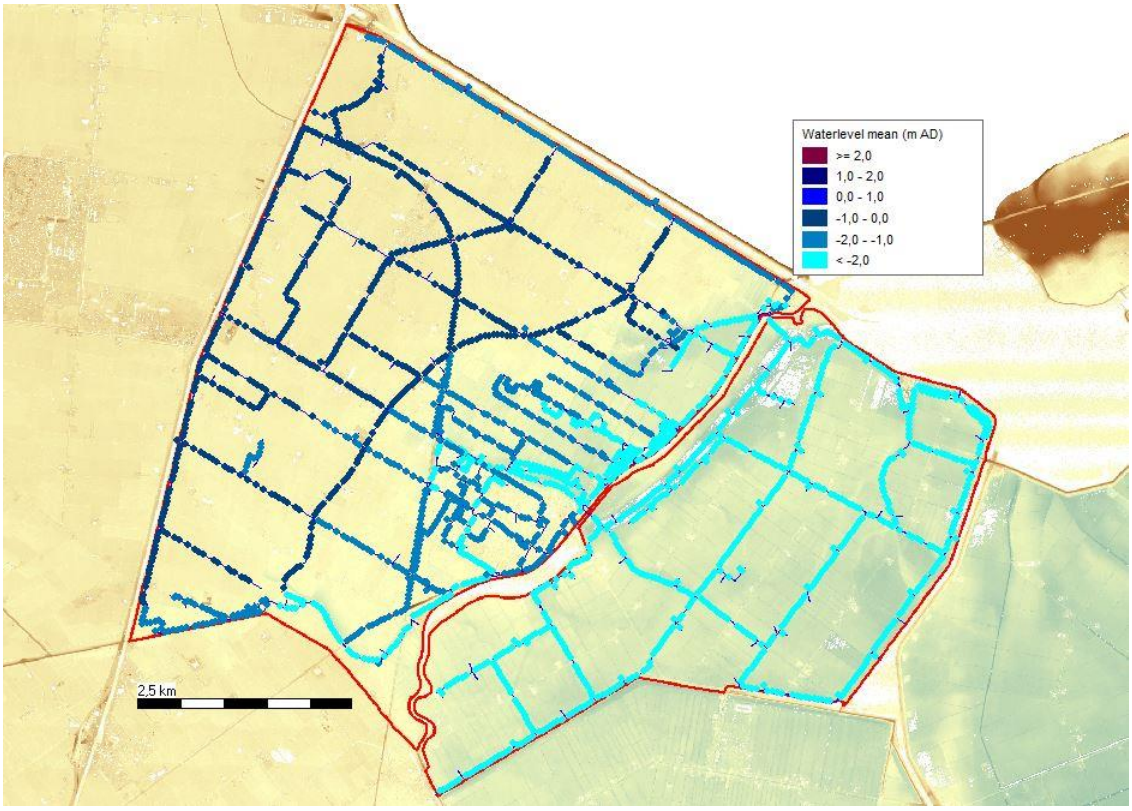


Figure 4.7. Water level in the watercourses during dry period in the coarse schematization

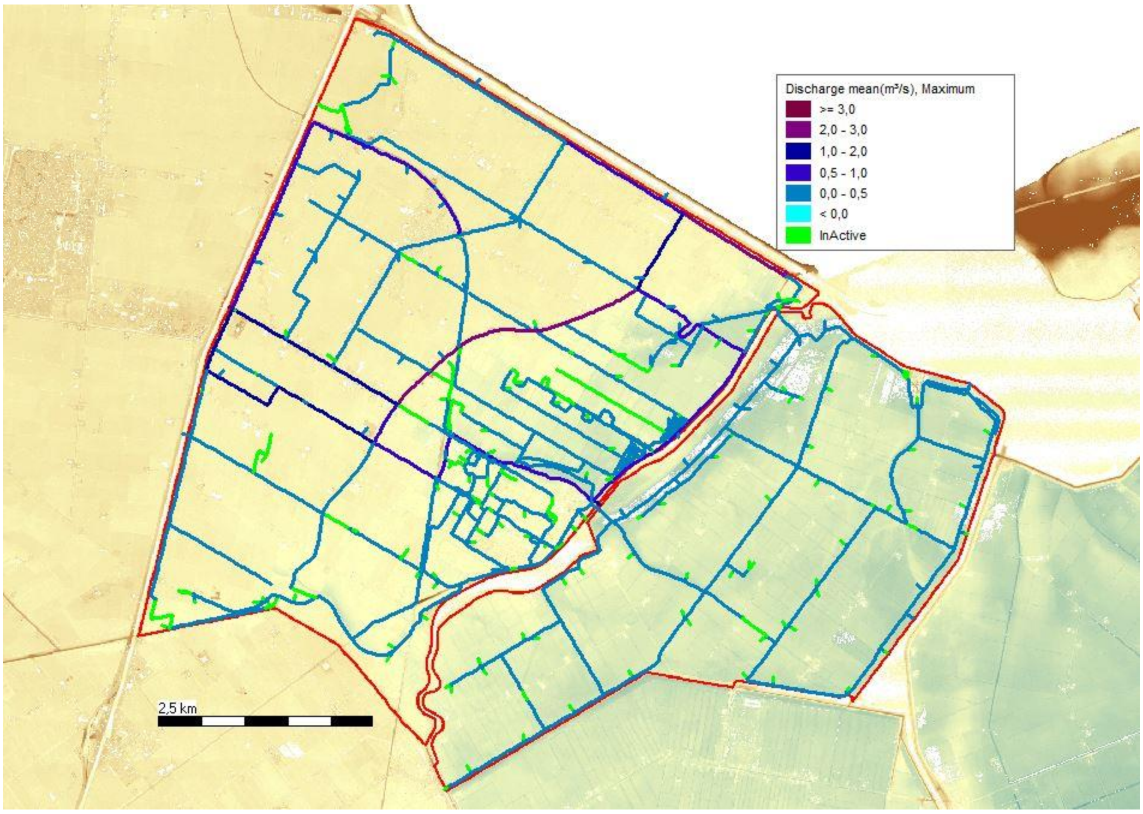


Figure 4.8. Maximum discharge in the area during dry period in the coarse schematization

4.3 Evaluation during a wet period

In this section the results of water system monitoring during a wet period are presented. Similar to the dry period, it is possible that watercourses get dry during a wet period. Actually, when the water level rises in a channel due to the rainfall, pumps start working to drain the excess water and decrease the water level. In this situation also, channels can get completely dry if they are not deep enough. Therefore, all cross-sections were evaluated under wet condition to check if their depth is enough to maintain the desired water level. So, both model were tested for a 0 mm rainfall in a wet month. This time the same parameters as mentioned in section 4.2 were checked as well to see whether the model performs properly in a wet period.

4.3.1 Evaluation of the fine (more detailed) model in wet period

Figure 4.9 and 4.10 show for the fine schematization respectively the minimum water depth and water level in the channels during a wet month. Results show appropriate water depth in almost of the channels (figure 4.9). Only one red spot can be seen in Anna Paulowna Laag (the circle on the map) in which the water depth is too low, but still not completely dry. Also, the water level variations are logical and between acceptable ranges. Figure 4.11 shows the maximum discharge during a wet month. As can be seen, the maximum discharge happened at the Wijdenes Spaans pumping station with a value of around 5 m^3/s. Since, this pump has enough capacity to pump out this volume of water; it would not be cause of any problem in the system. In general, inlets and pumps work as they should during a wet period.

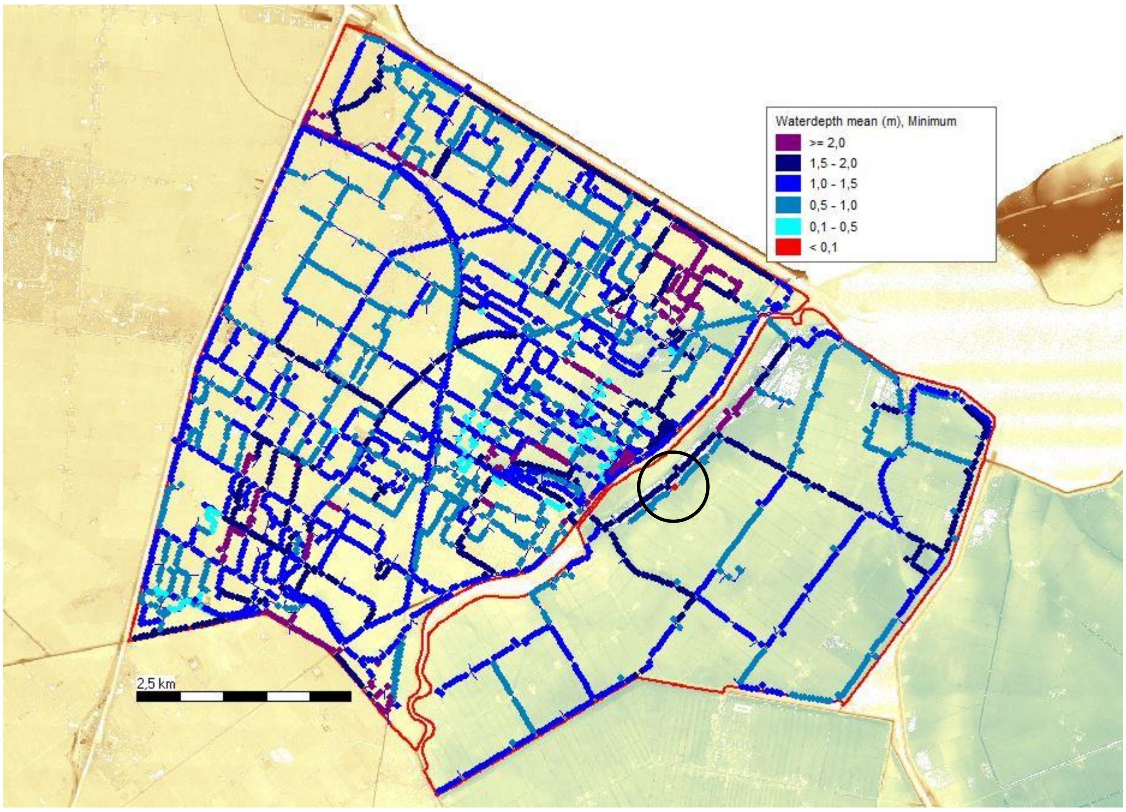


Figure 4.9. Minimum water depth in the watercourses during wet period in the fine schematization

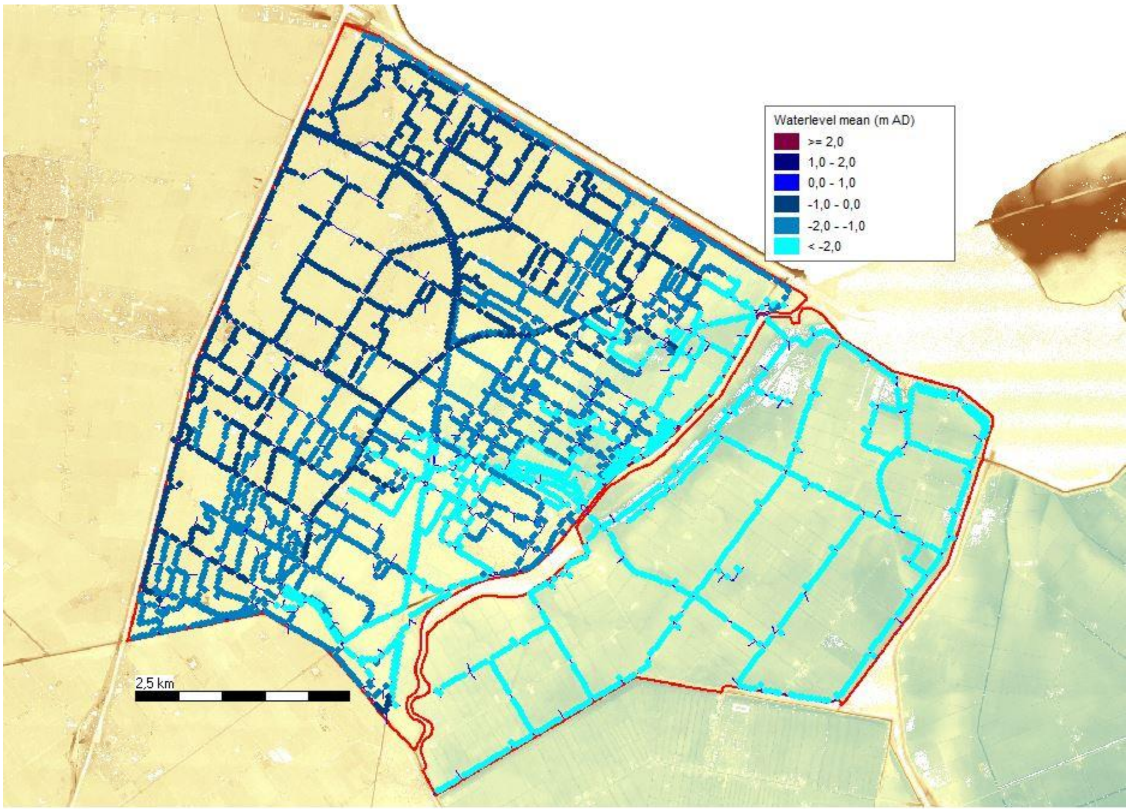


Figure 4.10. Water level in the watercourses during wet period in the fine schematization

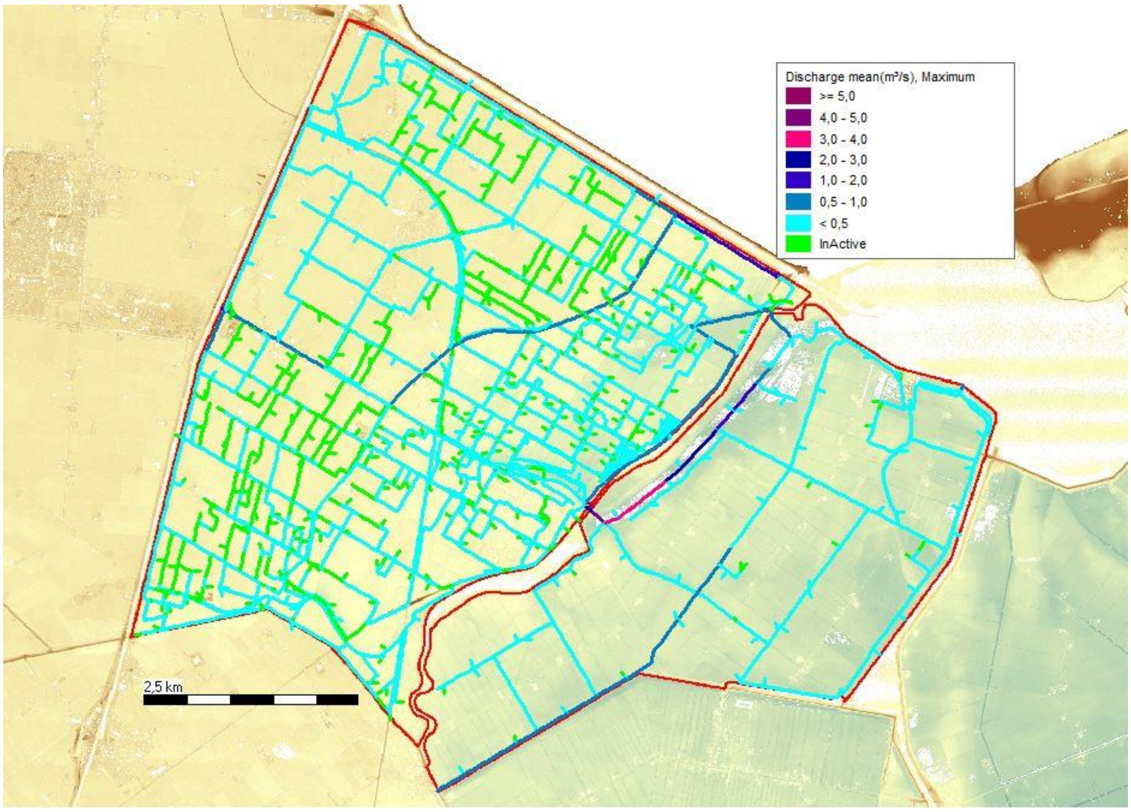


Figure 4.11. Maximum discharge in the area during wet period in the fine schematization

4.3.2 Evaluation of the coarse (less detailed) model during a wet period

Figures 4.12 and 4.13 represent for the coarse schematization respectively the minimum water depth and water level in the channels during a wet period. There is just one red point presented in figure 4.12 which shows water depth is too low in that part, and even so there is still a little amount of water in that channel and it is not completely dry. So, the model performs as it should and can be used for further study. Furthermore, there is no sudden fluctuation in water levels, but only in part of a channel in Anna Paulowna Hoog (which is shown on figure 4.13). Figure 4.14 shows the maximum discharge in a wet month. Monitoring the system in this condition showed that the coarse model can work under the wet period properly as well. The pumps were simulated correctly and the excess water could be pumped out of the system. Figure 4.14 displays the maximum discharge at the Wijdenes Spaans pumping station. As it mentioned above (section 4.3.1), as long as this pump has enough capacity to deal with this volume water, the model performs adequately

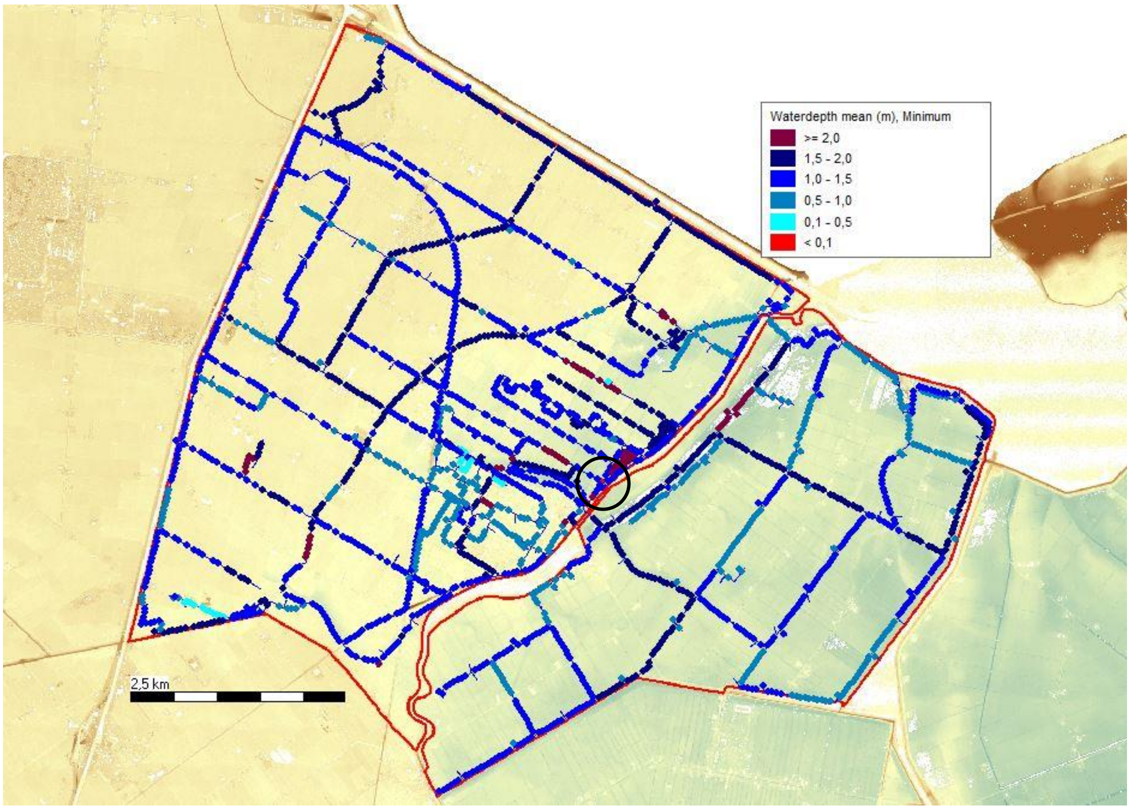


Figure 4.12. Minimum water depth in the watercourses during wet period in the coarse schematization

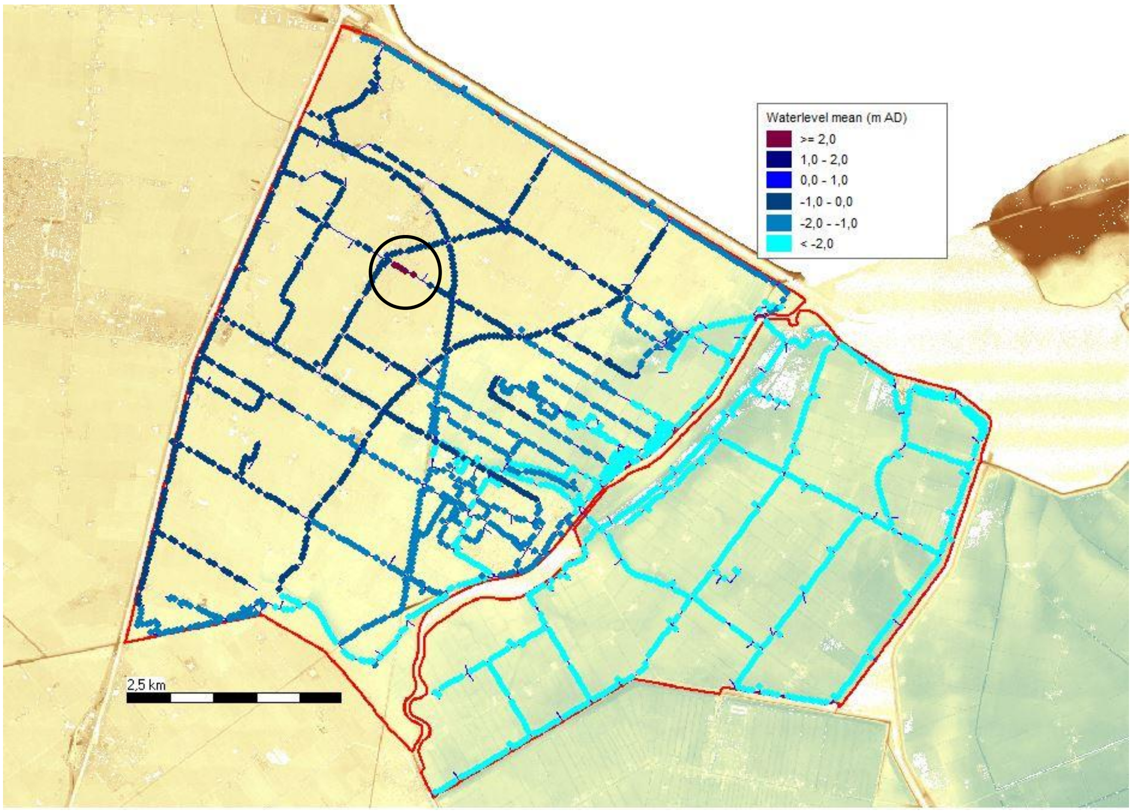


Figure 4.13. Water level in the watercourses during wet period in the coarse schematization

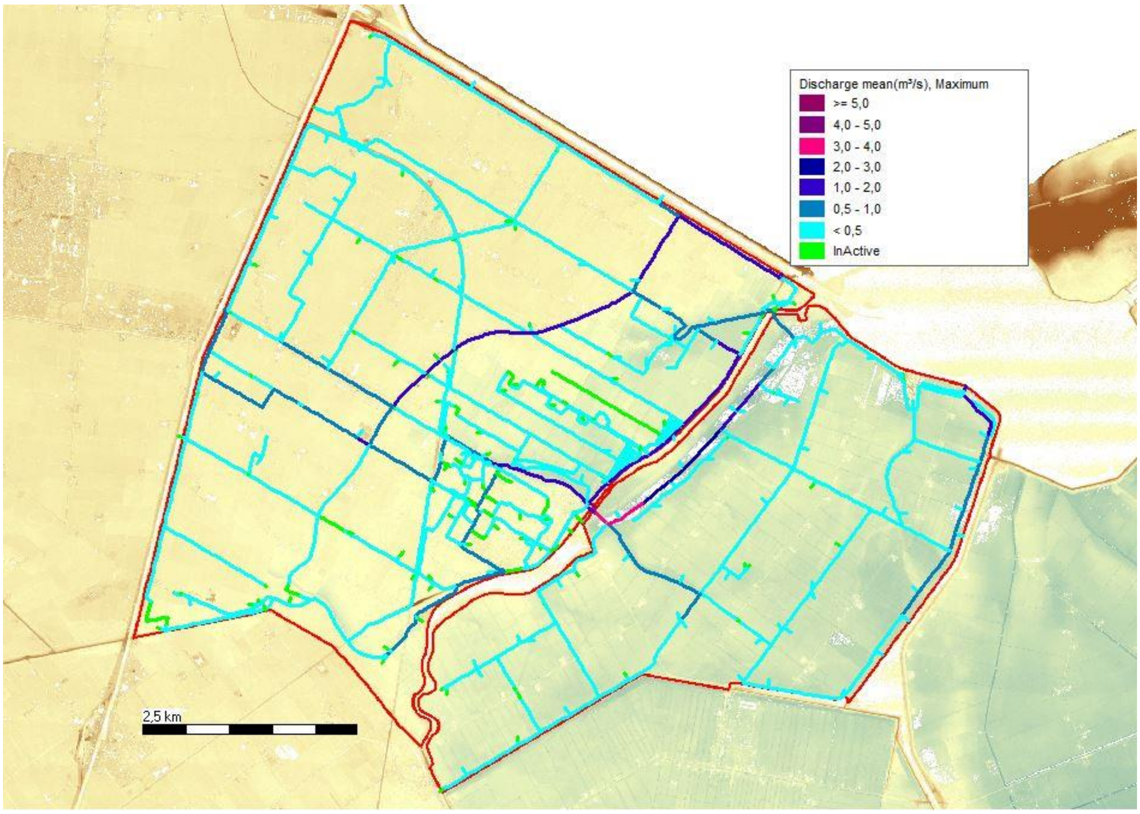


Figure 4.14. Maximum discharge in the area during wet period in the coarse schematization

4.4 Evaluation using daily rainfall during 2003

After evaluating the model during a dry and a wet period, the model was run for the actual daily rainfall that occurred in Anna Paulownapolder in 2003 with the intention to see whether the system can handle a real situation. In this situation, water depth, water level, water flow, water balance and functioning of main structures were monitored. The results of this section are evaluated in part 4.4.1 and 4.4.2.

4.4.1 Evaluating the fine (more detailed) model for daily rainfall during 2003

The fine schematization was inspected for the rainfall in 2003. The results were evaluated for water depth changes over the whole year. Figure 4.15 shows the minimum water depth under this condition. There is just one red spot on the map without enough water, but this channel is not completely dry and does not effect on this study. So, rest of watercourses contain enough water and channels are not dry for this simulation. The water levels were monitored as well to see if no sudden changes happen. The result of this part is depicted in figure 4.16. In fact, the water level fluctuations were according to the expectation in the study area and its variations follow the controllers which are introduced to the system. Figures 4.17 to 4.19 show the water level at 6 different points in the polder which were compared with their controllers. However, some differences can be seen between the registered water levels and the controllers. Since, the salinity is a major problem during dry period and differences in water level happened in the wet months they can be ignored in this study.

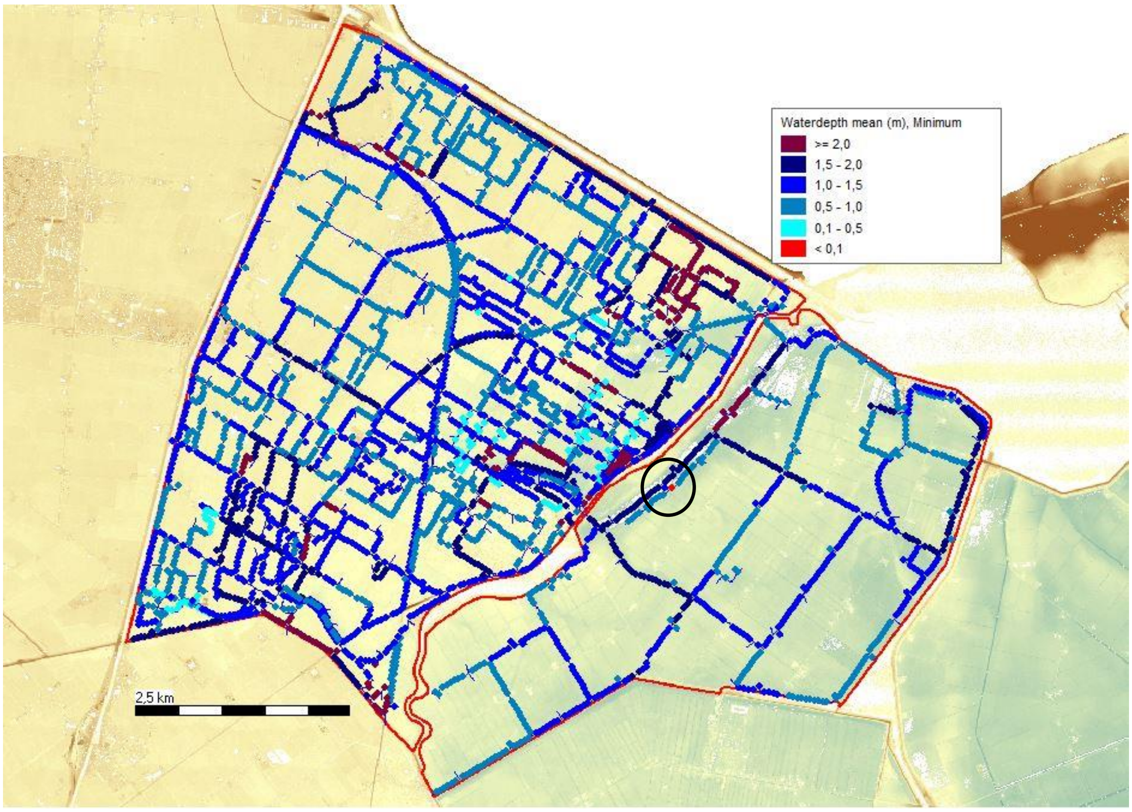


Figure 4.15. Minimum water depth in the watercourses for rainfall in 2003 in the fine model

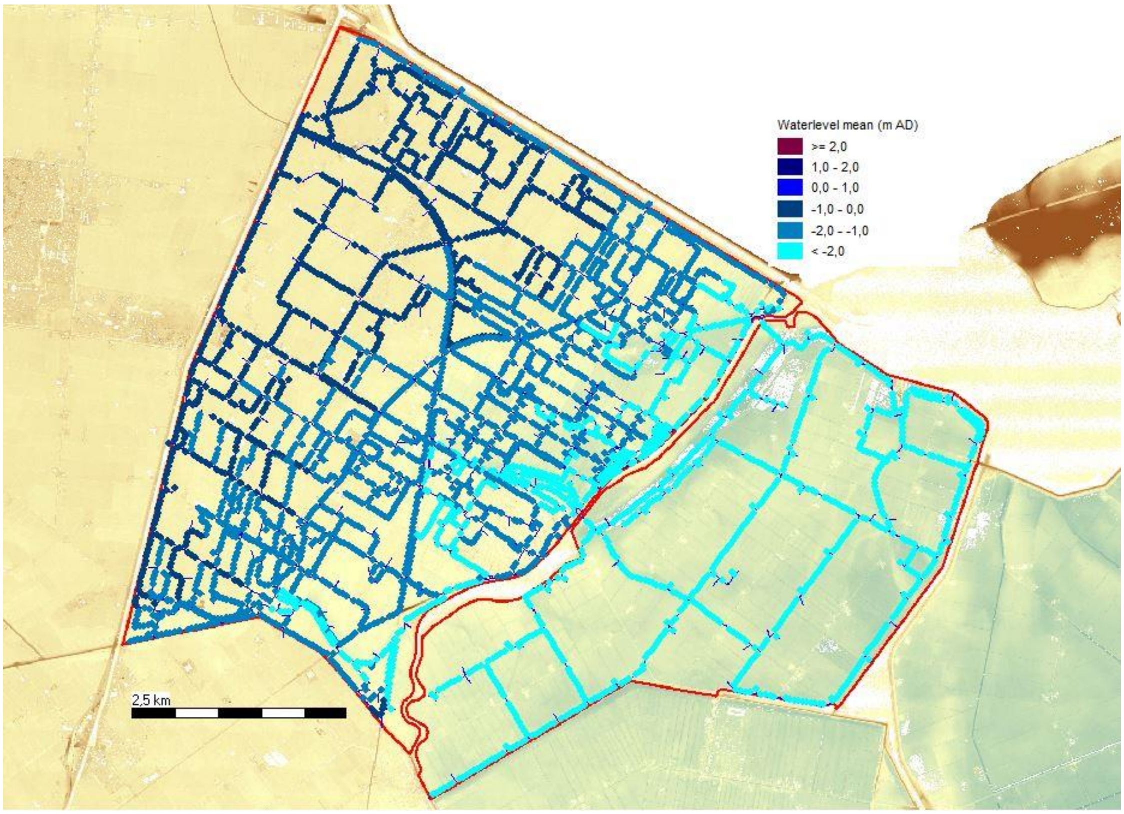


Figure 4.16. Water level in the watercourses for rainfall in 2003 in the fine model at the end of the period

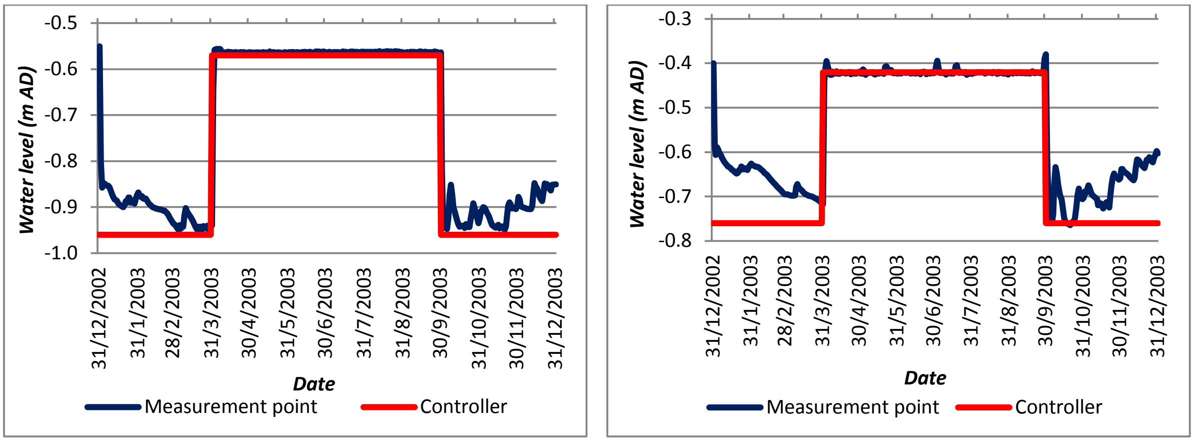


Figure 4.17. Water level fluctuations at measurement points in comparison with their controller in Anna Paulowna Hoog in 2003 in the fine model.

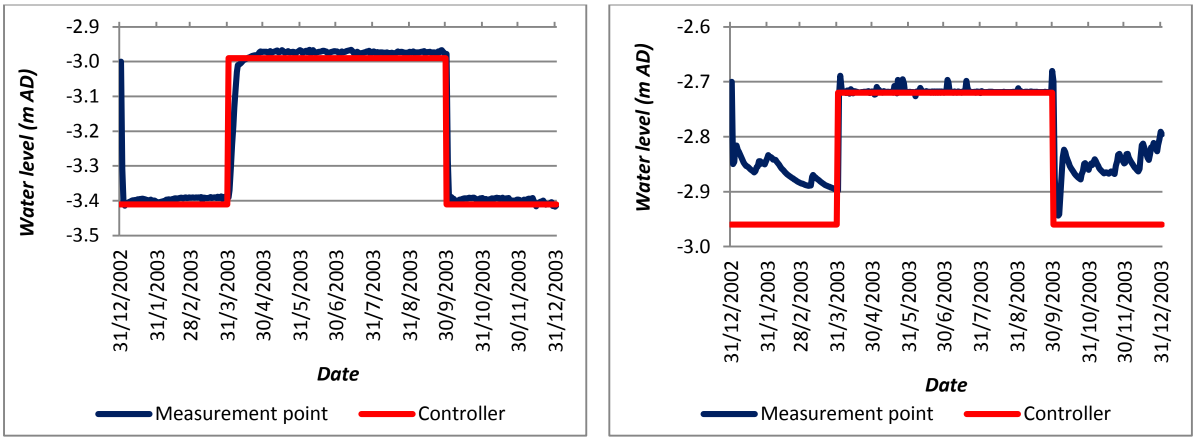


Figure 4.18. Water level fluctuations at measurement points in comparison with their controller in Anna Paulowna Laag in 2003 in the fine model.

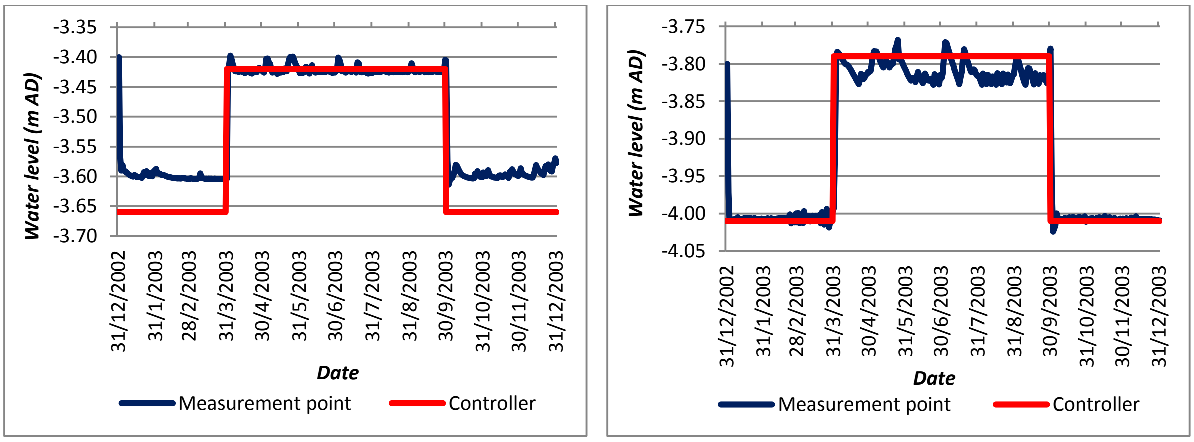


Figure 4.19. Water level fluctuations at measurement points in comparison with their controller in Oostpolder in 2003 in the fine model.

The water flow and maximum discharge were evaluated for actual forcing as shown in figure 4.20. Results did not show any specific problem in the area. Figure 4.21 represents a simple water balance for the fine model in 2003. Figure shows that at the beginning of the year (wet period) outlet is more than inlet which means that pumps work and drain out the excess water. With the approaching of the summer months, the difference between two curves decreases. After that, the inlet takes over the outlet to compensate for the lack of water. In figure 4.22 the results of functioning of inlets are presented. This figure shows that all inlets work as expected. For instance, inlet 3 just pumped water into the system at the beginning of the dry period and then stopped. It can be concluded that the water level at the measurement location of this inlet has not dropped below the allowable level during the rest of the period. Also in figure 4.23 the operating of pumping stations are shown. Obviously, they worked during the wet period as expected and also, during the dry period if that was necessary.

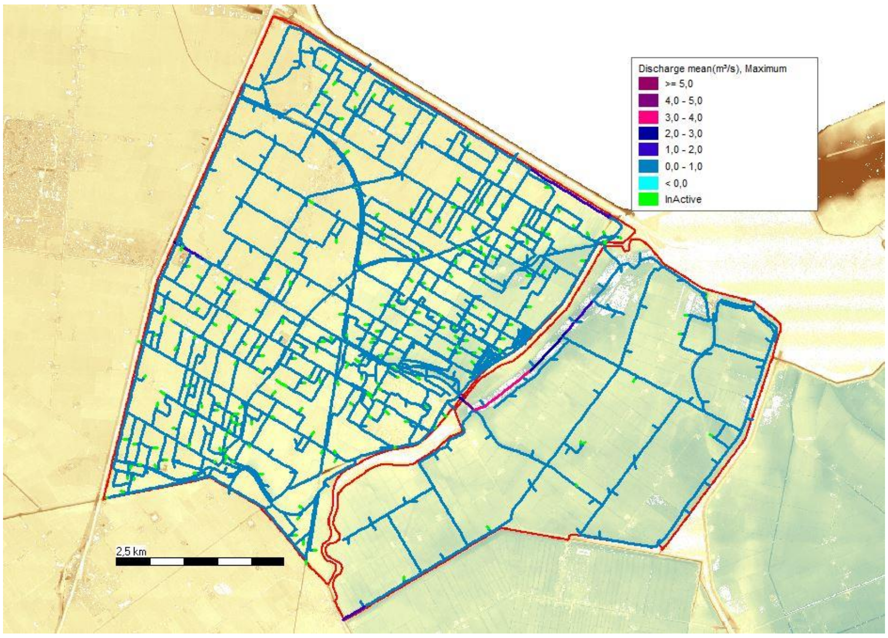


Figure 4.20. Maximum discharge in the area for rainfall in 2003 in the fine model

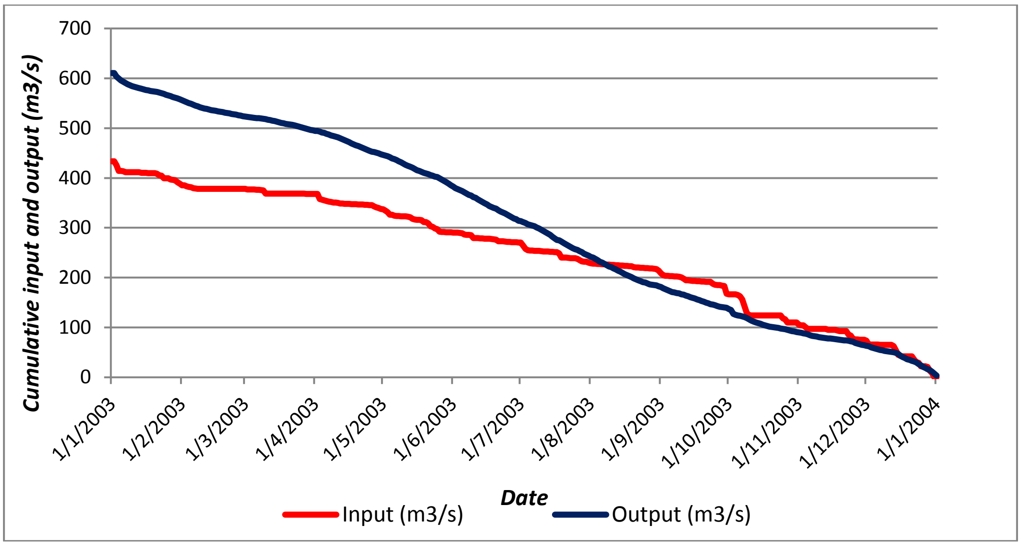


Figure 4.21. Water balance in the study area during 2003 in the fine model

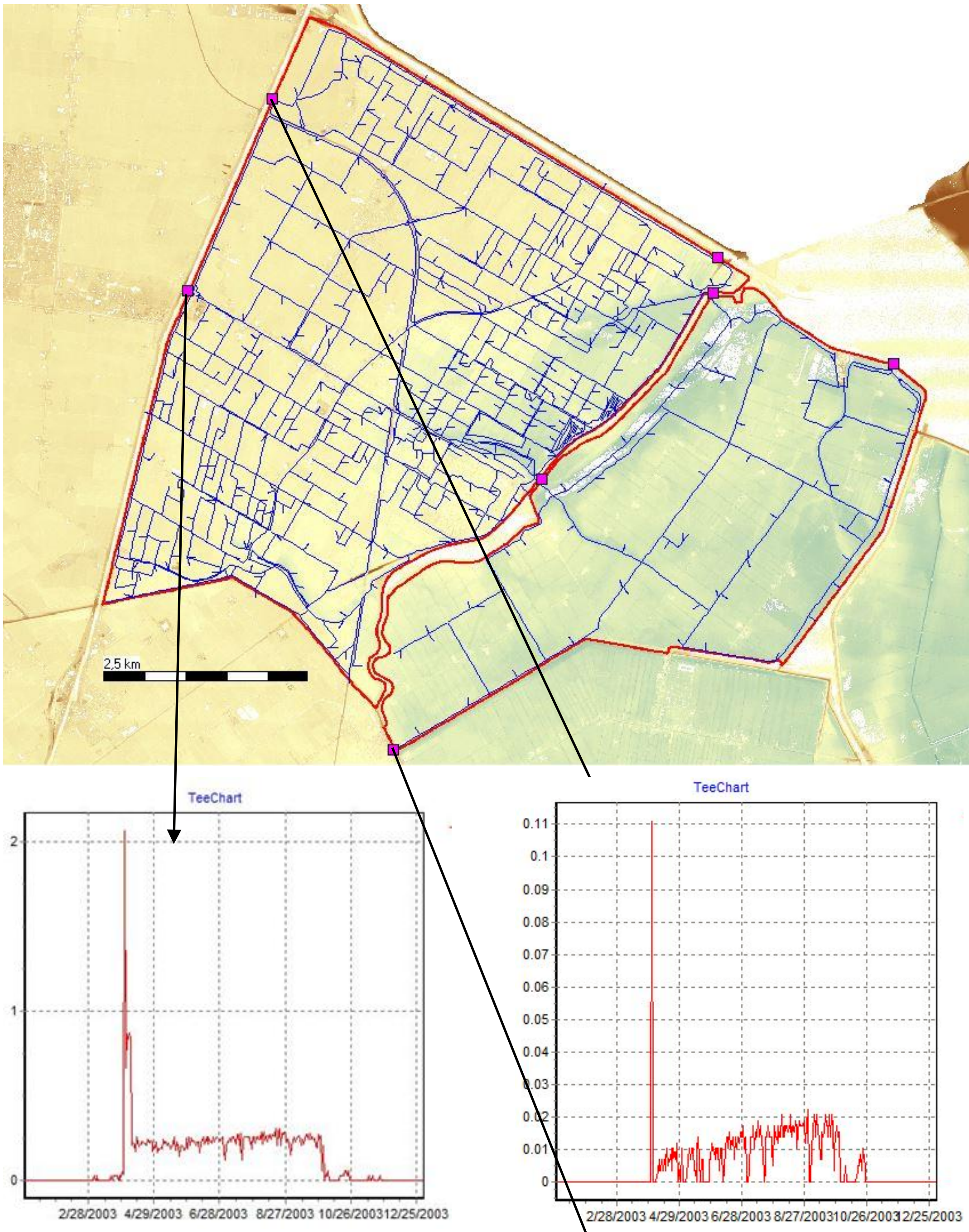
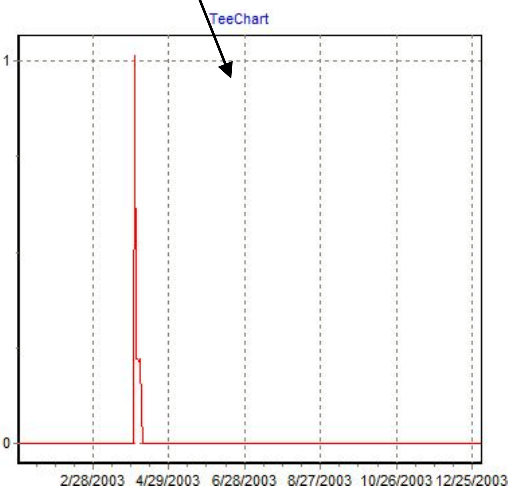


Figure 4.22. Functioning of inlets (m^3/s) in the fine model for rainfall in 2003



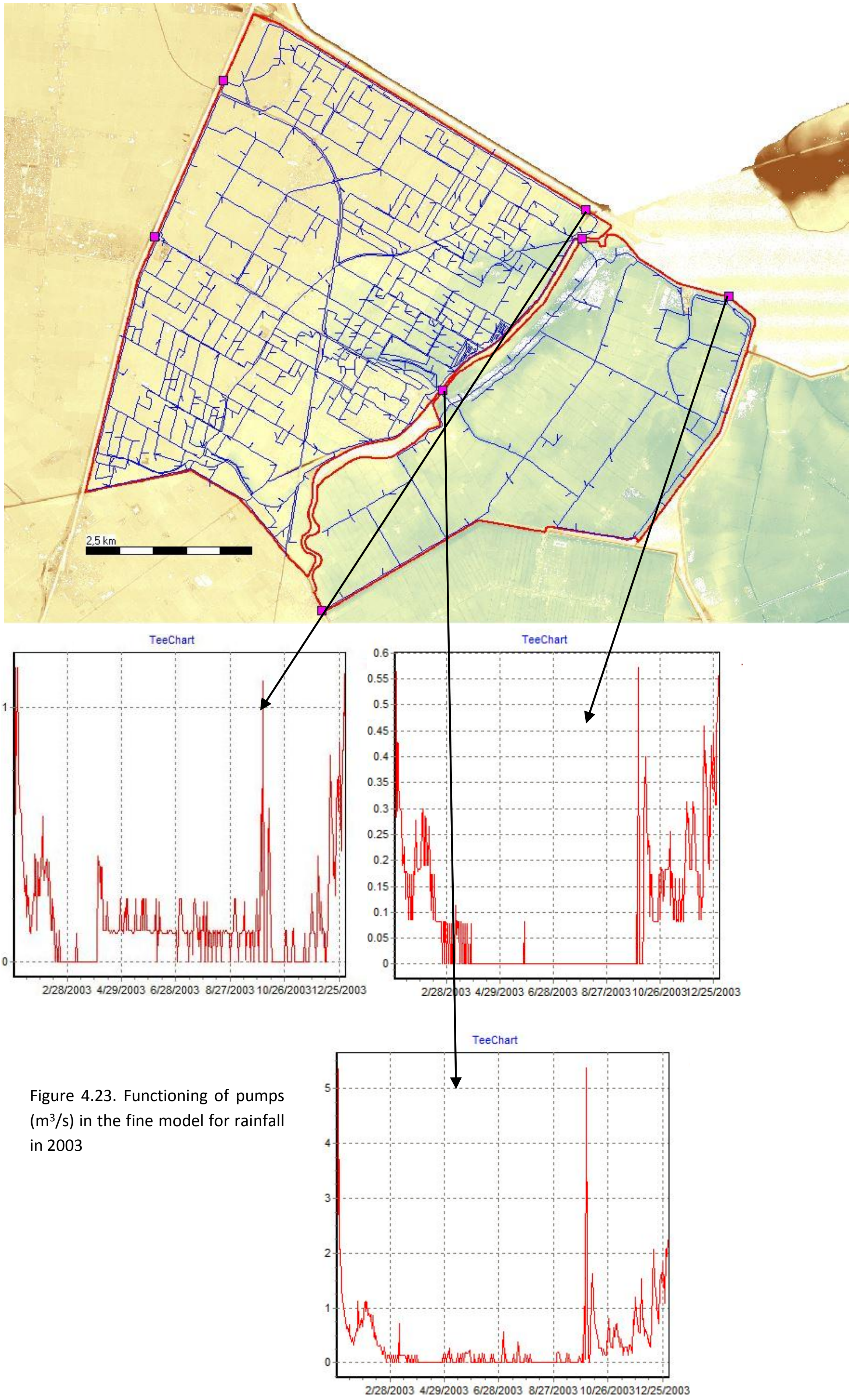


Figure 4.23. Functioning of pumps (m^3/s) in the fine model for rainfall in 2003

4.4.2 Evaluating the coarse (less detailed) model for daily rainfall during 2003

The coarse schematization was also monitored for the actual rainfall input of 2003. Figure 4.24 shows the minimum water depth during the period. As is shown in figure 4.24, in a small part of the study area water depth dropped to a very low amount. However, the channel was not completely dry. The water levels were also monitored in order to see if there were any abrupt fluctuations. The result of are shown in figure 4.25 which shows that the water level fluctuations were more or less according to expectation and its variations follow the controllers which are introduced to the system. Figures 4.26 to 4.28 show the water level at 6 different points in the polder which were compared with their controllers.

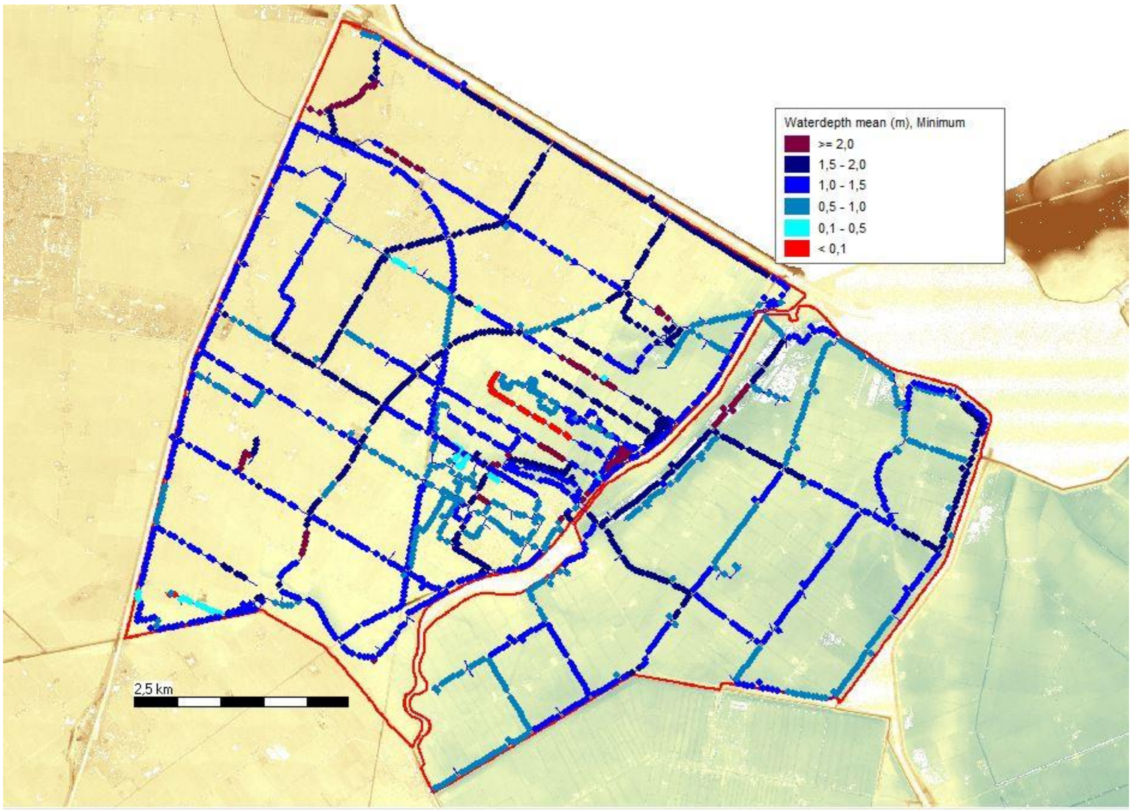


Figure 4.24. Minimum water depth in the watercourses for rainfall in 2003 in the coarse model

Although, some differences can be seen between the registered water levels and the controllers, they are not very crucial in this study. As it mentioned in the previous section, as differences mainly happened in the wet periods they can be ignored because, salinity problem is dominant during dry period in which system shows better results.

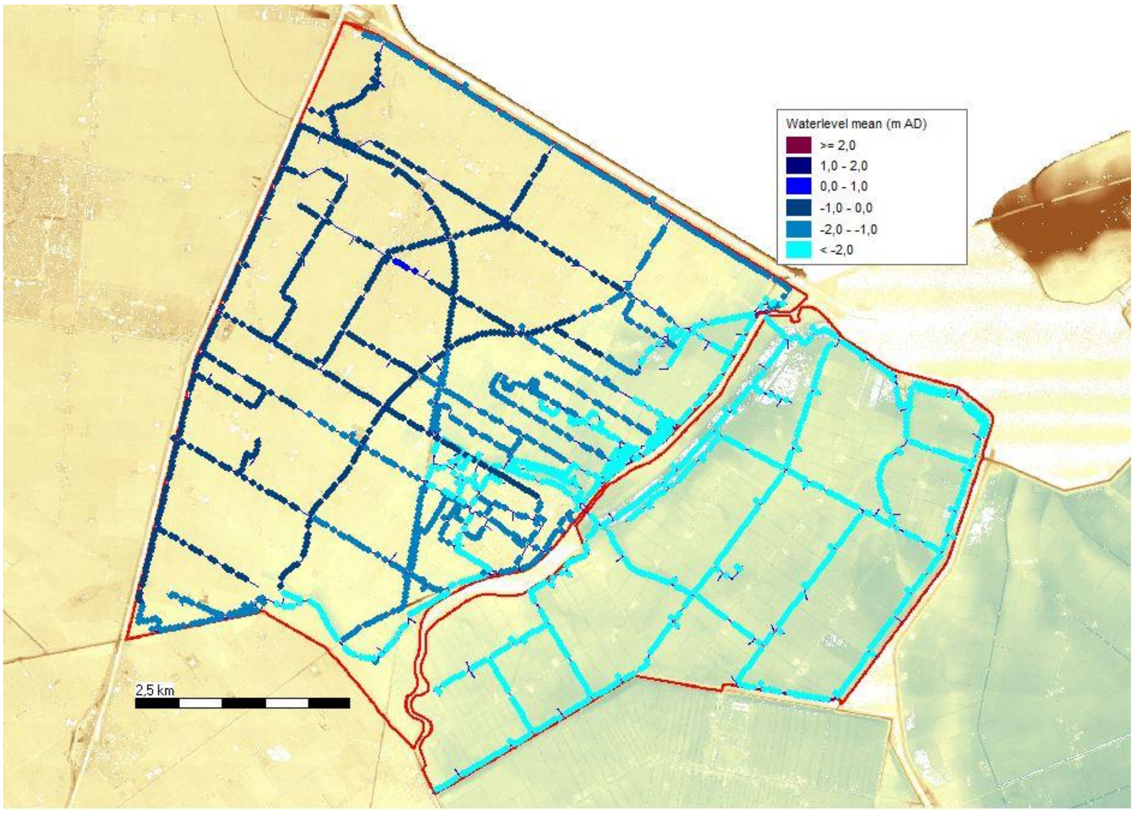


Figure 4.25. Water level in the watercourses for rainfall in 2003 in the coarse model at the end of the period

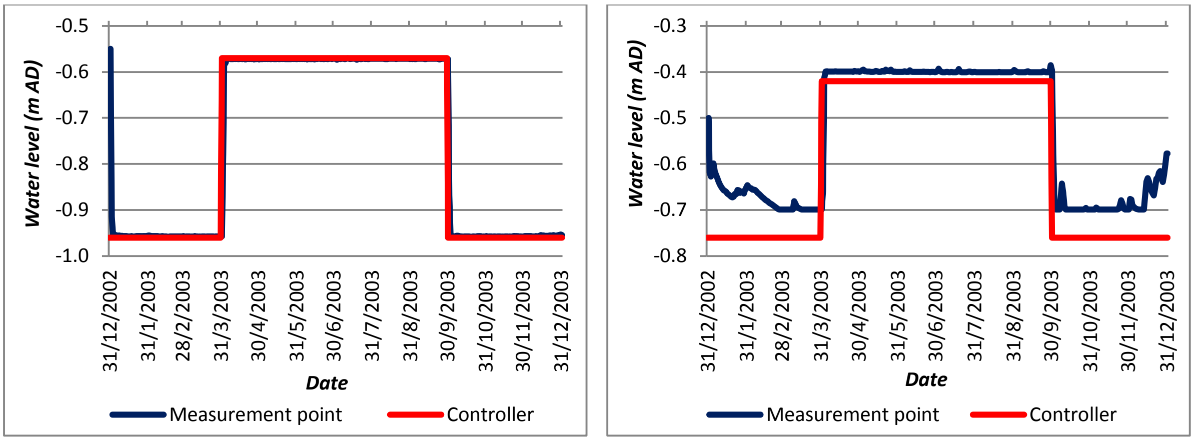


Figure 4.26. Water level fluctuations at measurement points in comparison with their controller in Anna Paulowna Hoog in 2003 in the coarse model.

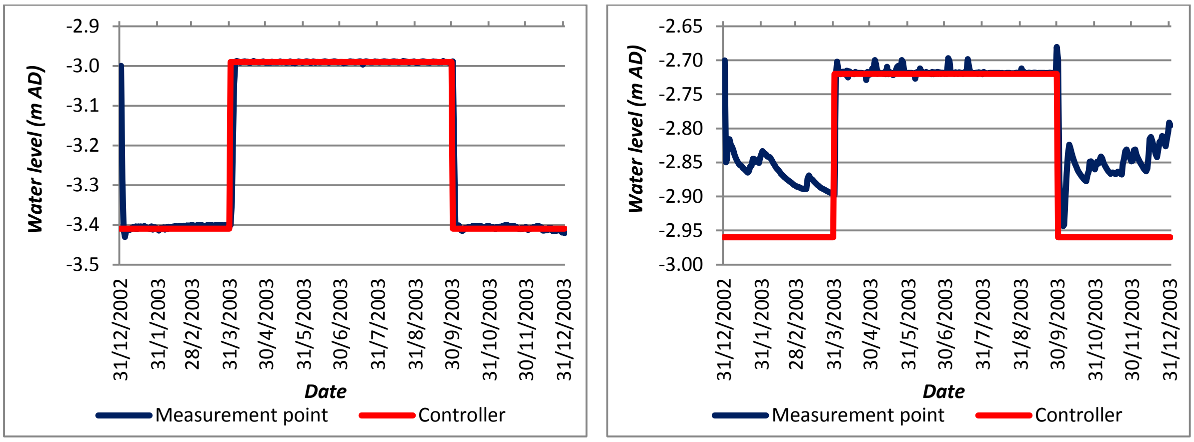


Figure 4.27. Water level fluctuations at measurement points in comparison with their controller in Anna Paulowna Laag in 2003 in the coarse model.

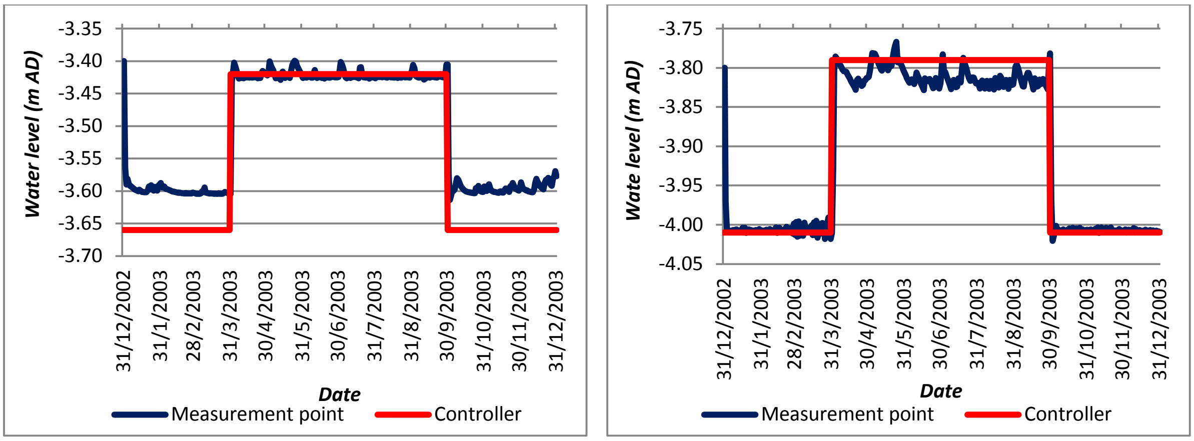


Figure 4.28. Water level fluctuations at measurement points in comparison with their controller in Oostpolder in 2003 in the coarse model.

Figure 4.29 shows the maximum discharge occurring. It can be seen that similar to the fine-scale case, the result did not show any specific problems in the area. In figure 4.30 the water balance for the whole period is presented. Here again, at the beginning of the wet period outlet is more than inlet which shows pumps work and drain out the excess water. When approaching the dry period, the difference between two curves declines. After that, inlet takes over the outlet to compensate the lack of water in the system. However, as can be seen the difference between the two is not as large as for the fine scale case. This can be expected as the water loss due to evaporation is less if in case less watercourses are resolved. Figure 4.31 and 4.32 show the results of functioning of inlets and pumps under this condition. All inlets and pumps worked properly according to the measurement locations. However, some unavoidable conditions can be detected in this model such as functioning of Balgdijk pumping station during the dry period (see figure 4.32).

In general, the results of validation of two models show that both fine and coarse models can be used for salinity simulation in the study area with the acceptable level of confidence in the functioning of the model.

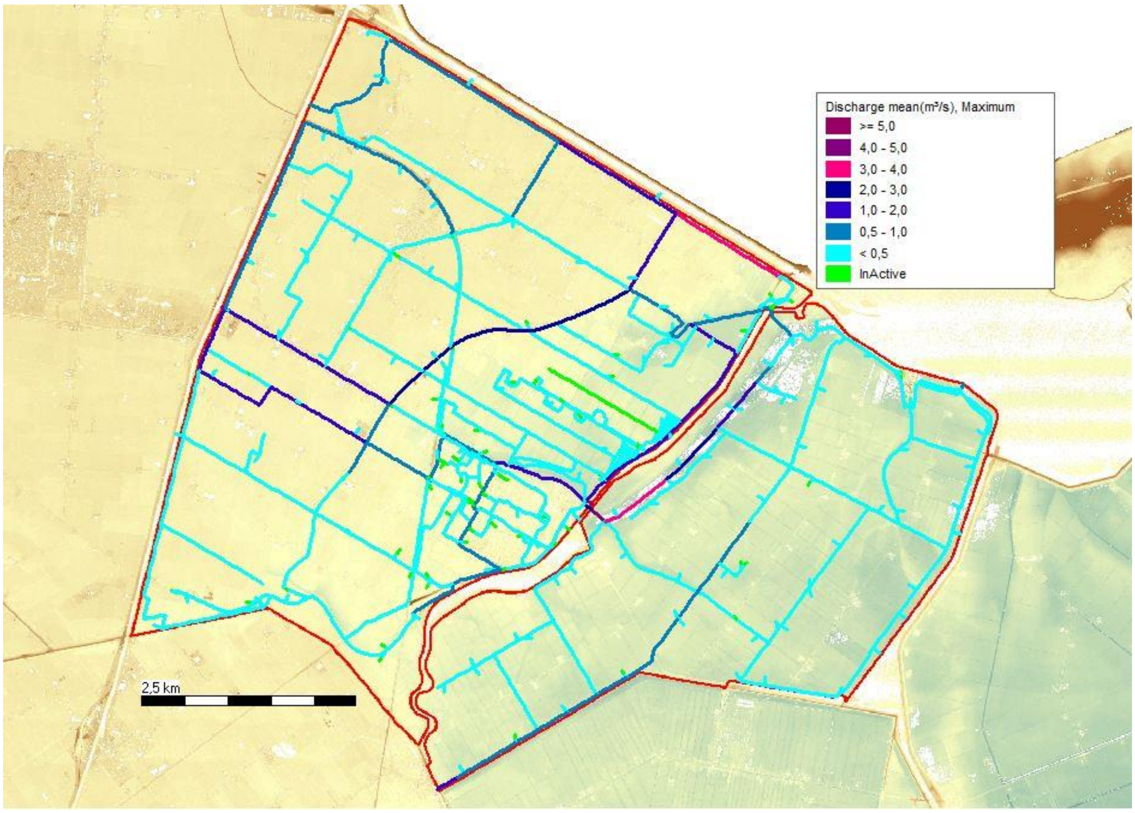


Figure 4.29. Maximum discharge in the area for rainfall in 2003 in the coarse model

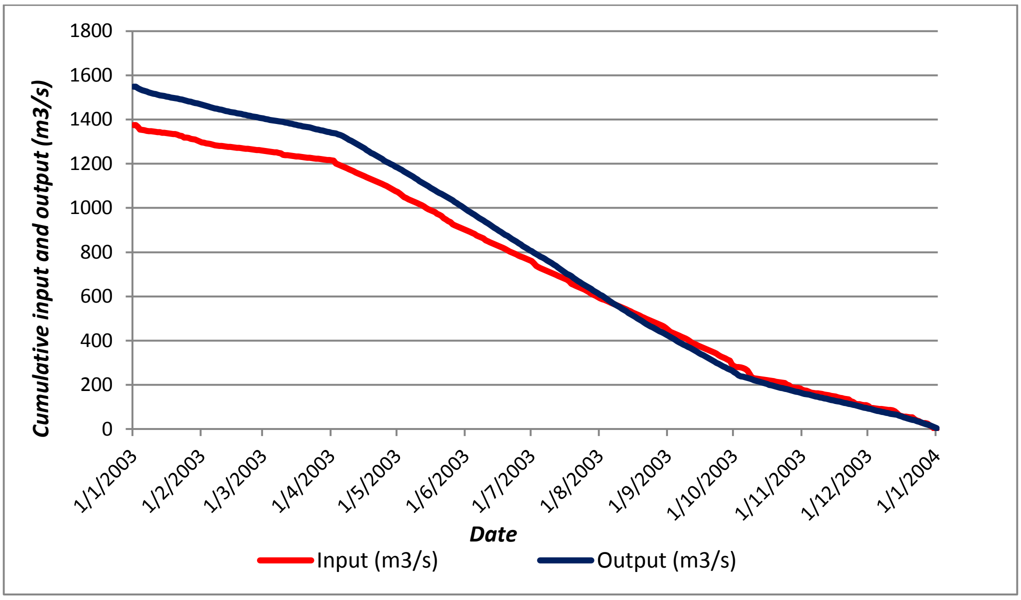


Figure 4.30. Water balance in the study area during 2003 in the coarse model

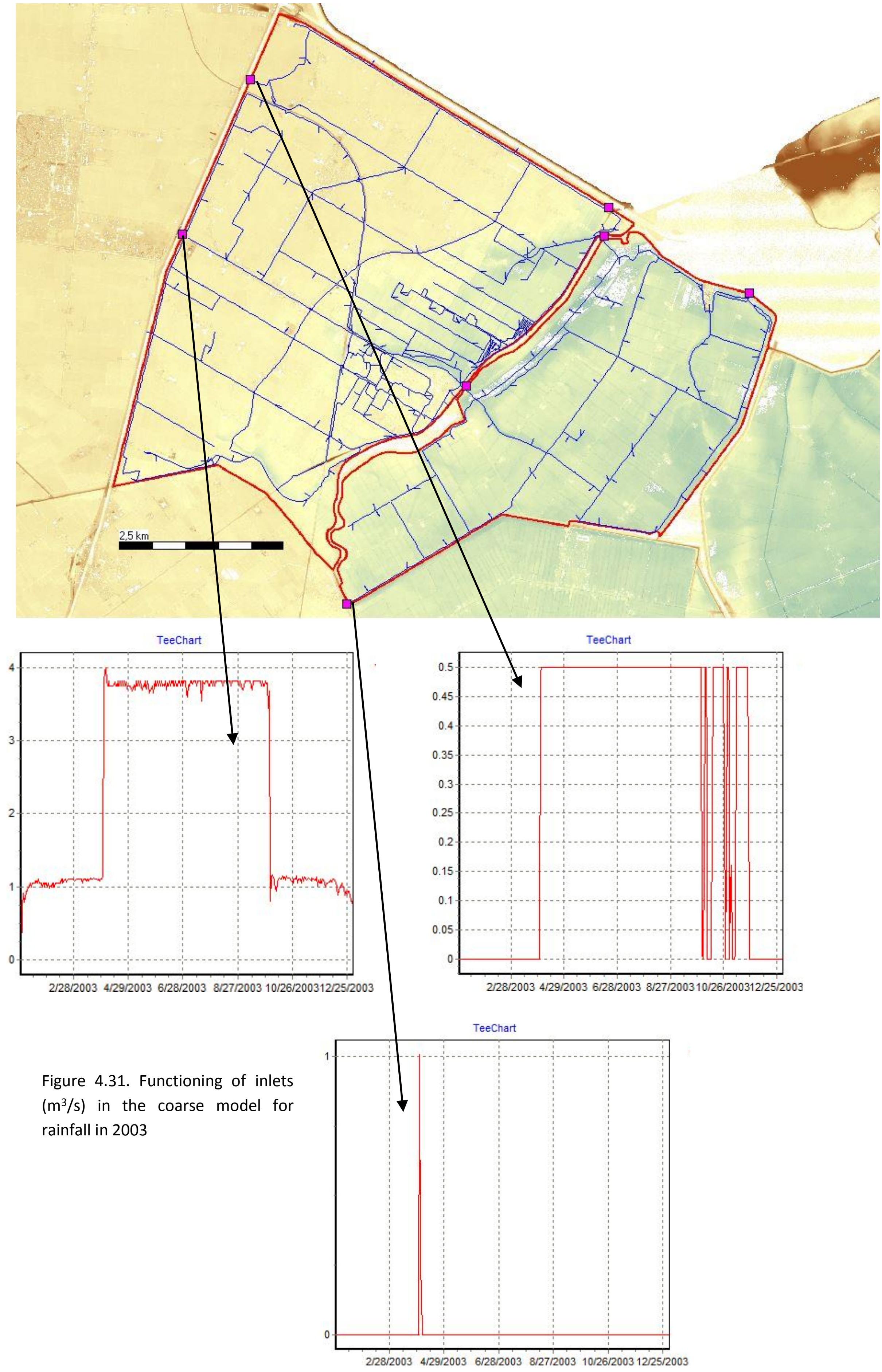


Figure 4.31. Functioning of inlets (m^3/s) in the coarse model for rainfall in 2003

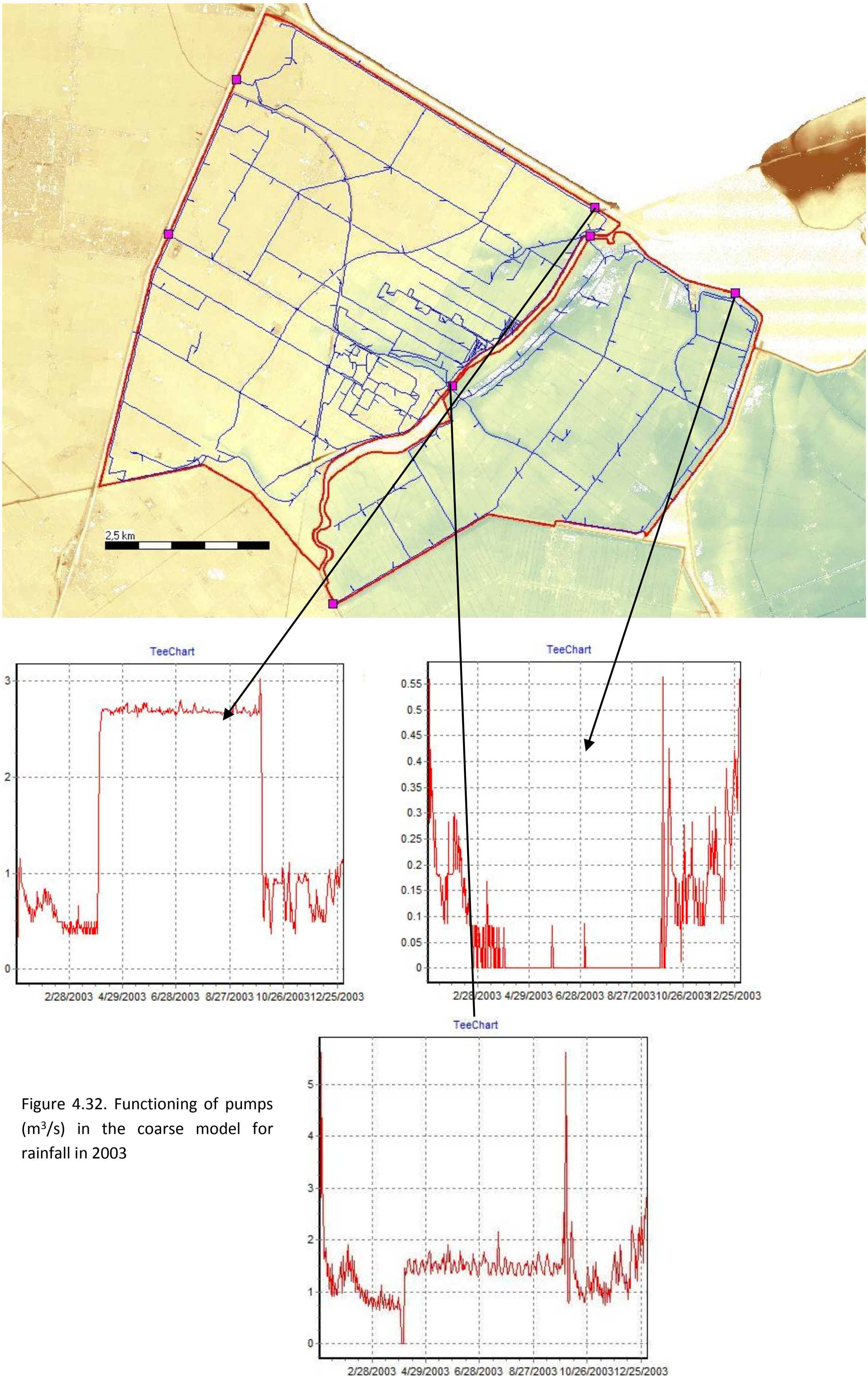


Figure 4.32. Functioning of pumps (m^3/s) in the coarse model for rainfall in 2003

5 Results from the simulation of two scenarios with two models

The SOBEK model was implemented in Anna Paulownapolder in North Holland. Two different models were schematized. In the first model all watercourses (primary and secondary) were included in the simulation, whereas in the second model only main watercourses were included. In order to compare the accuracy between these two models; a fraction analysis and two scenarios were performed. The result of these simulations is described in this chapter.

5.1 Fraction analysis

In order to find the origin of the salt in the study area a fraction analysis was performed for both models. The results show that the main source of salinity in Anna Paulownapolder is the boundary flow. The main salinity source can be assigned to the Helsdeur in Den Helder which is open especially during summer for shipping. Other factors such as seepage and rainfall do not have a significant contribution in the salinity of the area. The results of fraction analysis for boundary flows are summarized in table 5.1. Data in this table show when which fraction of salt should be expected when applying two different models. The distribution pattern of salinity through boundary flows is presented in appendix II (see figures II-1 to II-8) for both models as well. Also, the results of salt fraction in watercourses from precipitation and seepage are demonstrated in appendix III and IV respectively.

		More detailed model Cl fraction (1/1)				Less detailed model Cl fraction (1/1)			
Location		After 3 month	After 6 month	After 9 month	After 12 month	After 3 month	After 6 month	After 9 month	After 12 month
AP-Hoog	West	0.1-0.2	>0.9	>0.9	0.4-0.3	0.5-0.6	>0.9	>0.9	>0.8
	Mid	>0.9	>0.9	>0.9	0.5-0.6	>0.9	>0.9	>0.9	>0.8
	East	0.1-0.2	>0.9	>0.9	0.5-0.6	>0.9	>0.9	>0.9	>0.5
AP-Laag	West	-	0.7-0.8	>0.9	0.3-0.4	>0.9	>0.9	>0.9	0.4-0.5
	Mid	-	0.8-0.9	0.8-0.9	0.3-0.4	>0.9	>0.9	>0.9	0.6-0.7
	East	-	0.7-0.8	0.7-0.8	0.2-0.3	>0.9	>0.9	>0.9	0.6-0.7
Oostpolder		-	0.3-0.4	0.2-0.3	-	-	0.4-0.5	0.4-0.5	<0.1

Table 5.1. Observed maximum salinity fraction at the end of each 3 month period by boundary flow. Sign (-) means no observation because, water has not reached to that part yet.

The results show two different spatial and temporal distributions of salinity through boundary flows in the area. The fine schematization results in a smaller amount of brackish water in all parts of the area than coarse schematization. Also, the salinization of the polders occurs more slowly in the fine schematization than the in coarse schematization. The reason is that in the fine model the salt load is distributed over a much larger area/volume of water which slows down and buffers the replacement of fresh water by brackish and saline water.

At the end of 3 month, the fine model shows salinity only in Anna Paulowna Hoog close to the main inlet, while a high Chloride concentration is calculated for the entire Anna Paulowna Hoog and Laag in the coarse model. Also, slightly less Chloride was found out after 6 and 9 months in the fine model than in the coarse model. Moreover, the residence time of the brackish water in the area is longer in coarse schematization. As can be seen, at the end of the dry period the salinity is reduced by more rainfall in the study area. However, chloride concentration at the end of the simulation period is still higher in the coarse schematization.

Figures 5.1 and 5.2 display the salt fraction through boundary flow from the three inlets in the study area in the fine and coarse schematization respectively. As can be seen, the functioning of inlets is very different in two models. According to the coarse model, inlet 1 does not play an important role, while it is significant in the fine model.

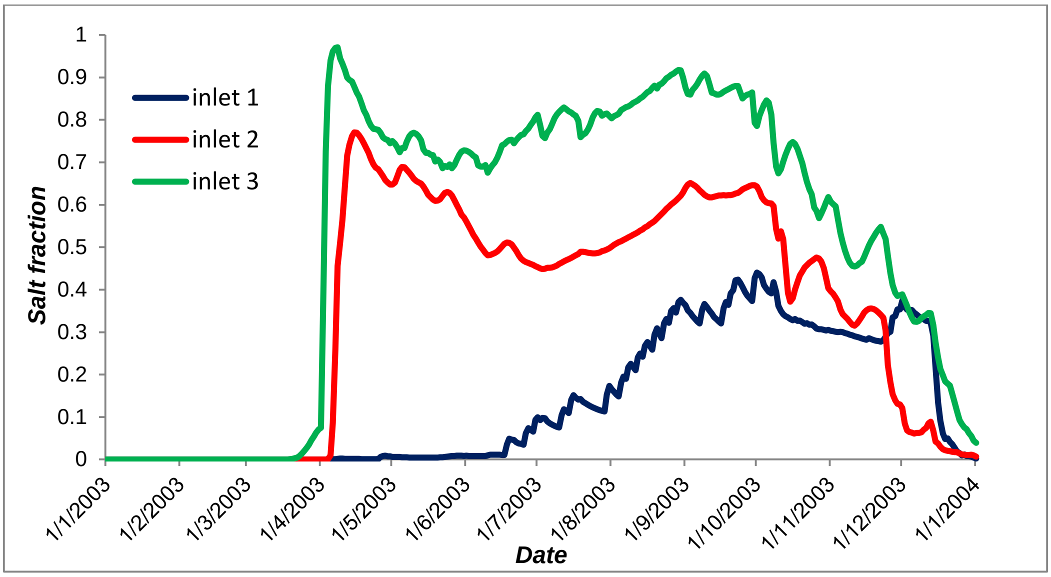


Figure 5.1. Salt fraction through boundary flows at three inlets in fine schematization

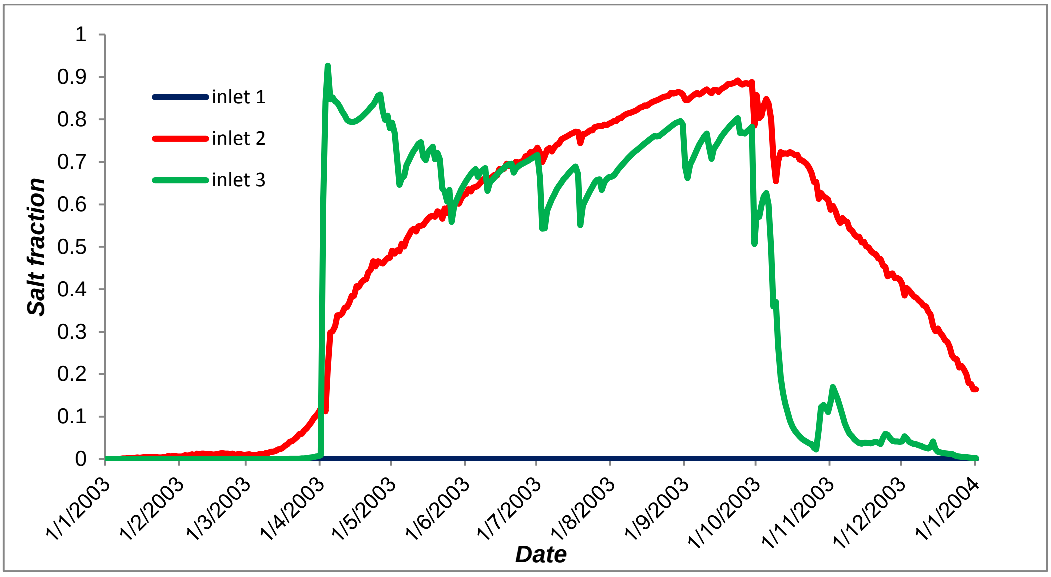


Figure 5.2. Salt fraction through boundary flows at three inlets in coarse schematization

As an example, figures 5.3 and 5.4 show the salinity spatial distribution after 6 months in the area in fine and coarse schematization respectively. Obviously, the major differences can be detected where the secondary channels are denser. This results show how important these secondary channels are. The small watercourses have a significant impact on the distribution pattern of salinity in the study area. These results clearly show that part of the salinity in the main channels can be diluted by secondary canals.

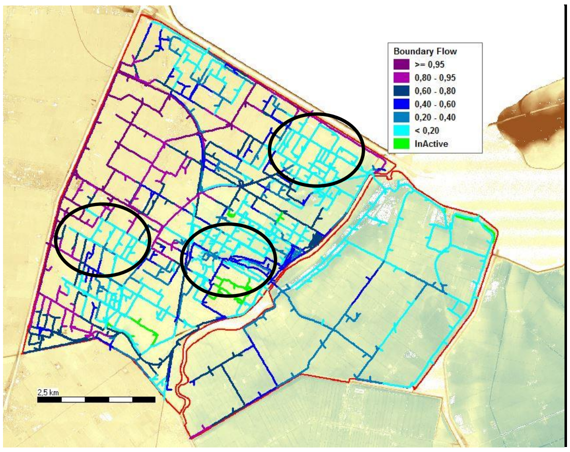


Figure 5.3. Chloride fraction analysis after 6 month in the fine schematization

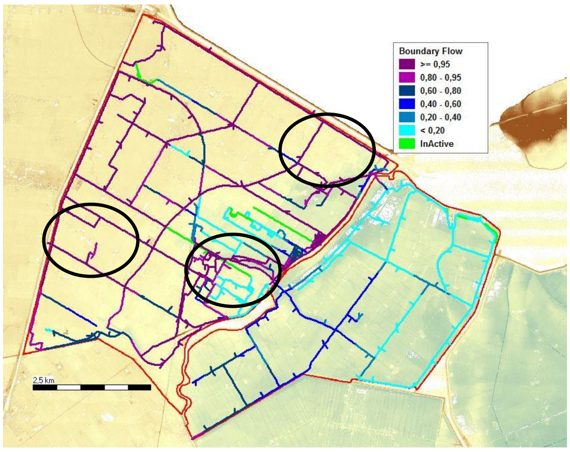


Figure 5.4. Chloride fraction analysis after 6 month in the coarse schematization

5.2 Scenario 1: simulation of salt transport before flushing by IJsselmeer water

As mentioned before, due to the location of the study area (near the Helsdeur at Den Helder); the sluice of the Helsdeur is open for ship movement especially during summer. Therefore, salinization of the polder waters at the water inlet points is caused by opening the Helsdeur for navigation in the Schermerboezem causing water with high salt content to leak into the canal. The problem is of larger importance during summer when there are more ships and there is not enough rainfall to dilute the added salt. Hence, during the dry periods when the amount of rainfall is too low to dilute the salt water, the Boezem is flushed (and thereby diluted) by IJsselmeer water 1 to 2 times per day only at low tide. The amount of flushing depends on the salt concentration in the Boezem which is monitored near the Helsdeur and near the Anna Paulownapolder.

In this scenario it is assumed that the study area is not flushed by IJsselmeer water during the dry period. As a result, the Chloride concentrations before the flushing event were used at the inlets to see how salinity transports and distributes in watercourses and how the amount of salinity changes over the time. The results of this scenario have been tabulated in table 5.2. Data in this table show the maximum amount of salinity which was observed at the end of each 3 month period in the study area. Also figures V-1 to V-8 in appendix V represent the spatial distribution of salinity for two different models when no flushing events happen.

	More detailed model Cl (mg/l)				Less detailed model Cl (mg/l)				Measurement in the field Cl (mg/l)
Location	After 3 month	After 6 month	After 9 month	After 12 month	After 3 month	After 6 month	After 9 month	After 12 month	
AP-Hoog	150-200	1050-1200	1050-1100	600-700	150-200	1050-1200	1050-1100	800-860	~1200
AP-Laag	150-200	750-900	1050-1000	400-450	150-200	900-1050	1100-1200	200-300	~1200
Oostpolder	150-200	300-350	250-300	<150	150-200	300-350	500-550	200-250	-

Table 5.2. Maximum observed salinity at the end of each 3 month period when no flushing happens in two different models

The detailed model estimated slightly lower salinity during the dry period compared to the coarse model. In fact, the maximum amount of Chloride (1200 mg/l) which was observed in both schematizations is the same and this number is in accordance with the measured value of Chloride in the study area during the dry period. Therefore, to see which schematization is more realistic and gives better results in the study area; three different segments were selected and simulations of chloride concentration compared to the measurement in the vicinity. The data in the field were taken by HHNK in the same year (2003) when the Chloride concentration were high and flushing had not happened yet. Here, it is assumed that these Chloride values were measured exactly before the flushing event and used for comparison. The results of this comparison represent in figures 5.5 to 5.7.

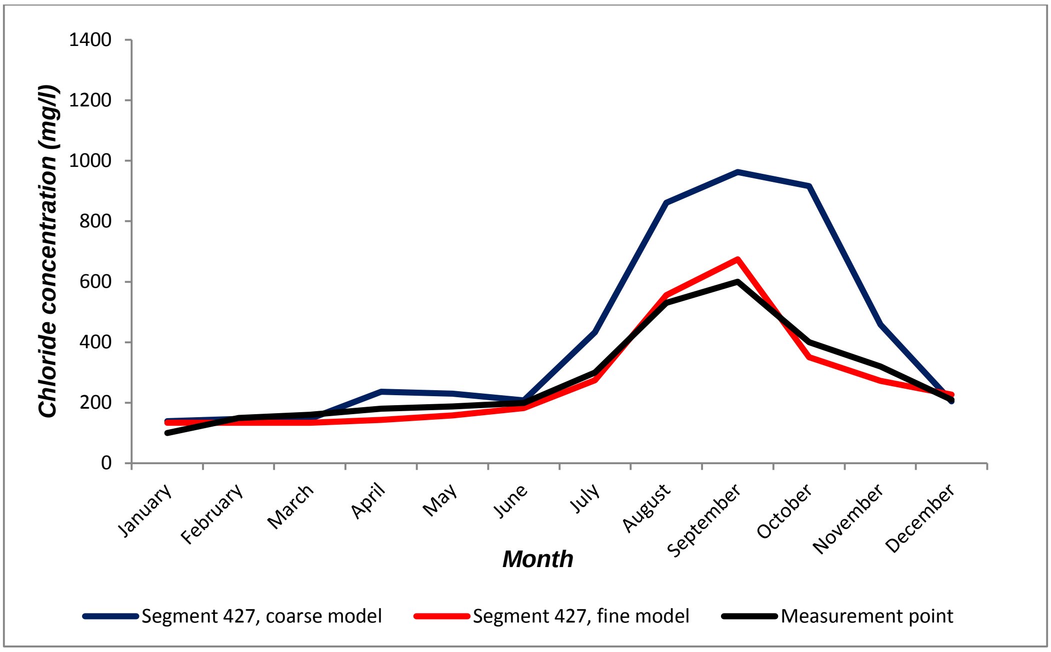


Figure 5.5. Comparison of segment 427 in two different models with the field data

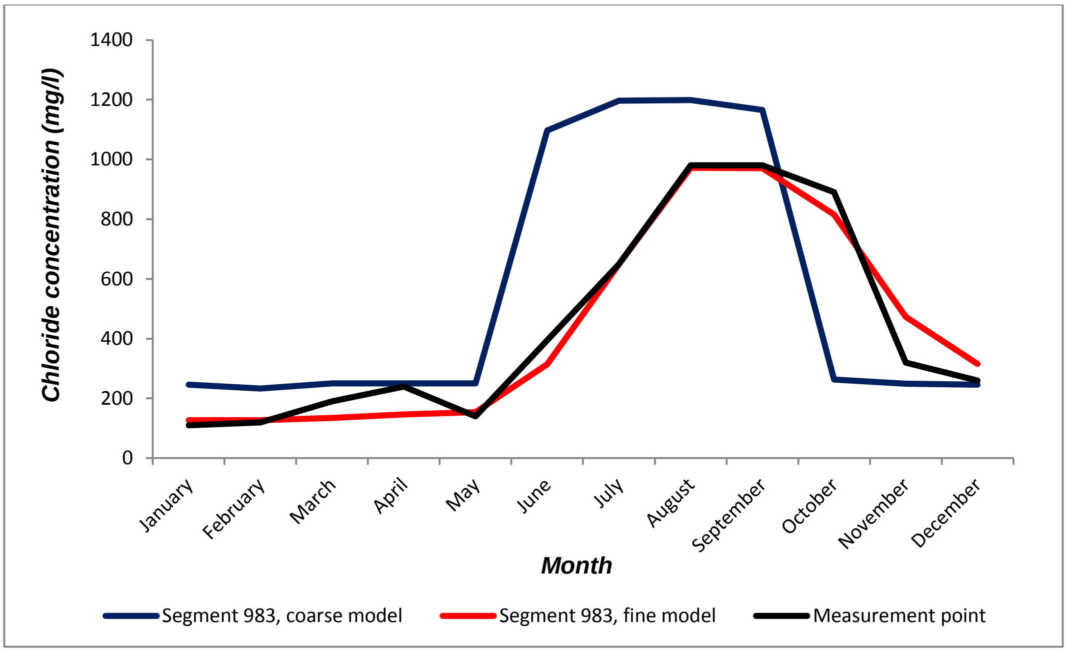


Figure 5.6. Comparison of segment 983 in two different models with the field data

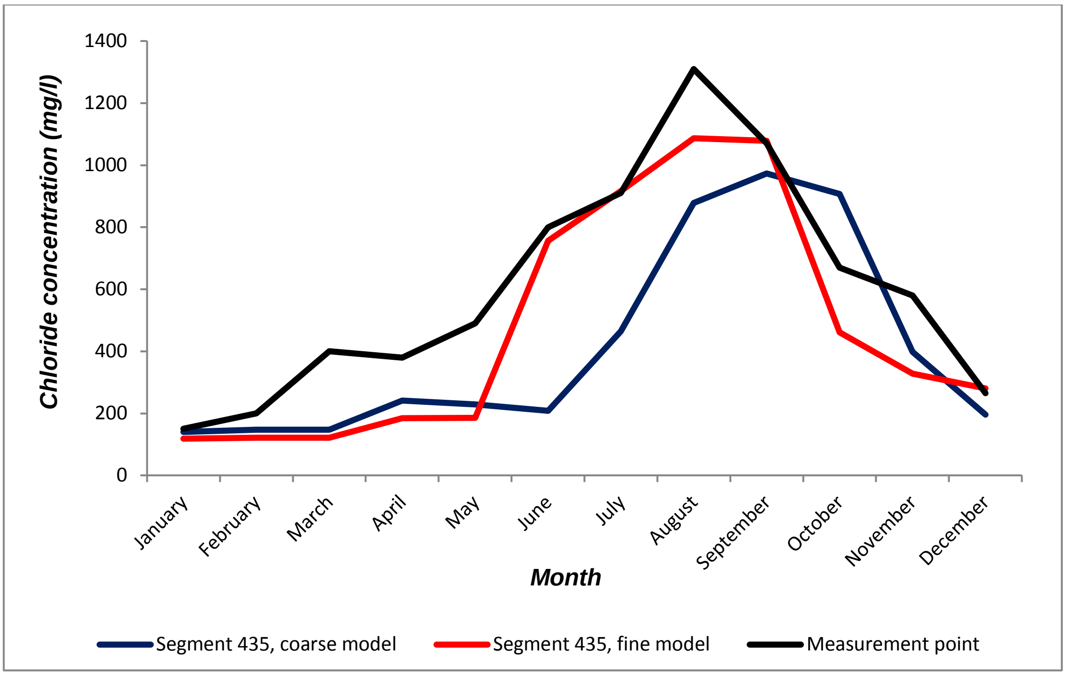


Figure 5.7. Comparison of segment 435 in two different models with the field data

Figures 5.5 and 5.6 show that the estimated values of Chloride in more detailed model correlated very well with the measured data in the study area. In both cases the predicted values by less detailed model show higher Chloride concentrations than observed. Also, figures 5.5 and 5.6 show that the less detailed model estimated longer period of salinity in the study area than more detailed model. As can be seen, the peak amount of Chloride in coarse schematization starts earlier and persists for longer time. In fact, as mentioned before in fine schematization; some parts of the saline water in main watercourses was drained by secondary channel which result in lower peak and shorter duration.

In figure 5.7, a higher Chloride concentration was simulated by fine model in segment 435 which is located in middle of Anna Paulowna Laag. However, this result is again closer to the observations. According to table 5.2 and presented figures in this section, it can be said that in coarse schematization, Chloride concentration reaches its highest value earlier and the salt water is transported faster through the area. This results in a longer duration of high salt content. Thus the role of the small ditches is to delay and regulate salinization by boundary flows.

Figure 5.8 shows an example map of chloride concentrations for scenario 1, wherein the predictions with the coarse (less detailed) schematization lead to higher Chloride concentrations than the predictions with the fine (more detailed) schematization at the end of 6 month. Also, the location of segments which compared in figures 5.5 to 5.7 are shown in figure 5.8.

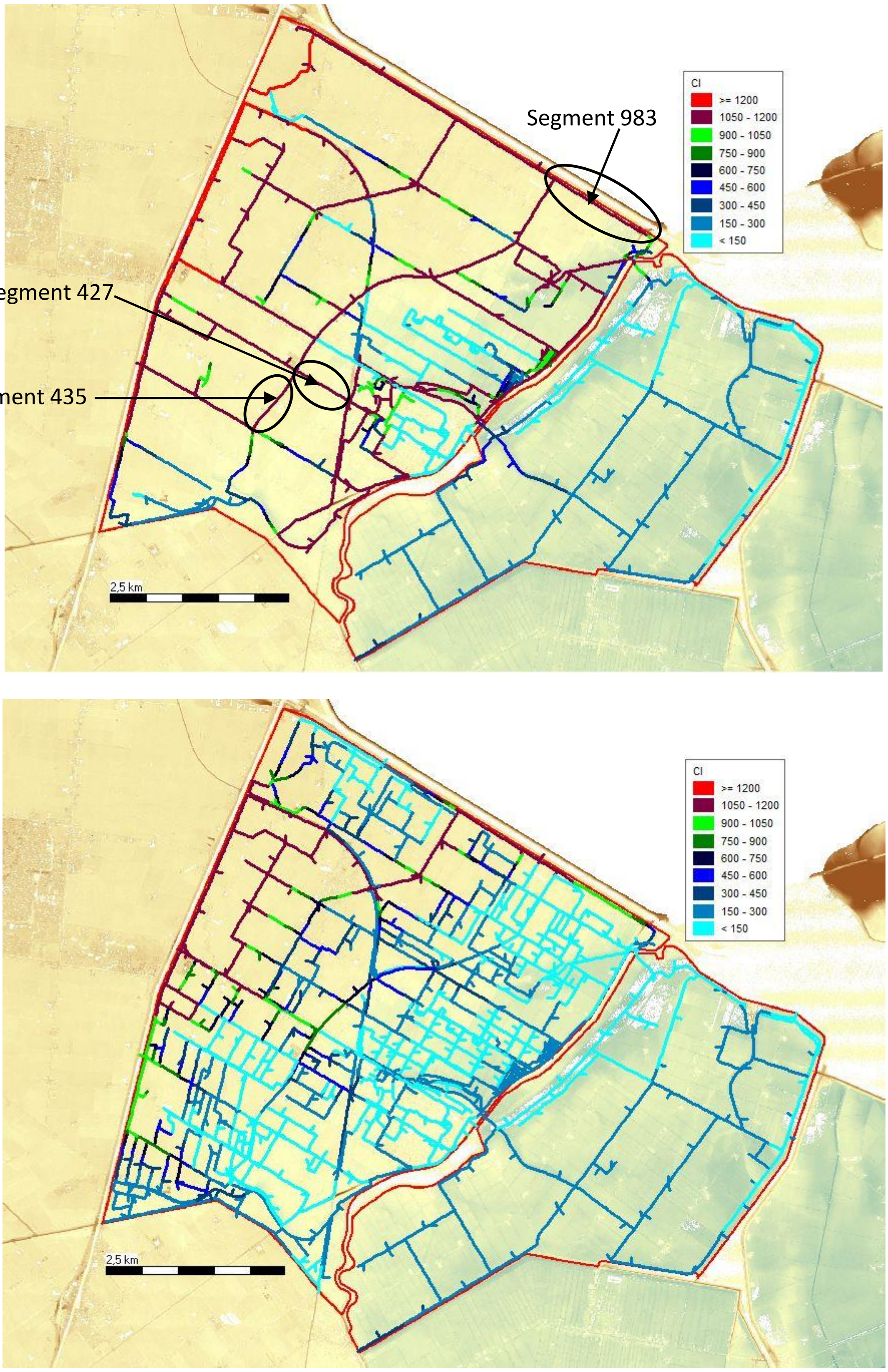


Figure 5.8. Example showing larger chloride concentrations for scenario 1 in the coarse model (upper) than in the fine model (bottom) at the end of 6 month

5.3 Scenario 2: simulation of salt transport after flushing by IJsselmeer water

As it mentioned in previous section (section 5.2), during the dry periods the Boezem is flushed by the IJsselmeer water 1 to 2 times per day in order to reduce the salt concentration. In this scenario, the chloride data (data after flushing event) were used at the inlets to see how salt water transfers through the watercourses in the fine and coarse models and how the amount of salinity changes over the time. The results of this scenario are shown in table 5.3. Also figures VI-1 to VI-8 in appendix VI represent the spatial distribution of salinity for two different models after the flushing events.

	More detailed model Cl (mg/l)				Less detailed model Cl (mg/l)				Measurement in the field Cl (mg/l)
Location	After 3 month	After 6 month	After 9 month	After 12 month	After 3 month	After 6 month	After 9 month	After 12 month	
AP-Hoog	250-300	400-403	250-300	150-200	250-300	400-403	250-300	200-250	~350
AP-Laag	150-200	300-350	350-400	150-200	250-300	400-500	>500	200-250	~415
Oostpolder	150-200	250-300	200-250	150-200	150-200	250-300	150-200	150-200	-

Table 5.3. Maximum observed salinity at the end of each 3 month period after flushing event in two different models

As can be seen, the prediction of Chloride concentration by the more detailed model is again lower than the less detailed model. In this scenario, the maximum amount of Chloride as estimated by two models is different. In order to see whether the fine model is again better in predicting the spatial distribution in Chloride concentration than the coarse model, three different segments (on primary watercourses) were selected and compared with the measurement from their vicinity. This time, the Chloride data which were measured in the field after the flushing event was used for comparison. The results of this comparison are represented in figures 5.9 to 5.11.

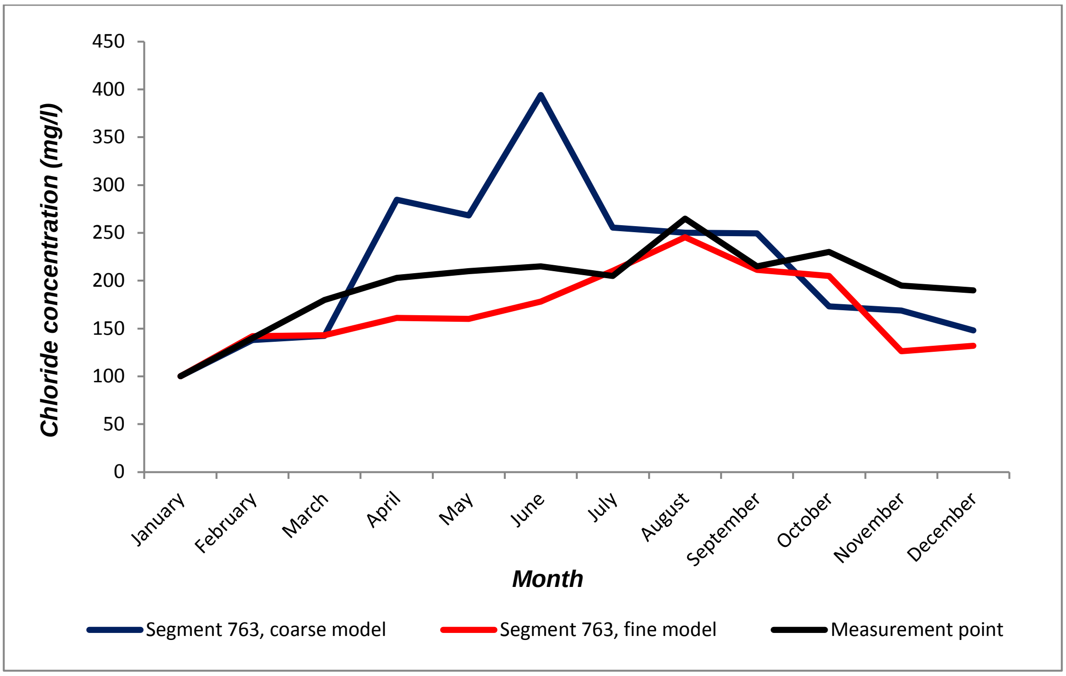


Figure 5.9. Comparison of segment 763 in two different models with the field data

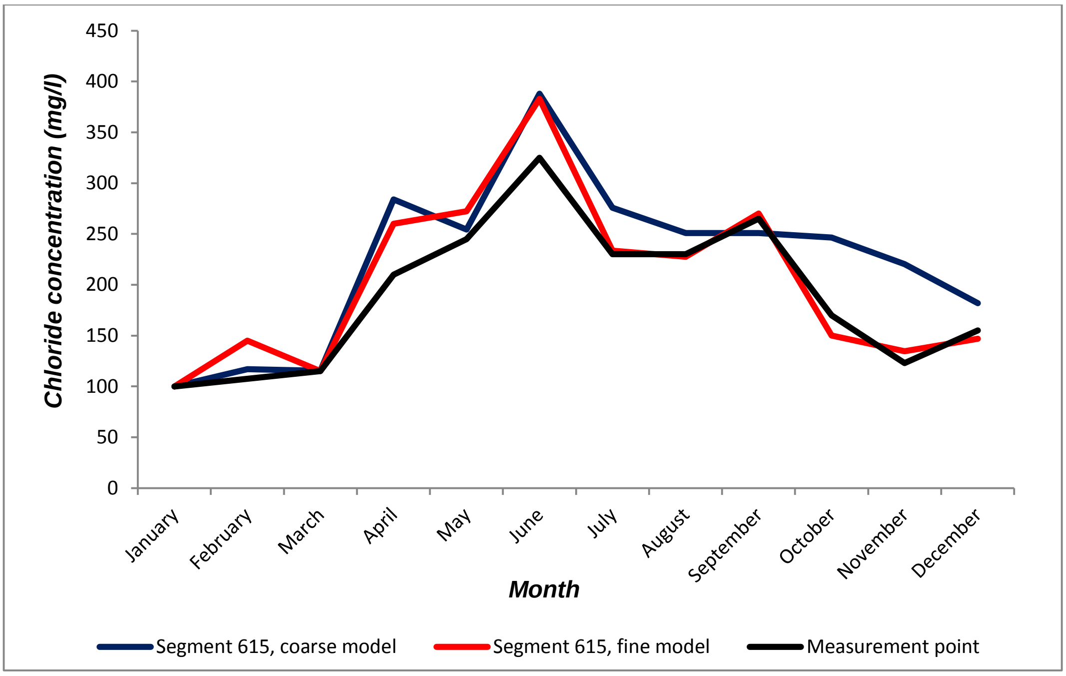


Figure 5.10. Comparison of segment 615 in two different models with the field data

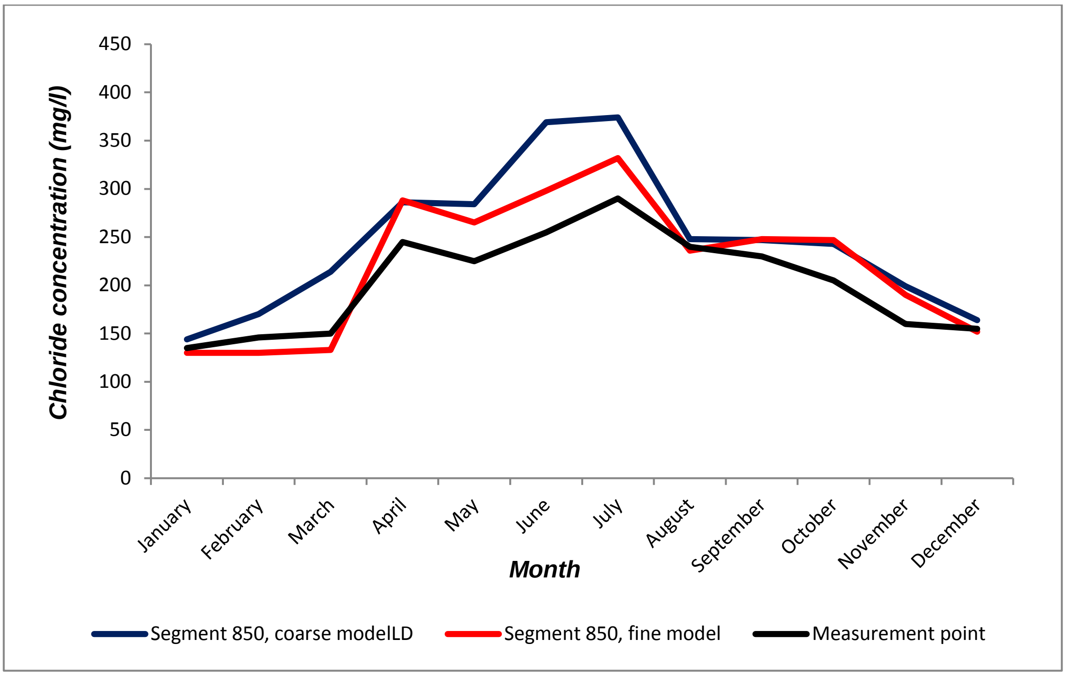


Figure 5.11. Comparison of segment 850 in two different models with the field data

These figures show that the results of the fine model better fit the field measurements than the results of the coarse model. Similarly as was the case in the first scenario, peak values of Chloride were reached earlier and lasted longer in the coarse schematization results. These results confirm again that the fine model is better suited in modelling the spatio-temporal development of Chloride concentration in these polders.

Figure 5.12 demonstrates also an example presentation of chloride concentrations for scenario 2, wherein the forecasts of the coarse (less detailed) schematization are larger than the predictions of the fine (more detailed) schematization at the end of 6 month. The location of segments which compared in figures 5.9 to 5.11 are shown in figure 5.12 as well.

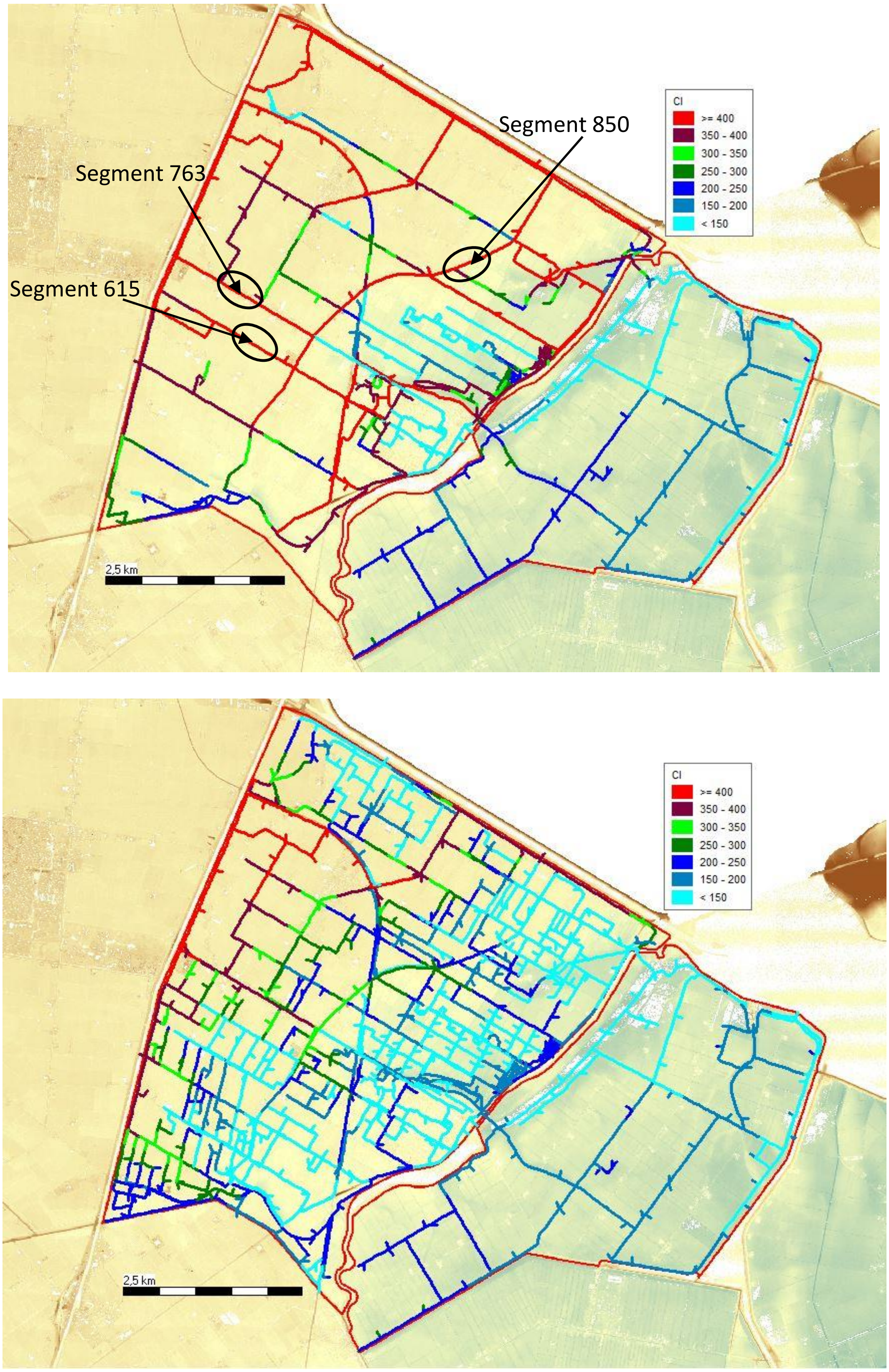


Figure 5.12. Example showing larger chloride concentrations for scenario 2 in the coarse model (upper) than in the fine model (bottom) at the end of 6 month

5.4 Summary results of comparing the two models

The results of two schematization were compared qualitatively and summarized in table 5.4.

Model	Salinity prediction	Comments	Field measurement
More detailed model	• Less saline water in the study area (lower Chloride concentration)	• Salinity transports and distributes in watercourses slower • Shorter residence time of Chloride in main channels due to dilution by secondary channels • Concentration peak reached later	• High correlation with the filed measurements before and after flushing event • Predictions closer to the measured data in the study area
Less detailed model	• More saline water in the study area (higher Chloride concentration)	• Salinity transports and distributes in watercourses faster • Longer residence time of Chloride in main channels due to lack of secondary channels in the model • Concentration peak reached sooner	• Low correlation with the filed measurements before and after flushing event • Predictions overestimate measured data in the study area most of the time

Table 5.4. Comparison of two different schematization (fine and coarse) based on the gained results

Generally, the information from the table above and from outcomes of previous sections show that the fine schematization provides more realistic information about the Chloride concentration and salinity transport in the Anna Paulownapolder. The dilution and delay by the small watercourses is absolutely necessary to realistically predict the spatio-temporal variation of Chloride concentration in the study area.

6 Discussion

6.1 General vision

In this study, SOBEK which has been widely used in the Netherlands, was implemented to determine the salinity transport in the Anna Paulownapolder in the province North Holland. In order to see how the details of a model can affect the results; SOBEK was implemented as a fine (more detailed) model which schematized all main and small watercourses, and as a coarse (less detailed) model which schematized only the main watercourses. Results of the study showed that more detailed model was better applicable to this study area and resulting in better results.

Several authors compared different water quality models at more and less detailed scale (e.g. Arnold et al., 2011; Tsakiris and Alexakis, 2012). However, in these studies it is not generally concluded that more detailed models are more accurate than less detailed models. According to Tsakiris and Alexakis (2012), the simpler the model is the more difficult to understand. Consequently, less detailed models could be used for just initial characterization of a surface water quality. Also, they argued when more reliable data are available, a more detailed and improved model could be better.

In fact, there is trade-off between data requirements, resolution, scope, objective, and computing time. For instance, in this study more data were needed for the more detailed model while the time of processing and computation was so longer. So, to reduce the processing time, a less detailed model can be also used as an alternative and effective model for a broad understanding of salinity transport. In addition, providing spatial and temporal simulation through a less detailed model is appropriate when due to lack of existing scientific knowledge and data, good results cannot be produced with confidence by a more detailed model (Arnold et al., 2011).

Needless to say, that the crucial issue in choosing a model is the availability of the required data for that specific model. However, it should not been forgotten that complicated and more detailed models do not necessarily result in more accurate understanding of the processes and more reliable outcomes (Arnold et al., 2011; Tsakiris and Alexakis, 2012).

In addition, in this case study only one hydrodynamic model (SOBEK) was used to answer the research question. The question is whether other highly detailed models could provide the same or even better results. For instance MIKE models are integrated hydrological models (MIKE package is developed and maintained by DHI an international research and consulting organization) This model suite is known as a highly detailed due and well suited to the complex systems (Tsakiris and Alexakis, 2012; Anastasiadis et al., 2013). Different version of this software (e.g. MIKE 11) have been used to model water quality at various watersheds such as Northern India and England (Crabtree et al., 1996; Kazmi and Hansen, 1997). SWAT (Soil and Water Assessment Tool) is another example of a model suite with detailed water quality capabilities. Due to the level of detail incorporated into this model it has large input requirements. SWAT is maintained by the United States Department of Agriculture but is widely used by an international community of researchers (e.g. Waidler et al., 2009; Arnold et al., 2011; Neitsch et al., 2011).

6.2 Uncertainty in validation of the model

One of the uncertainties of the present study arose from the evaluation of the models. As was shown in section 4.1.1 and 4.1.2, the water levels in some part of the study area were higher than they should, be especially during the wet period. This issue has been ignored in this study since, salinity is a major problem during the dry period. However, this problem can cause inundation as was discussed previously by Nelen and schuurmans (2012). This problem was identified to occur in catchment areas with small drainage intensities and low pumping capacity.

The current situation of the water system in the Anna Paulownapolder does not correspond to the desired situation. This requires some changes to the required system. The Water Board is committed to the highest possible level of management in such areas, while the catchment areas with different surface water level are still small and difficult to manage (Nelen and schuurmans, 2012). Also, it is argued by Nelen and schuurmans (2012) that, the real dimension of some watercourses are unknown. Furthermore, there are several structures (e.g. culverts) which do not meet the criteria of the Water Board. However, these do not lead to flooding.

Therefore, applying all these corrections (which should be provided by HHNK) may lead to the better performance of the implemented models. The problem of (semi) dry watercourses as shown in part 4 of this study can be solved by implementing the accurate dimension of channels and cross sections as well.

Since, these issues mainly pertain to the wet period, they it do not significantly influence the results of this study. However, if these models are to be used for other applications (e.g. flood risk analysis) they may be important.

6.3 Uncertainty in applied data

No hydrodynamic and water quality model can precisely and correctly reproduce historical outcomes. Each model is an approximate solution of a proximate demonstration of the reality (Fleenor and Bombardelli, 2013).

In order to simulate the salinity transport in the study area, the Chloride concentration values have been applied at the location of inlets in both models. In fact, those data are taken from the closest measurement location (De Kooy) to the inlets (inlets 1 and 2) at the Schermerboezem. This adds to the uncertainty in the predictions. Actually, De Kooy station is closer to the Helsdeur than inlets of the Anna Paulownapolder. As a result, the data at this measurement point could be a bit higher than the Chloride loads at the location of inlets. Although the results of this study compared well to the field measurements, this issue can lead to a higher prediction of salinity in the area. This uncertainty can be reduced by incorporating daily or weekly observation of Chloride concentration at the exact location of inlets (de Louw et al., 2011).

Furthermore, as mentioned before, there is brackish open water in the middle of the polder that has not been taken into account in this study. Since, at high tide, the salt water intrusion happens from sea towards this area; saline seepage at this part of the polder will sum up to the rest of saline seepage (from catchment areas upstream) which is insignificant as evaluated in this study (fraction analysis). Ignoring this part of the system can lead to some underestimation and uncertainties in the Chloride concentration at this part of the study area. However, according to the location of inlets in the Schermerboezem; Den Helder sluice is the most important threat for the salinity of the Anna Paulownapolder especially during the dry period. Therefore, more accurate study of the seepage does not change the main origin of the salt in the study area, but can improve the results of salinity in Anna Paulowna Laag. So, to improve the reliability of this model, one should incorporate salt water upconing by groundwater discharge and boil seepage (de Vos et al., 2002; de Louw et al., 2010; de Louw et al., 2013).

7 Conclusions

In this Master thesis I studied and modelled the transport of Chloride in Anna Paulownapolder. A, SOBEK hydrodynamic model was used in order to answer the research question: *How do details of a SOBEK model affect the simulation of the salinity transport especially during the dry period in the Anna Paulownapolder?*

The objective of the study was to see if more detailed and accurate model can provide more realistic and reliable results than less detailed model. Therefore, two different models were implemented in the study area: one model that calculated the water flow in all primary and secondary watercourses (fine schematization), and one model calculating the water flow in only primary watercourses (coarse schematization).

Beforehand, the origin of the salt in the study area was identified by fraction analysis. The results of both models showed that, salt intrusion through boundary flow is the most dominant origin of the salinity in Anna Paulownapolder. After that, the spatio-temporal distribution of Chloride concentration was simulated under two scenarios with the two different models for the year 2003.

In the first scenario, the data of Chloride concentration before a flushing event were used at the inlets. Both model showed strong variation as a function of time. During the dry period in the summer, when there is no dilution of the saline and brackish water, the maximum Chloride concentration increased to 1100 (mg/l) in the fine model and 1200 (mg/l) in the coarse model. Predictions of the fine model compared better to the field measurements than those of the coarse model.

In the second scenario, which expresses the current condition of the study area, the Chloride concentration values after the flushing event were applied at the location of inlets. In this scenario, both models showed strong variation as a function of time as well. During the dry period, when there is no rainfall to dilute the saline water, the maximum Chloride concentration increased to around 400 (mg/l) in fine model and more than 500 (mg/l) in the coarse model. To validate the models, both schematizations were compared with the field measurements. Again, the fine model resulted in the better predictions over the whole period than the coarse model.

It was observed that the Chloride peaks happened later in the fine model than in the coarse model. Moreover, the removal time of saline water was longer in the coarse model than in the fine model under both scenarios. This situation arose due to the fact that salt in the main channels was diluted by the secondary channels in the fine schematization. Hence, the simulation of salt transport in the Anna PaulownaPolder is affected by the level of detail incorporated in the model and a more detailed model indeed results in more reliable outcomes.

8 Recommendations

In the current situation of the Anna Paulownapolder, flushing of the system by IJsselmeer water during the dry period is the most effective way to reduce the salinity. Therefore, this study focused on two different scenarios which are: schematization of salt transport through watercourses before and after flushing the polder by IJsselmeer. However, this strategy can lead to some adverse consequences for the ecosystem of the polder (Augustijn et al., 2010). However, locking the inlets during the dry period can fail the system as water level will drop in the channels very fast (Hermans, 2014).

In fact, the schermerboezem suffers from salt intrusion through ships passing the sluices and also the salt seepage from the surrounding agricultural fields. Hence, applying some other scenarios such as research on the distribution and origin of the salt in the main channel (Boezem) of the polder can improve and validate the results of this study. Also, it can be an effective way to reduce flushing the polder by the IJsselmeer water. As it is argued in previous studies (e.g. Van Overloop et al., 2008; Augustijn et al., 2010), the dynamic control of the drainage sluice and inlets based on real-time chloride concentrations can be a promising strategy to anticipate the Chloride loads in the study area.

Based on the experiences gained in this research the following additional recommendations are made:

- It is strongly recommended to use more detailed model to simulate water quality if it is possible and there is sufficient data available;
- Applying the correct dimensions of watercourses and structures in order to have a more valid model (which was also discussed in section 6.2);
- More investigation into the seepage phenomena in the study area as was discussed in section 6.3;
- Implementing a scenario in which the inlets and sluice will be controlled based on real-time observations of Chloride concentrations, as was mentioned above;
- Study on the relocating the main inlet (Westeinde) of the study area in order to reduce salt intrusion through the boundary flows. However, this strategy may be too costly.

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10 Appendix

Appendix I: Equations

Appendix II: Simulation of salt fraction in the watercourses from boundary flow

Appendix III: Simulation of salt fraction in the watercourses from precipitation

Appendix IV: Simulation of salt fraction in the watercourses from seepage

Appendix V: Simulation of salt transport before flushing by IJsselmeer water

Appendix VI: Simulation of salt transport after flushing by IJsselmeer water

Appendix I: Equations

Continuity equation and momentum equation

SOBEK is a hydrodynamic software package for integral water solutions. In the calculations the De Saint- Venant equations are solved: the continuity equation and the momentum equation as follows:

Continuity equation:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial (uh)}{\partial x} = 0$$

Momentum equation:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + g\frac{\partial \zeta}{\partial x} + g\frac{u|u|}{C^2 h} = 0$$

Where:

u = Velocity [m/s]

ζ = Water level above reference level [m]

C = Chezy friction coefficient [$m^{1/2}/s$]

h = Total water depth ($h = \zeta + d$) [m]

d = Depth below reference level [m]

Strickler formula

$$C = k_s R^{1/6} = 25(R/k_n)^{1/6}$$

Where:

C = Chezy coefficient [$m^{1/2}/s$]

R = Hydraulic radius [m]

k_s = Strickler roughness coefficient [$m^{1/3}/s$]

Ernst formula

$$q = \frac{dH}{\gamma}$$

Where:

q = Drainage flux [m/d]

dH = Difference between groundwater level and drainage basis [m]

γ = Drainage resistance [d]

Salinity formula

$$\frac{\partial A_t\, C}{\partial t} + \frac{\partial}{\partial x}\left(QC - A_f D \frac{\partial C}{\partial x}\right) - S_s$$

Where:
C is the concentration of Chloride (kg/m^3), D the dispersion coefficient (m^2/s), S_s is a source term (kg/ms), Q the discharge (m/s), A_t refers to total cross-sectional area (m^2) and A_f the flow area (m^2).

Appendix II: Simulation of salt fraction in the watercourses from boundary flow

Figures II-1 to II-4: fraction analysis based on the fine model

Figures II-5 to II-8: fraction analysis based on the coarse model

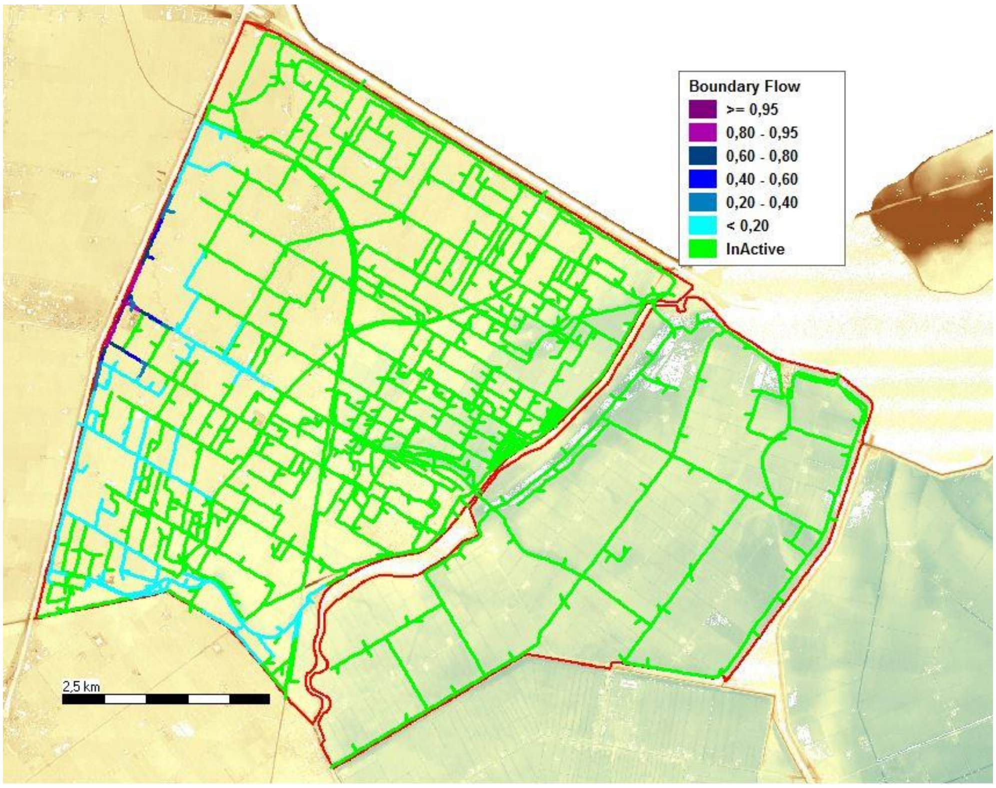

Figure II-1. Salt fraction in the watercourses from boundary flow at the end of 3 month in fine model

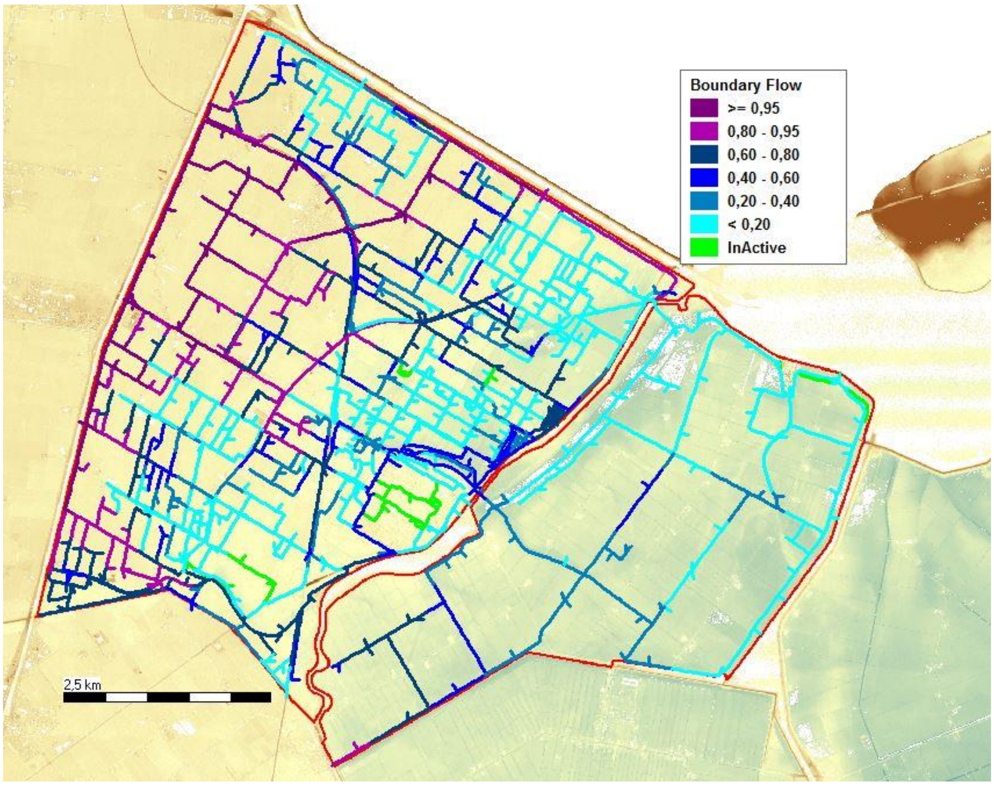

Figure II-2. Salt fraction in the watercourses from boundary flow at the end of 6 month in fine model

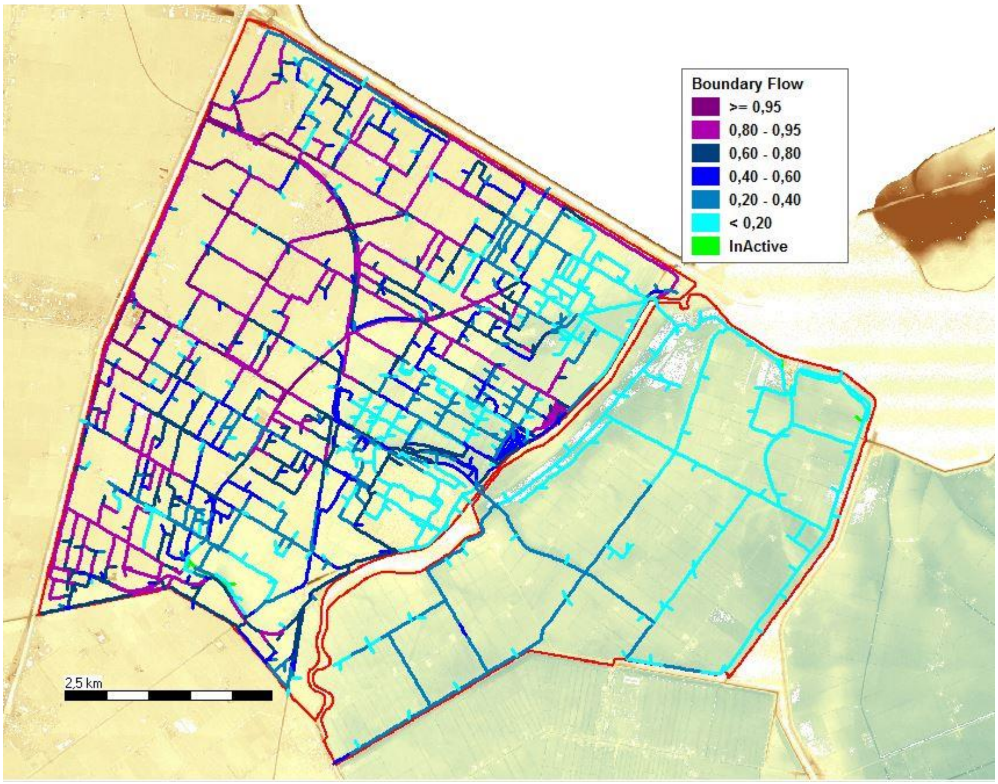

Figure II-3. Salt fraction in the watercourses from boundary flow at the end of 9 month in fine model

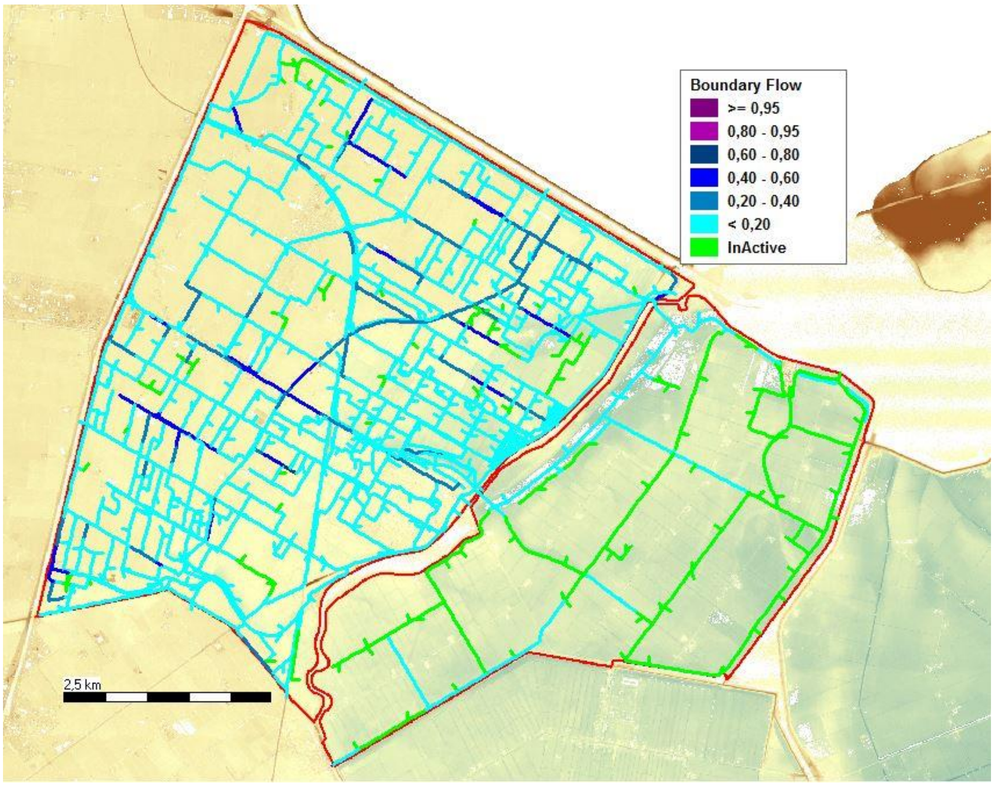

Figure II-4. Salt fraction in the watercourses from boundary flow at the end of 12 month in fine model

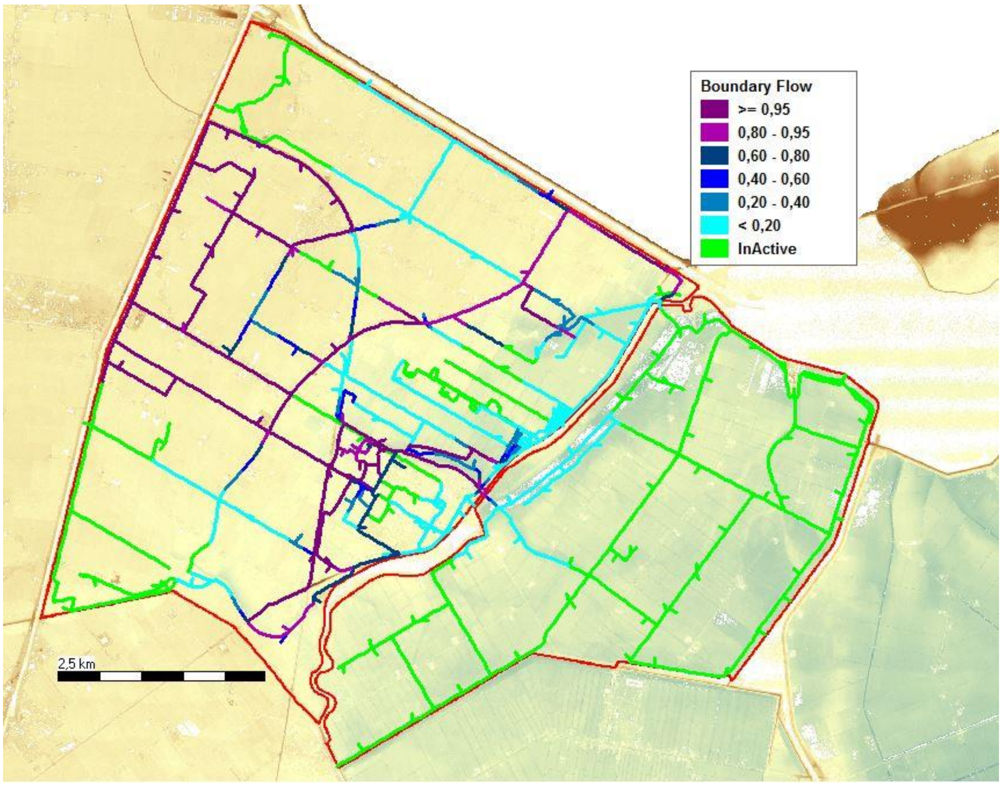

Figure II-5. Salt fraction in the watercourses from boundary flow at the end of 3 month in coarse model

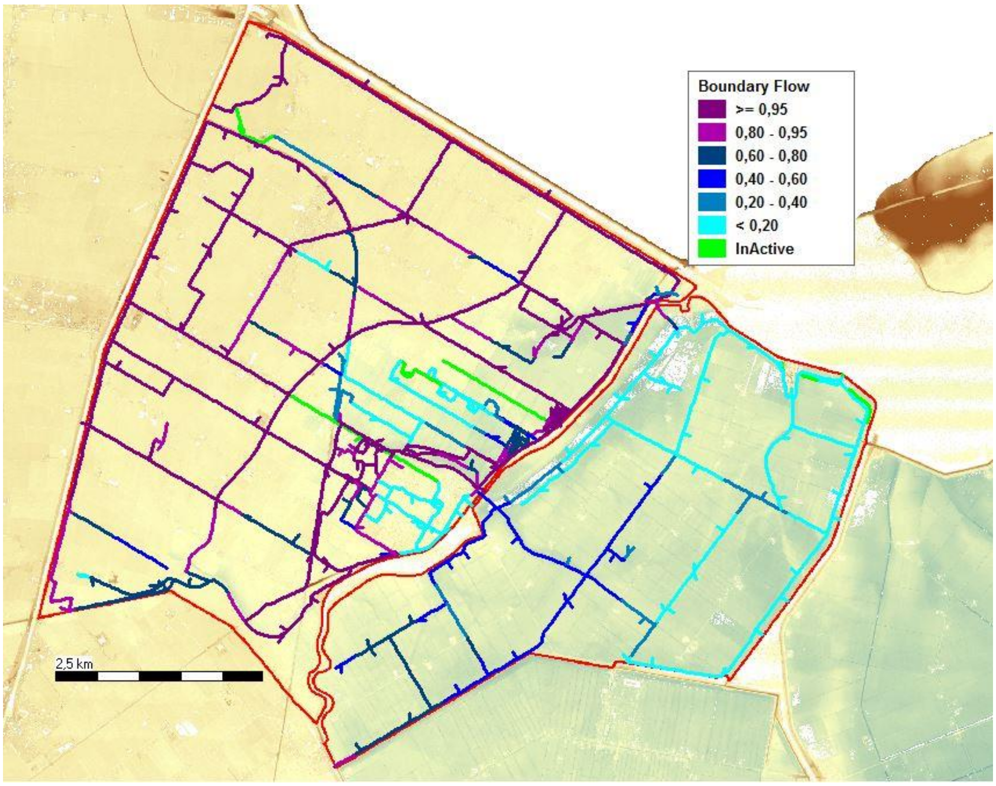

Figure II-6. Salt fraction in the watercourses from boundary flow at the end of 6 month in coarse model

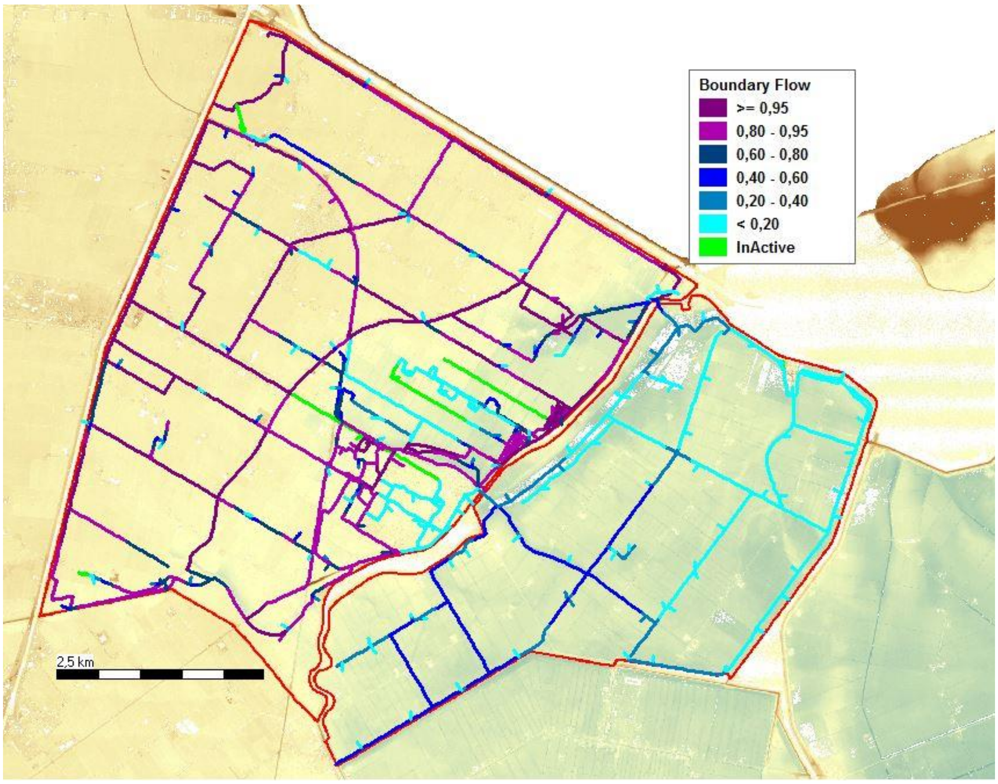

Figure II-7. Salt fraction in the watercourses from boundary flow at the end of 9 month in coarse model

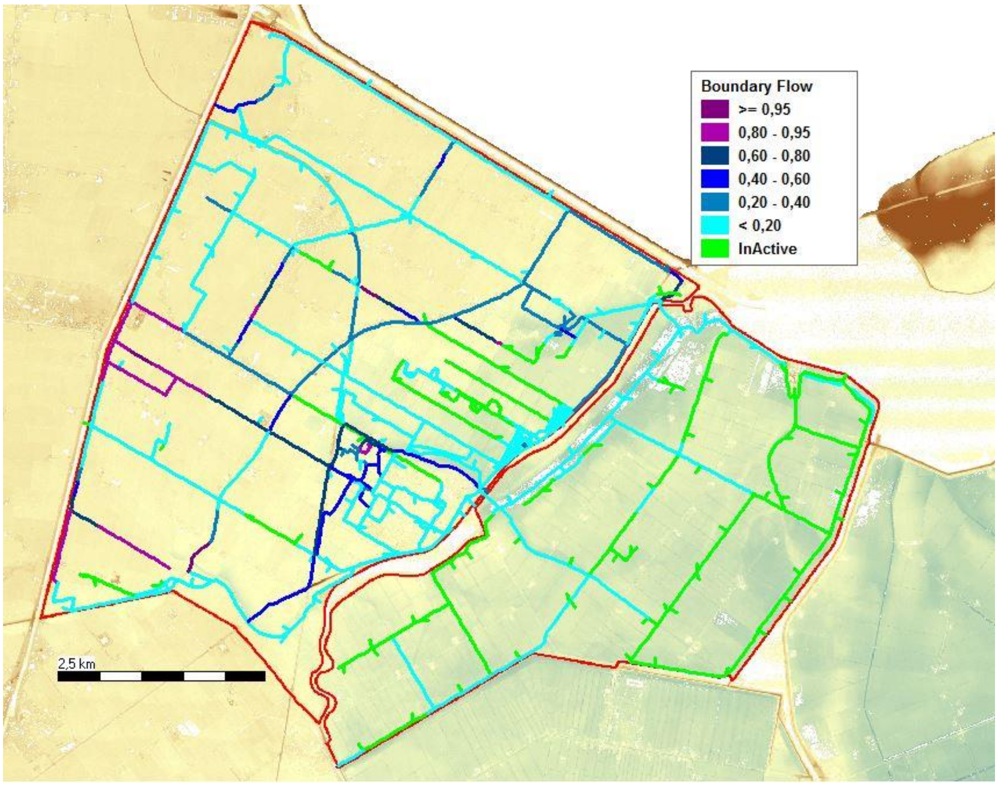

Figure II-8. Salt fraction in the watercourses from boundary flow at the end of 12 month in coarse model

Appendix III: Simulation of salt fraction in the watercourses from precipitation

Figures III-1 to III-4: fraction analysis based on the fine model

Figures III-5 to III-8: fraction analysis based on the coarse model

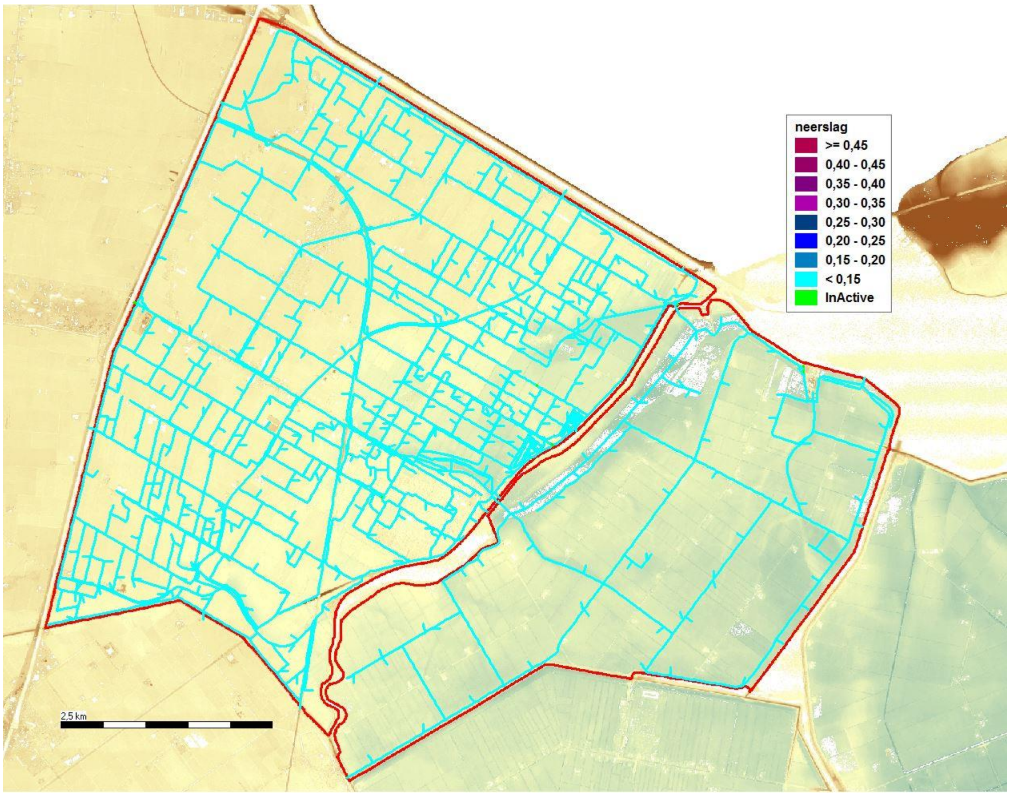

Figure III-1. Salt fraction in the watercourses from precipitation at the end of 3 month in fine model

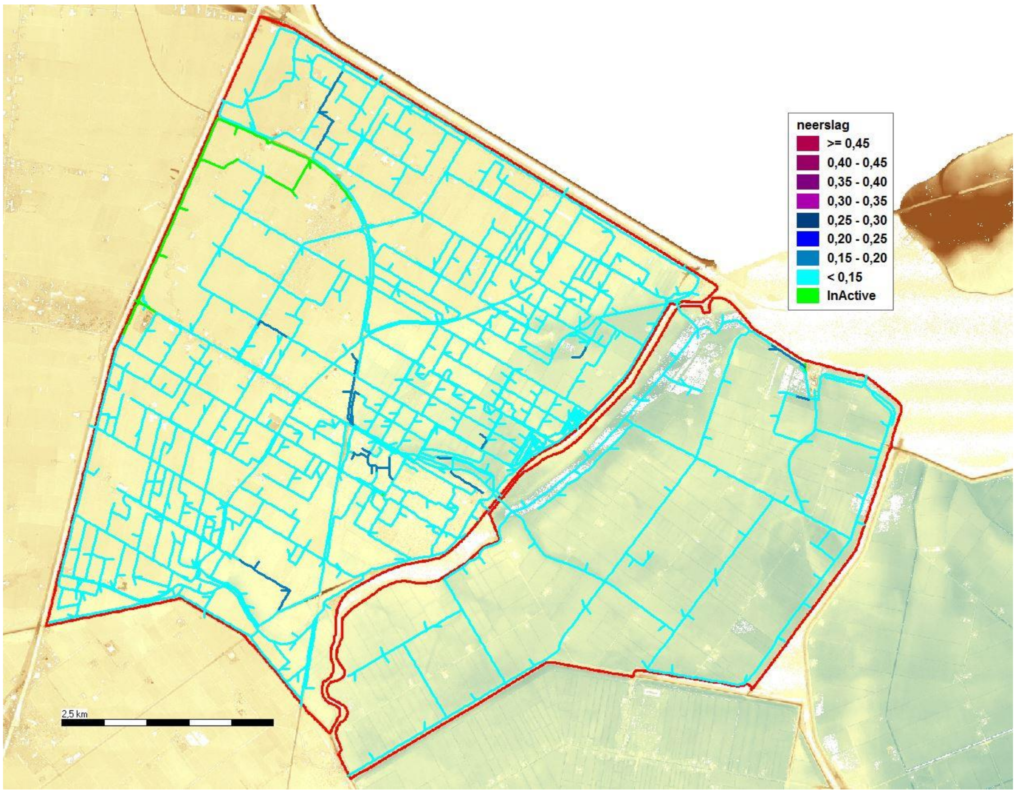

Figure III-2. Salt fraction in the watercourses from precipitation at the end of 6 month in fine model

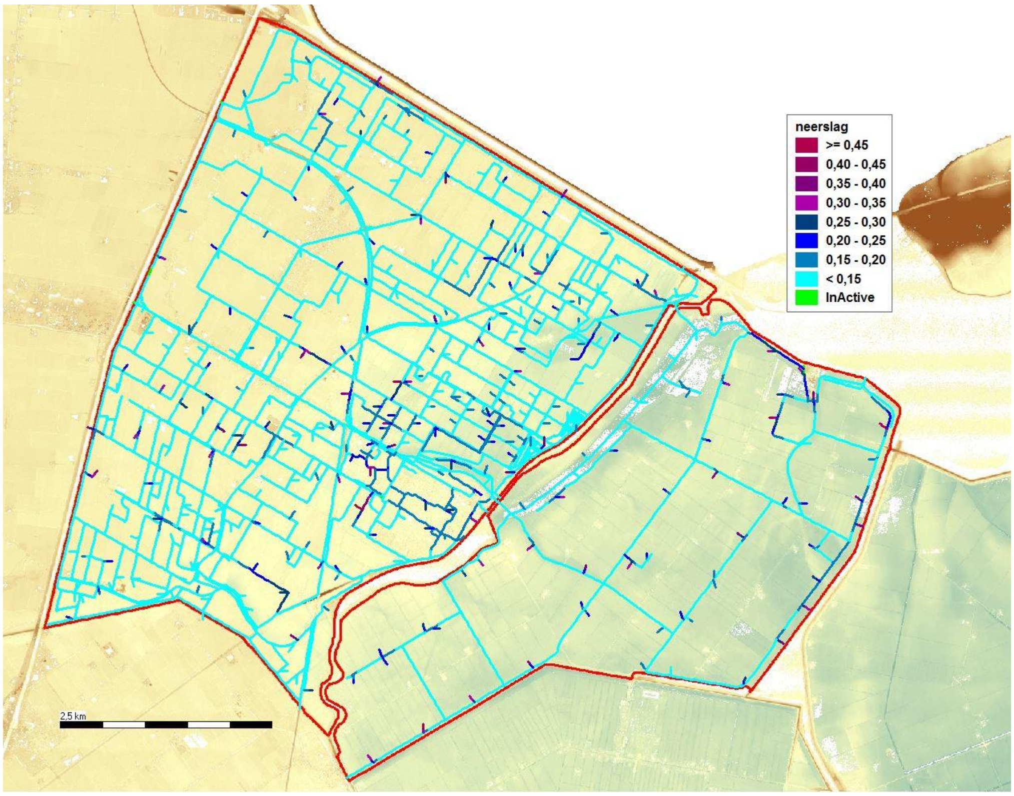

Figure III-3. Salt fraction in the watercourses from precipitation at the end of 9 month in fine model

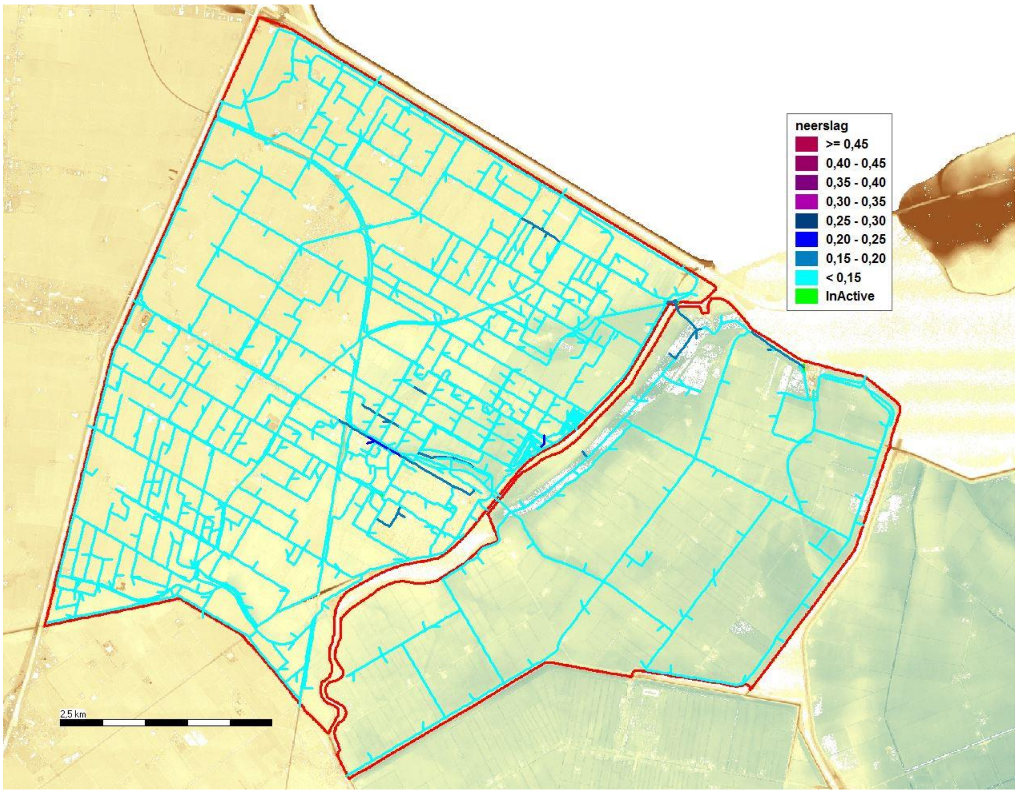

Figure III-4. Salt fraction in the watercourses from precipitation at the end of 12 month in fine model

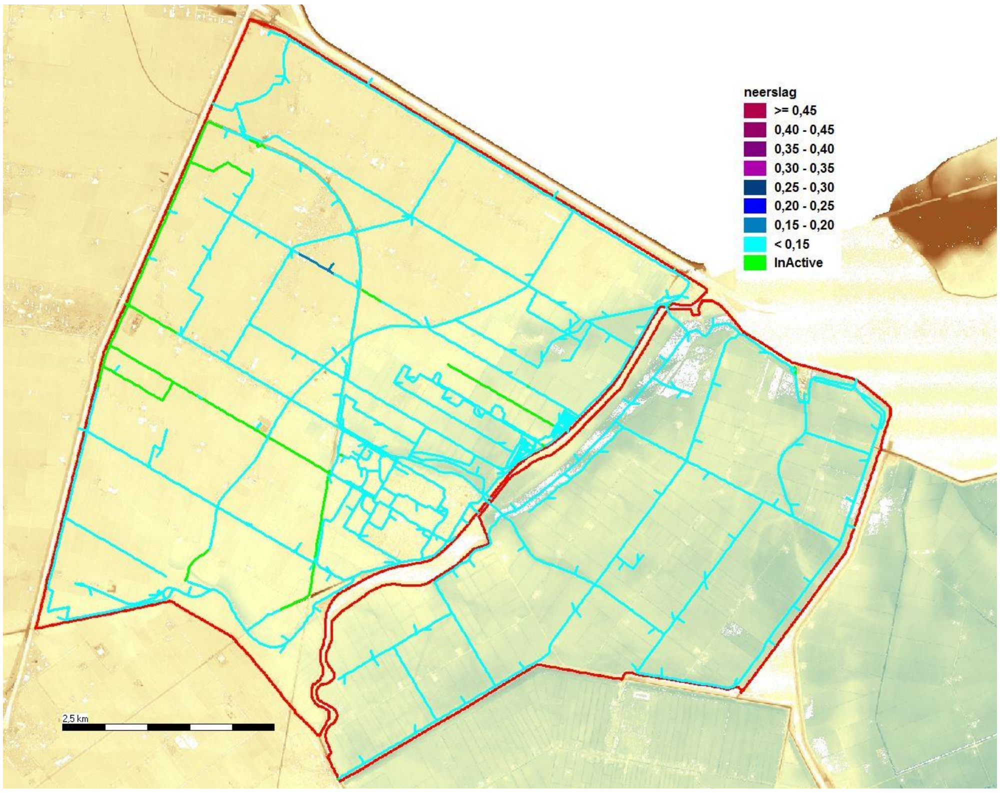

Figure III-5. Salt fraction in the watercourses from precipitation at the end of 3 month in coarse model

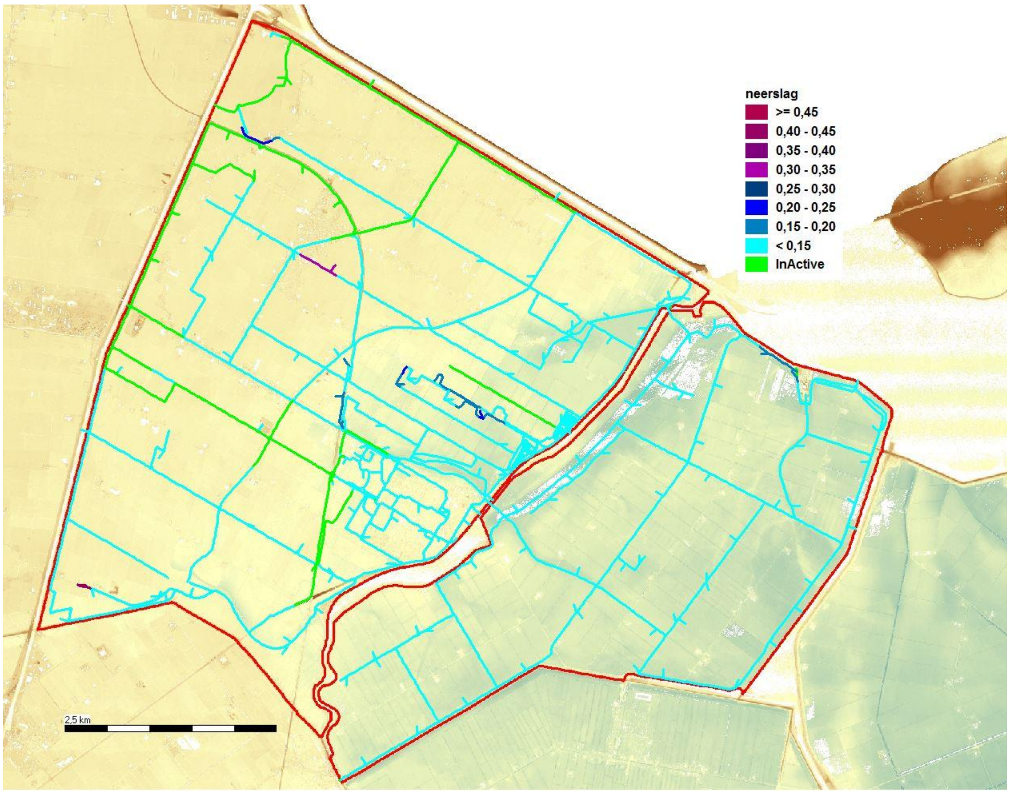

Figure III-6. Salt fraction in the watercourses from precipitation at the end of 6 month in coarse model

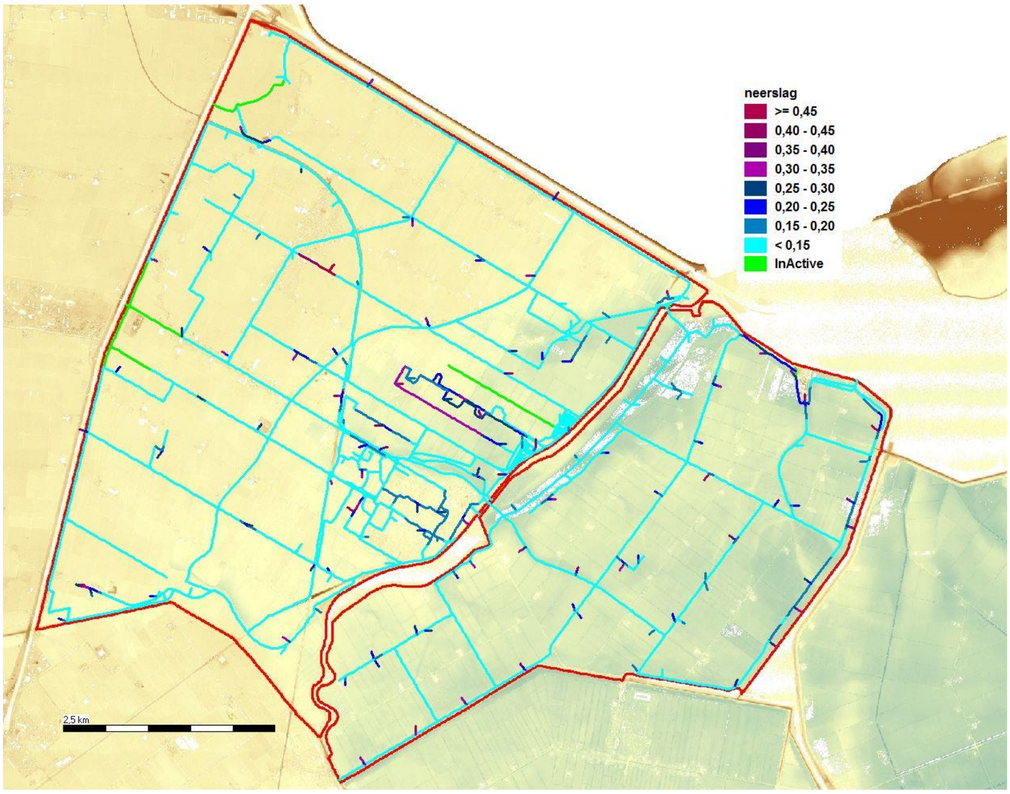

Figure III-7. Salt fraction in the watercourses from precipitation at the end of 9 month in coarse model

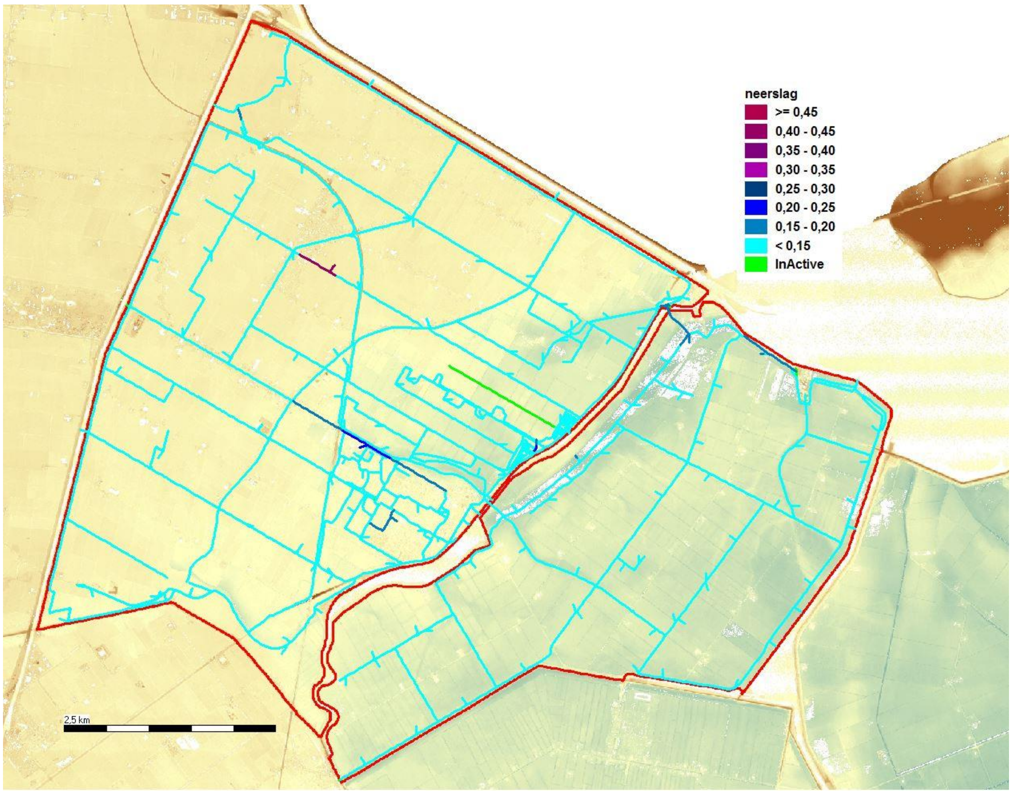

Figure III-8. Salt fraction in the watercourses from precipitation at the end of 12 month in coarse model

Appendix IV: Simulation of salt fraction in the watercourses from seepage

Figures IV-1 to IV-4: fraction analysis based on the fine model

Figures IV-5 to IV-8: fraction analysis based on the coarse model

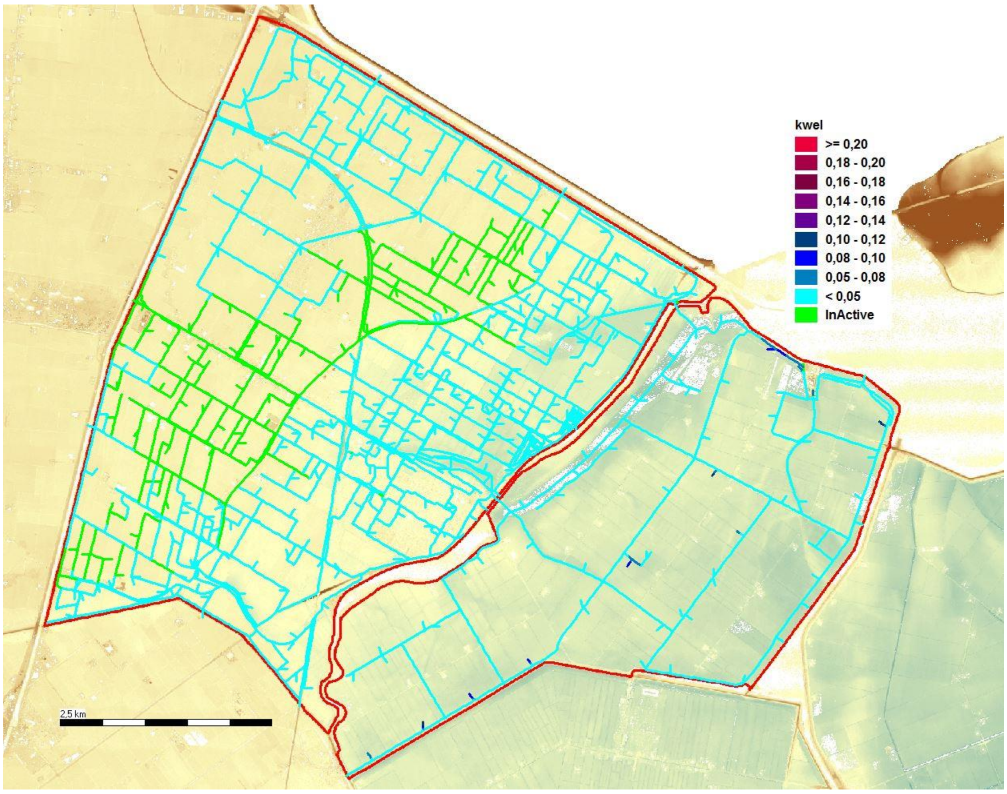

Figure IV-1. Salt fraction in the watercourses from seepage at the end of 3 month in fine model

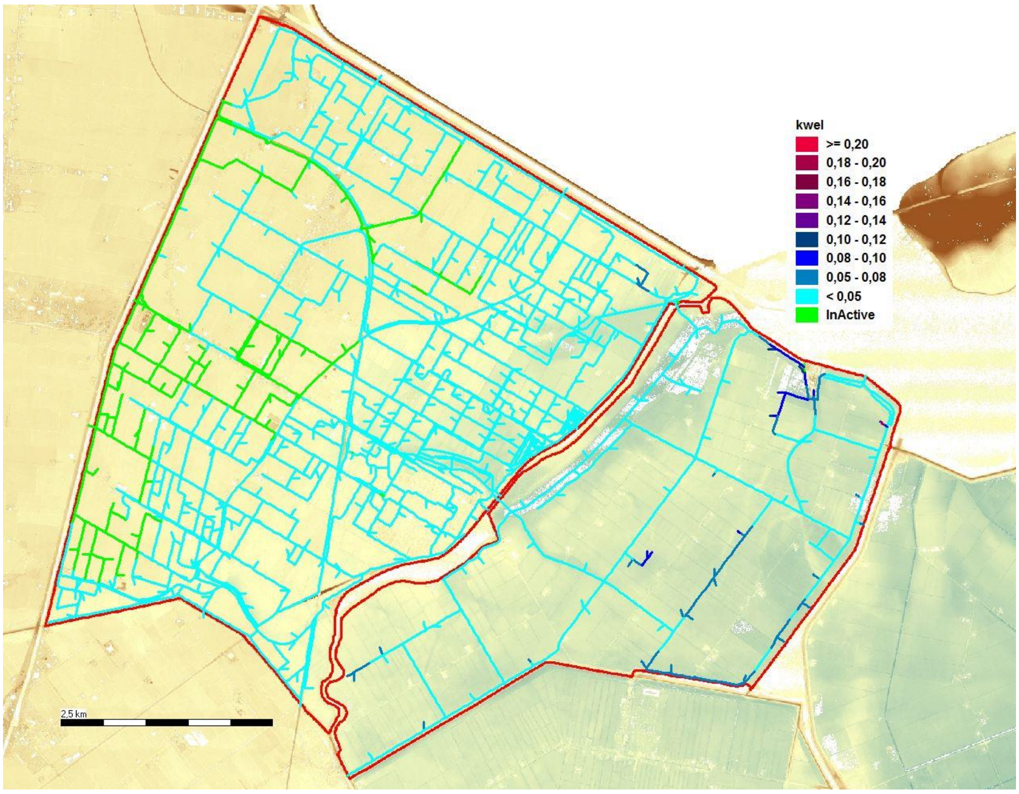

Figure IV-2. Salt fraction in the watercourses from seepage at the end of 6 month in fine model

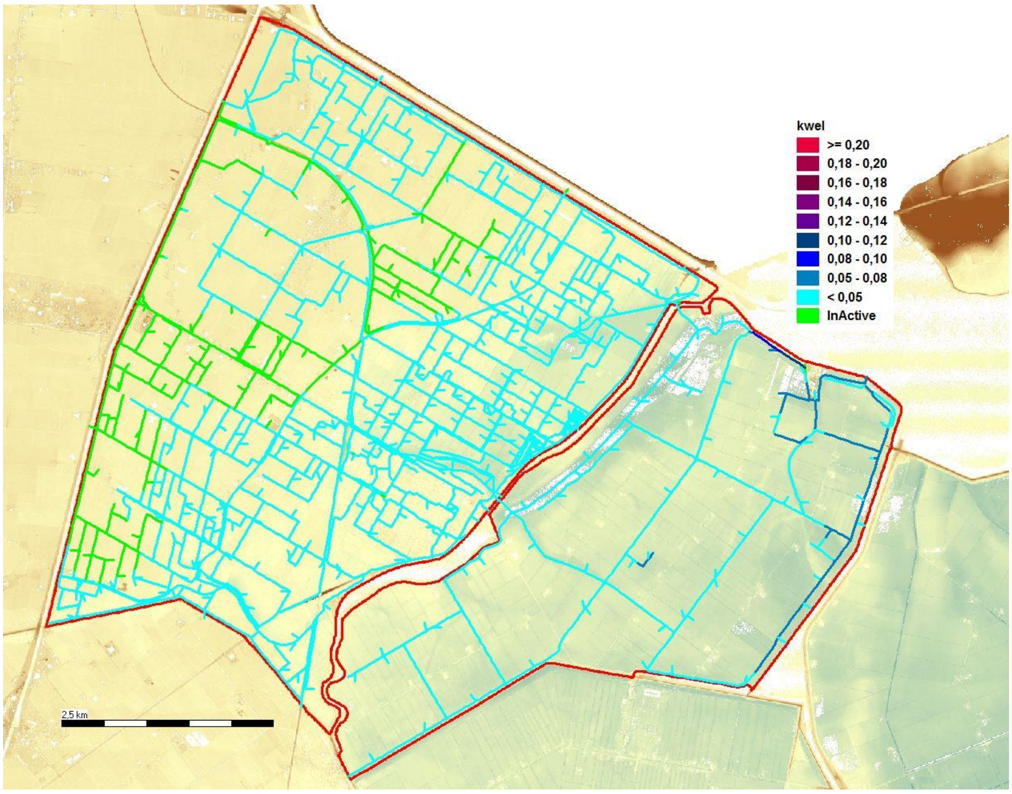

Figure IV-3. Salt fraction in the watercourses from seepage at the end of 9 month in fine model

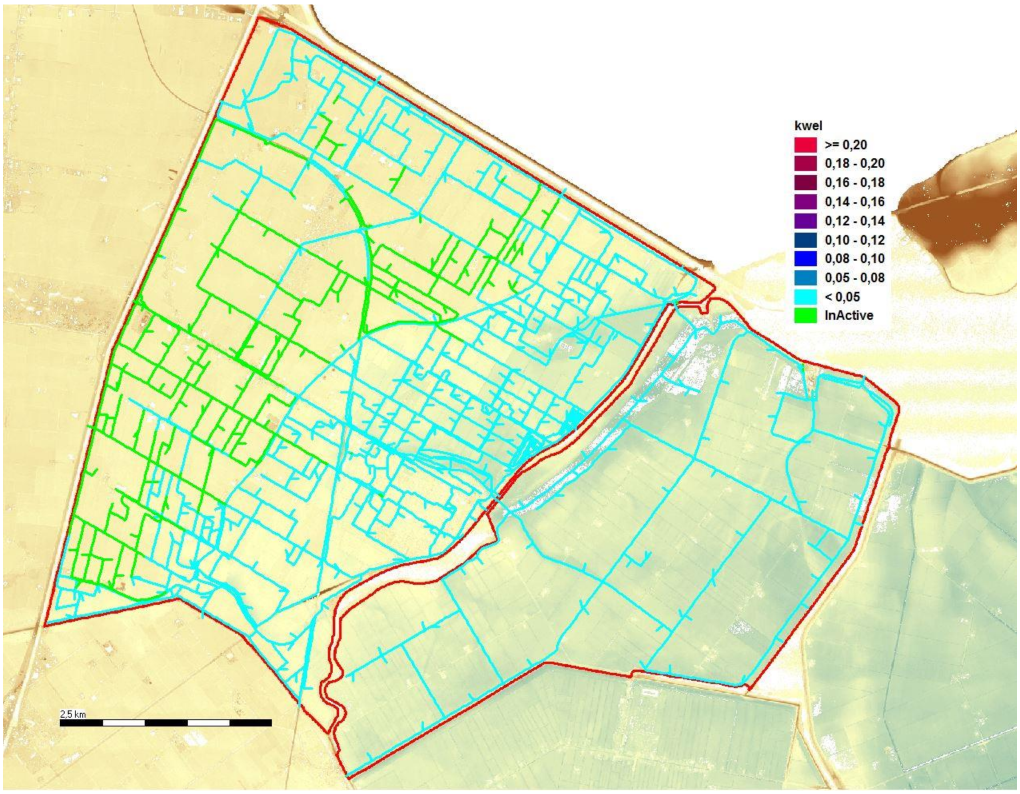

Figure IV-4. Salt fraction in the watercourses from seepage at the end of 12 month in fine model

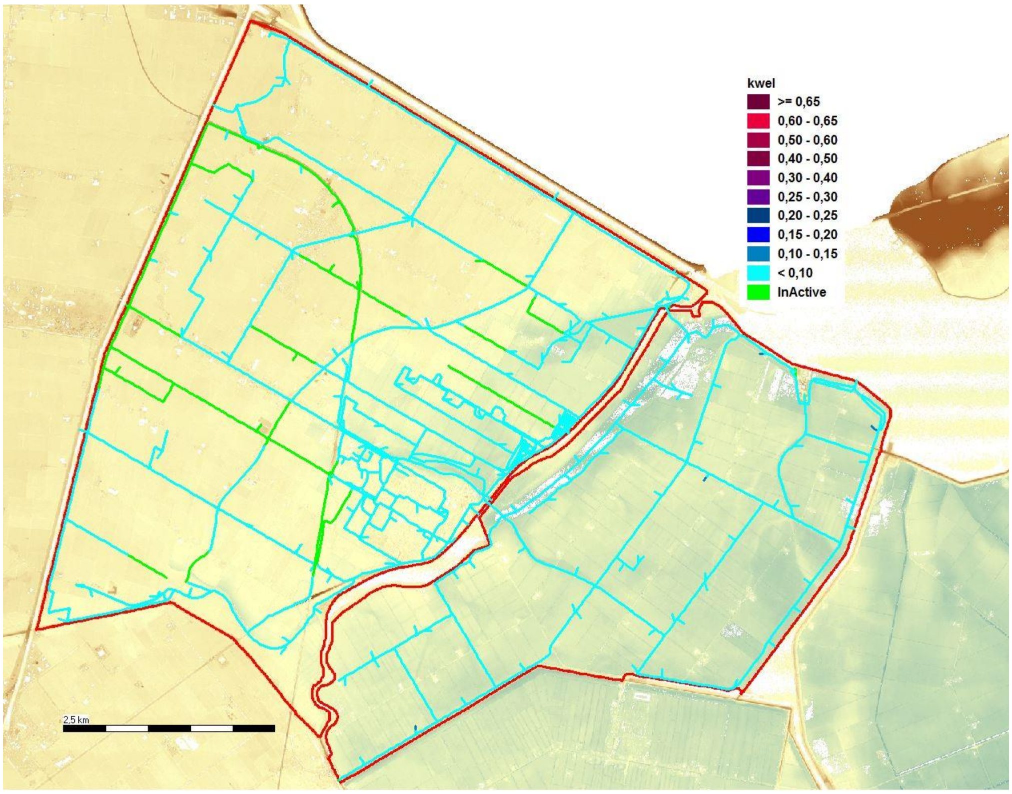

Figure IV-5. Salt fraction in the watercourses from seepage at the end of 3 month in coarse model

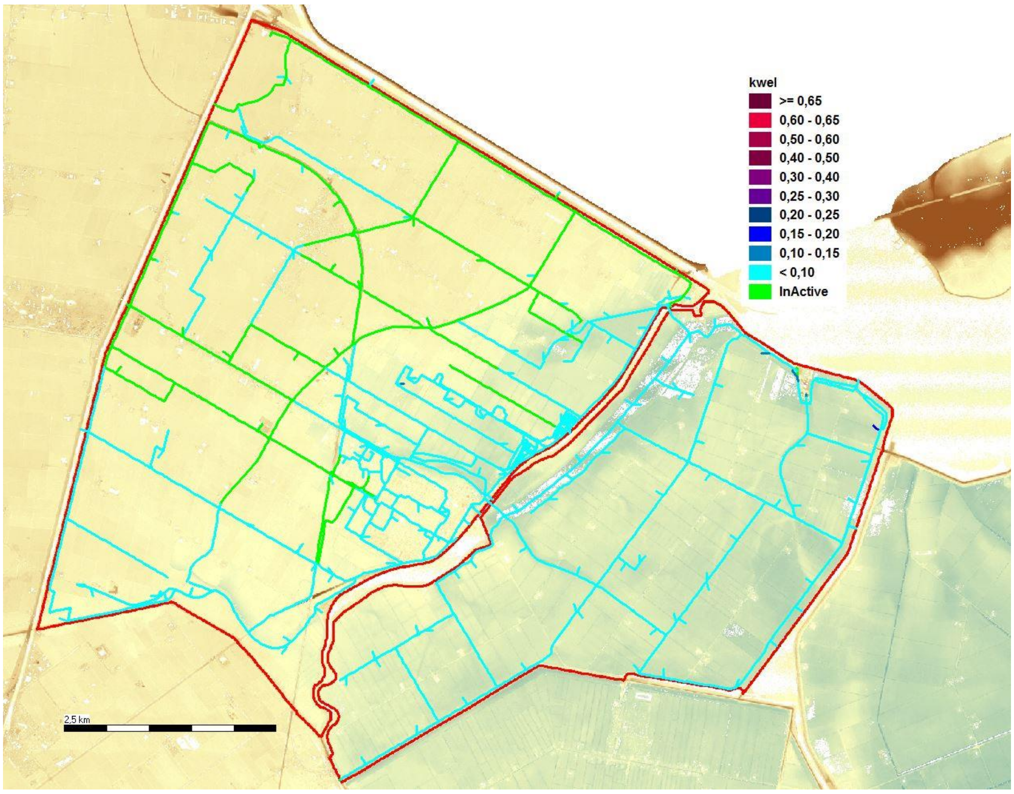

Figure IV-6. Salt fraction in the watercourses from seepage at the end of 6 month in coarse model

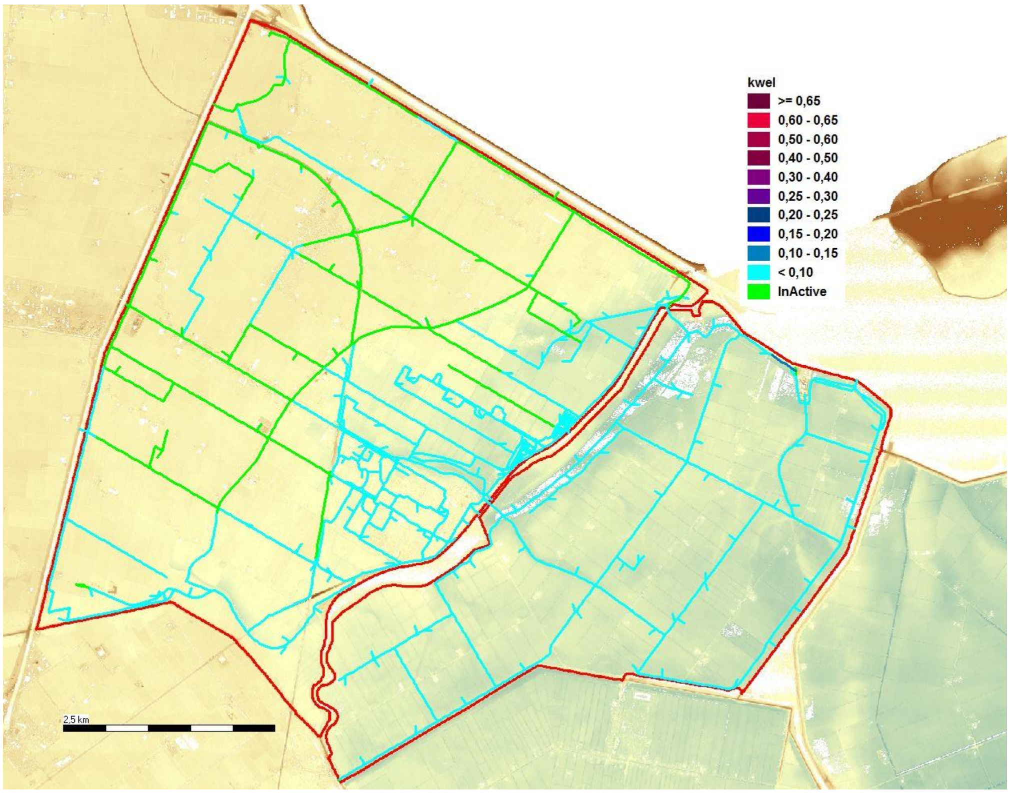

Figure IV-7. Salt fraction in the watercourses from seepage at the end of 9 month in coarse model

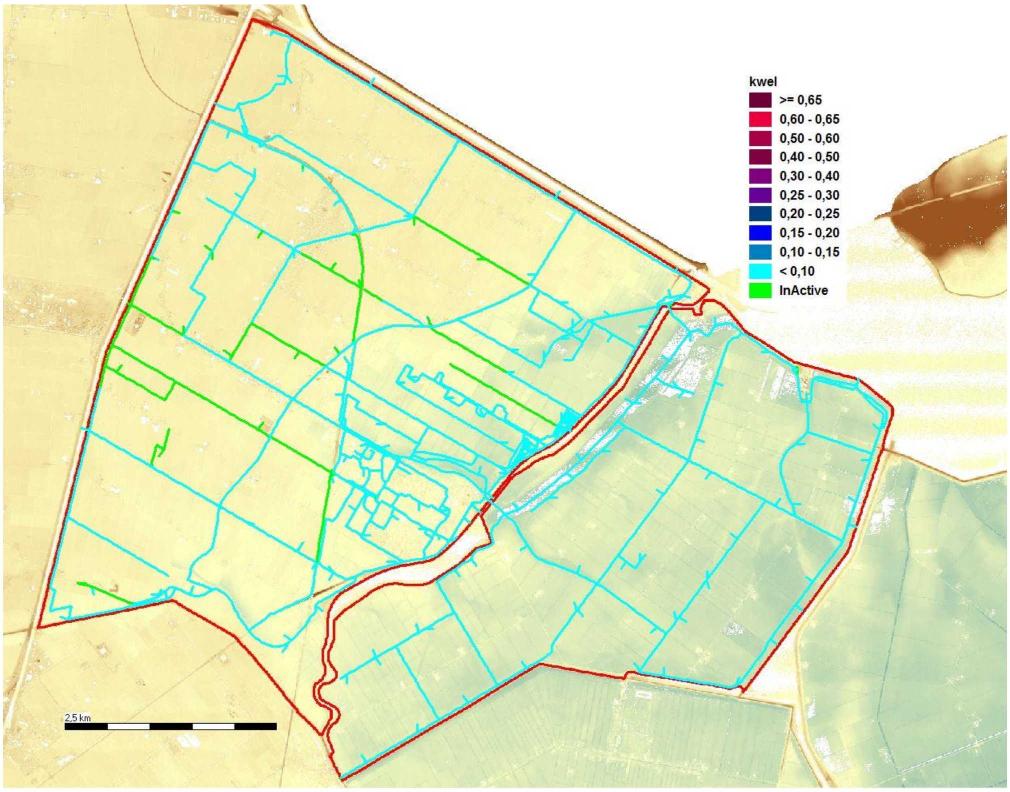

Figure IV-8. Salt fraction in the watercourses from seepage at the end of 12 month in coarse model

Appendix V: Simulation of salt transport before flushing by IJsselmeer water

Figures V-1 to V-4: Chloride concentration based on the fine model

Figures V-5 to V-8: Chloride concentration based on the coarse model

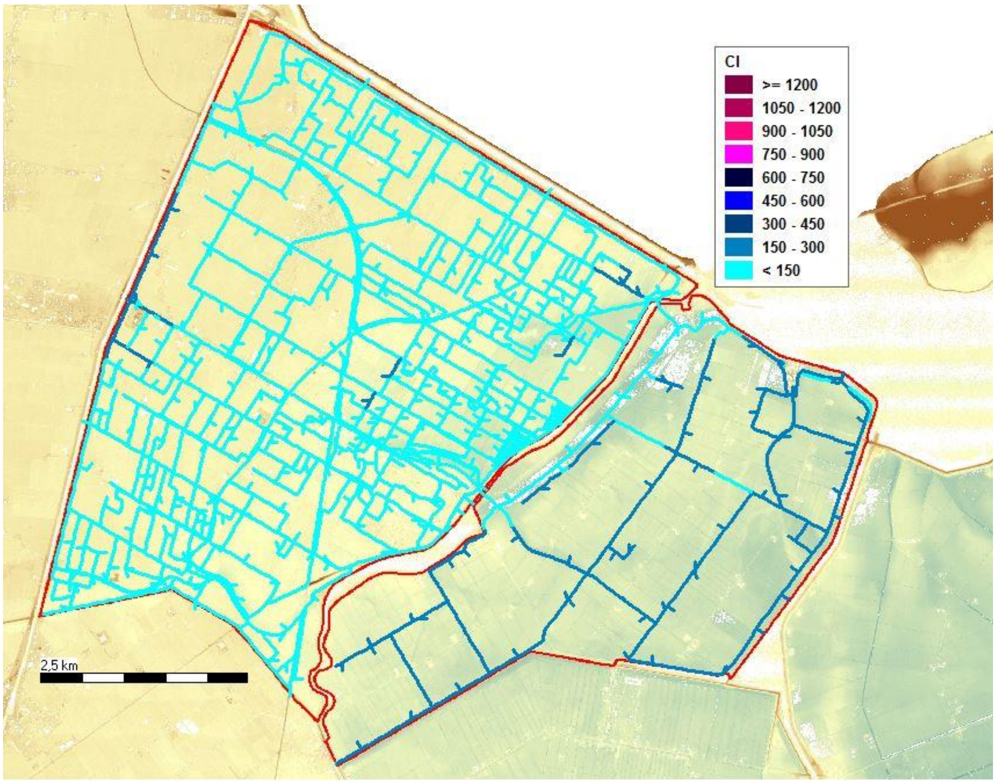

Figure V-1. Chloride concentration at the end of 3 month (before flushing event) in fine model

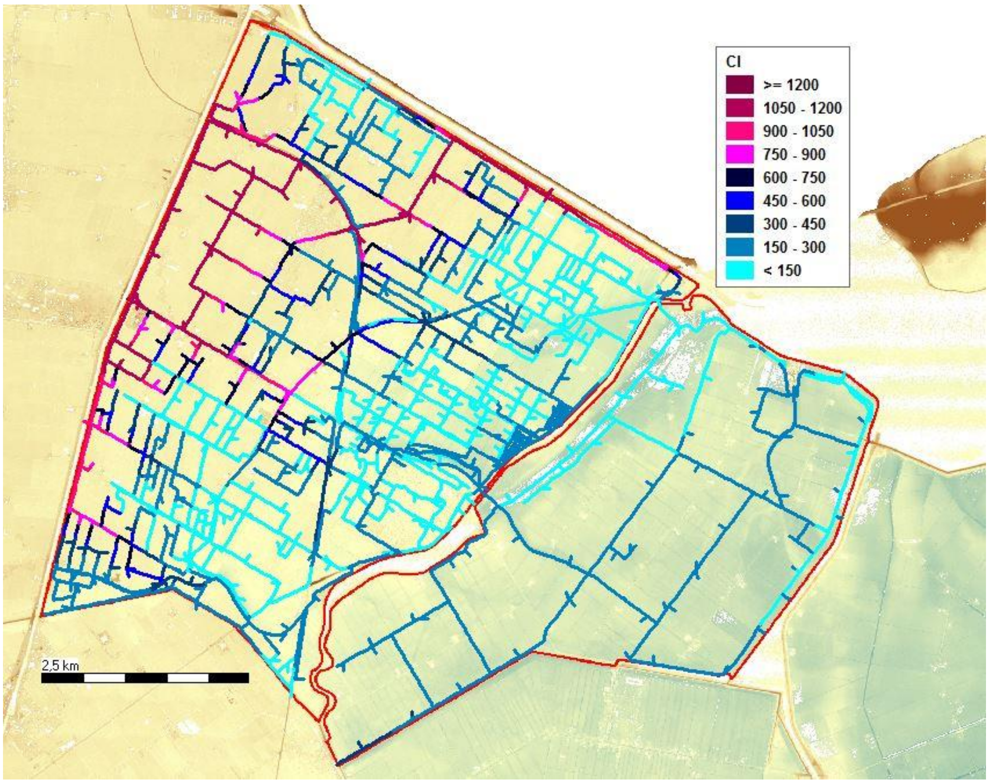

Figure V-2. Chloride concentration at the end of 6 month (before flushing event) in fine model

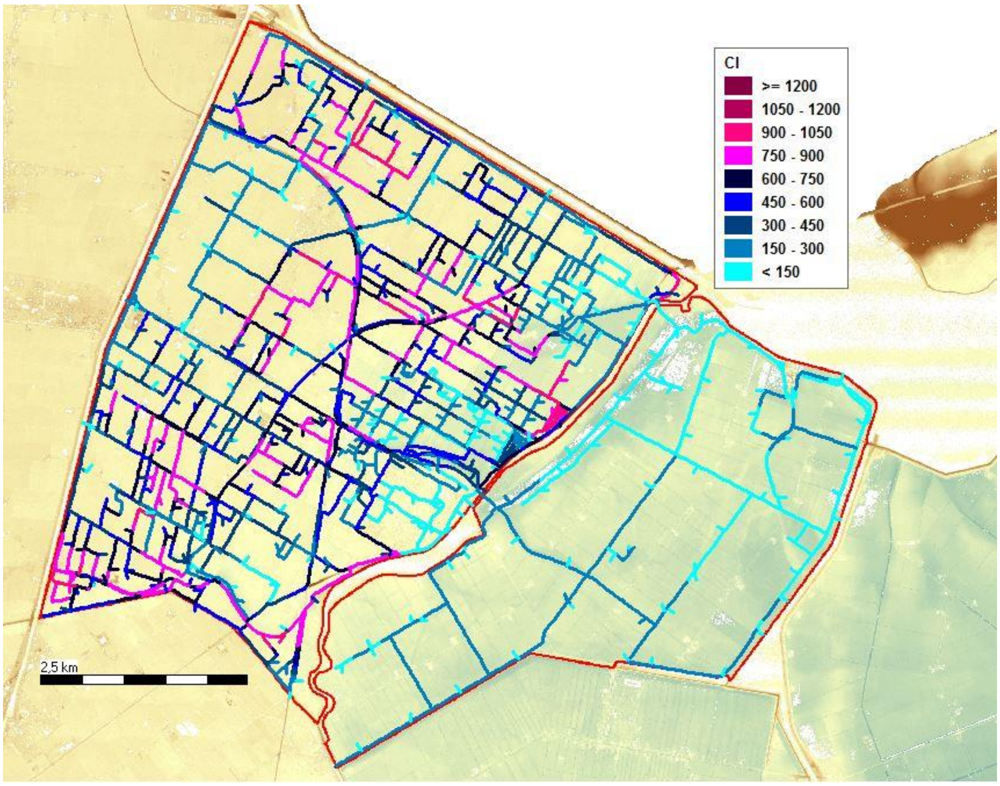

Figure V-3. Chloride concentration at the end of 9 month (before flushing event) in fine model

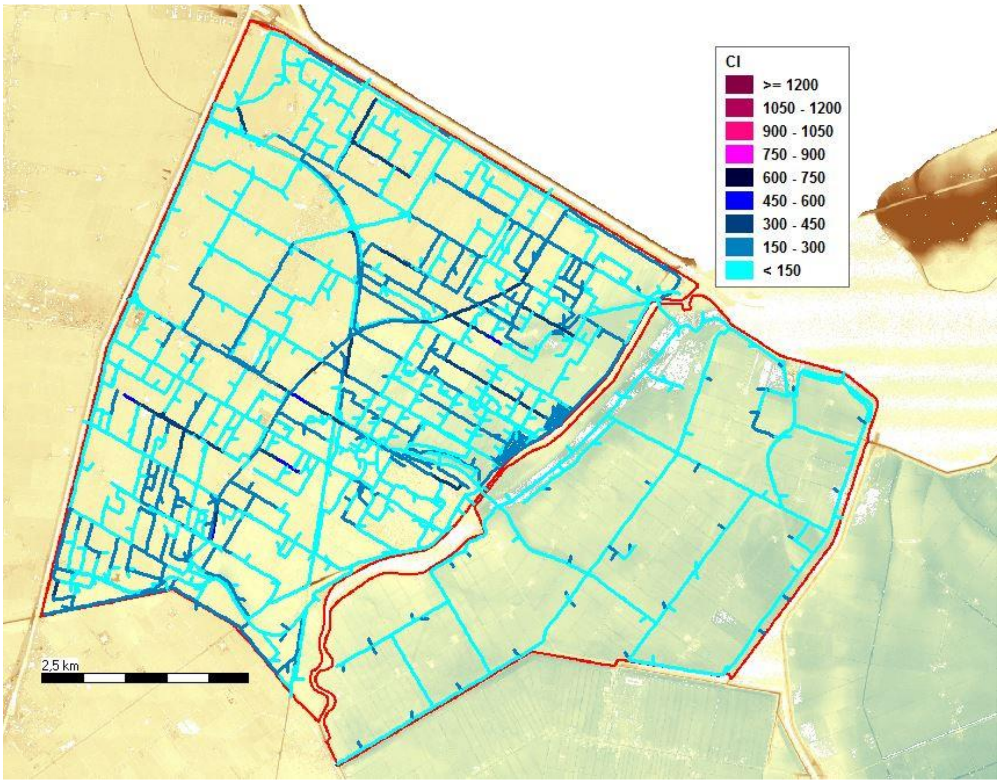

Figure V-4. Chloride concentration at the end of 12 month (before flushing event) in fine model

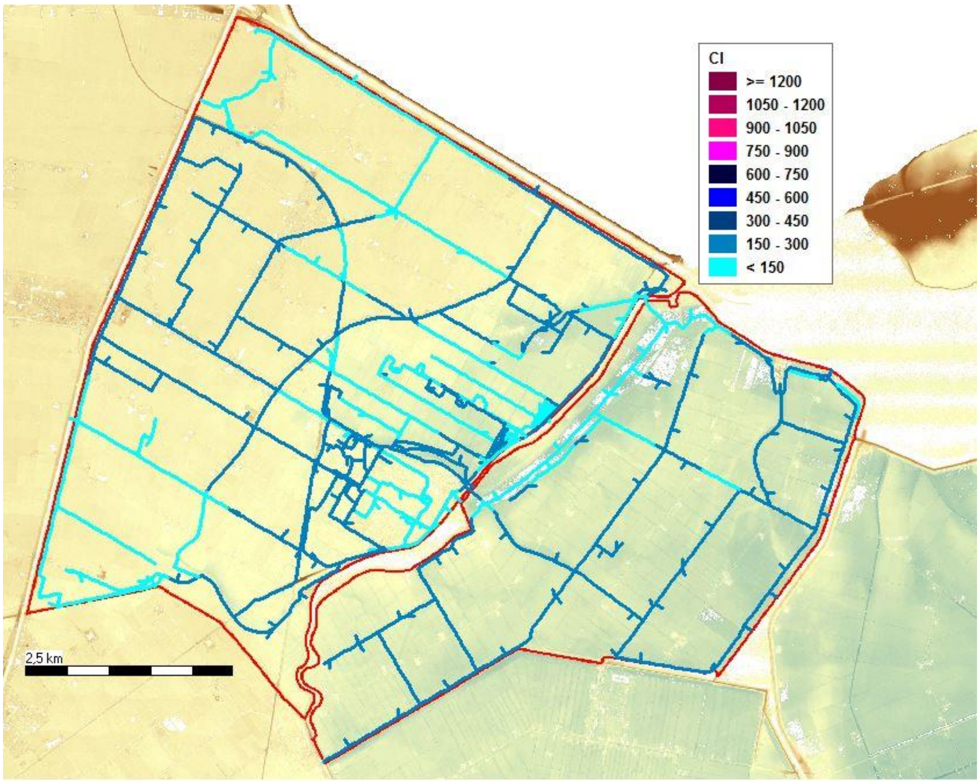

Figure V-5. Chloride concentration at the end of 3 month (before flushing event) in coarse model

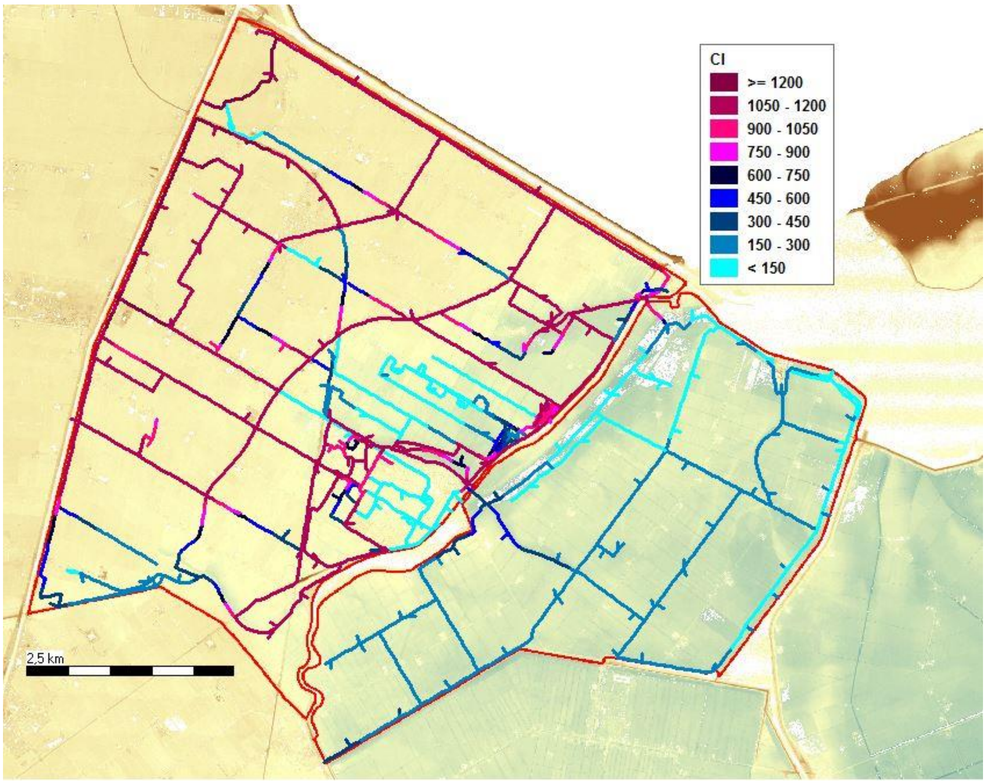

Figure V-6. Chloride concentration at the end of 6 month (before flushing event) in coarse model

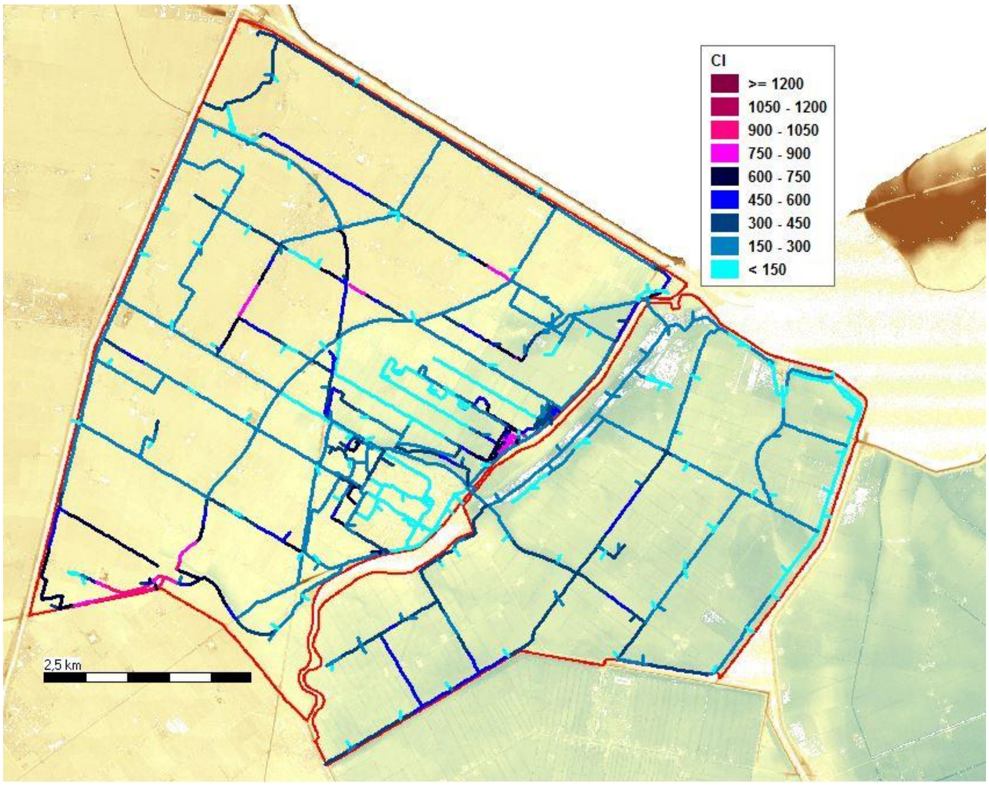

Figure V-7. Chloride concentration at the end of 9 month (before flushing event) in coarse model

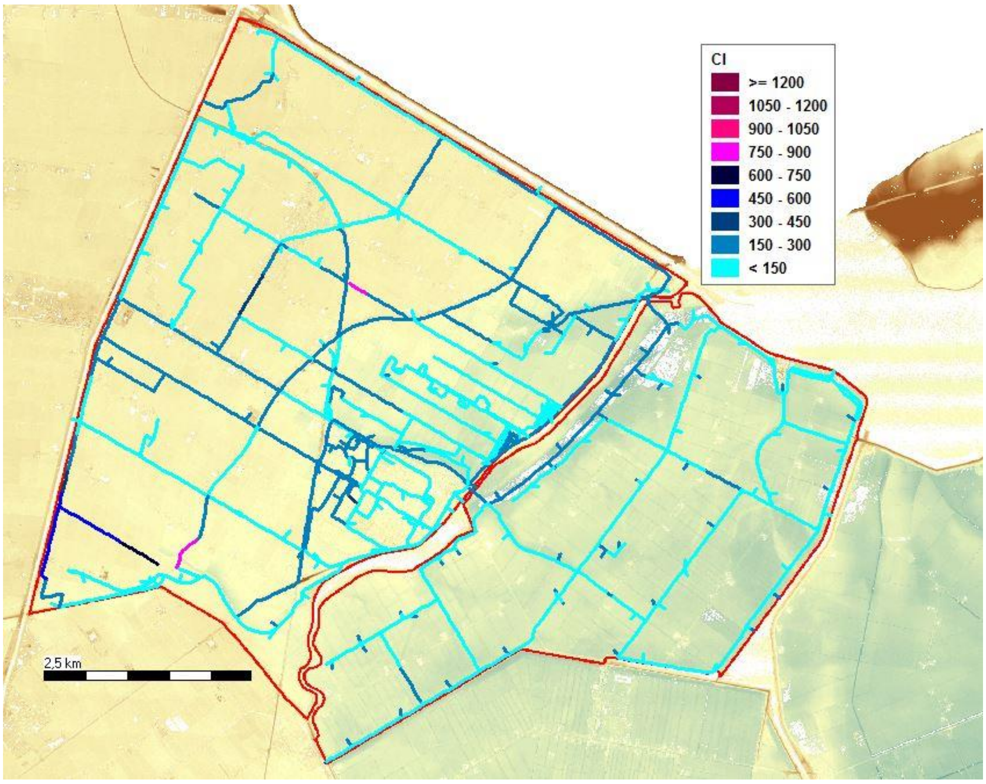

Figure V-8. Chloride concentration at the end of 12 month (before flushing event) in coarse model

Appendix VI: Simulation of salt transport after flushing by IJsselmeer water

Figures VI-1 to VI -4: Chloride concentration based on the fine model

Figures VI -5 to VI -8: Chloride concentration based on the coarse model

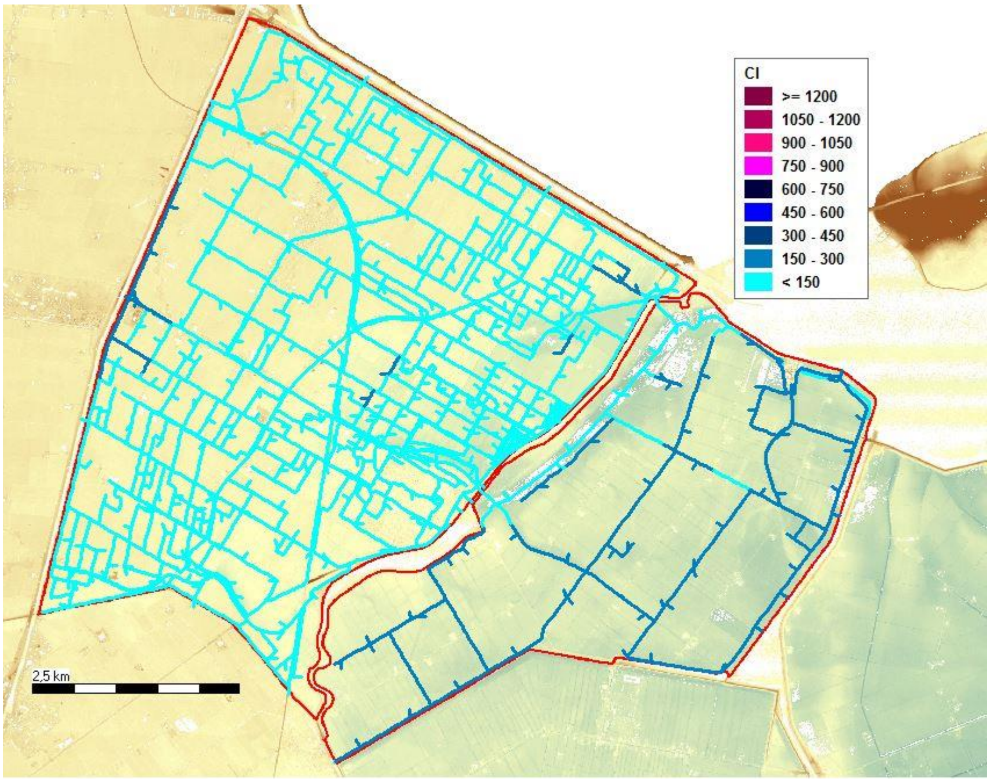

Figure VI-1. Chloride concentration at the end of 3 month (after flushing event) in fine model

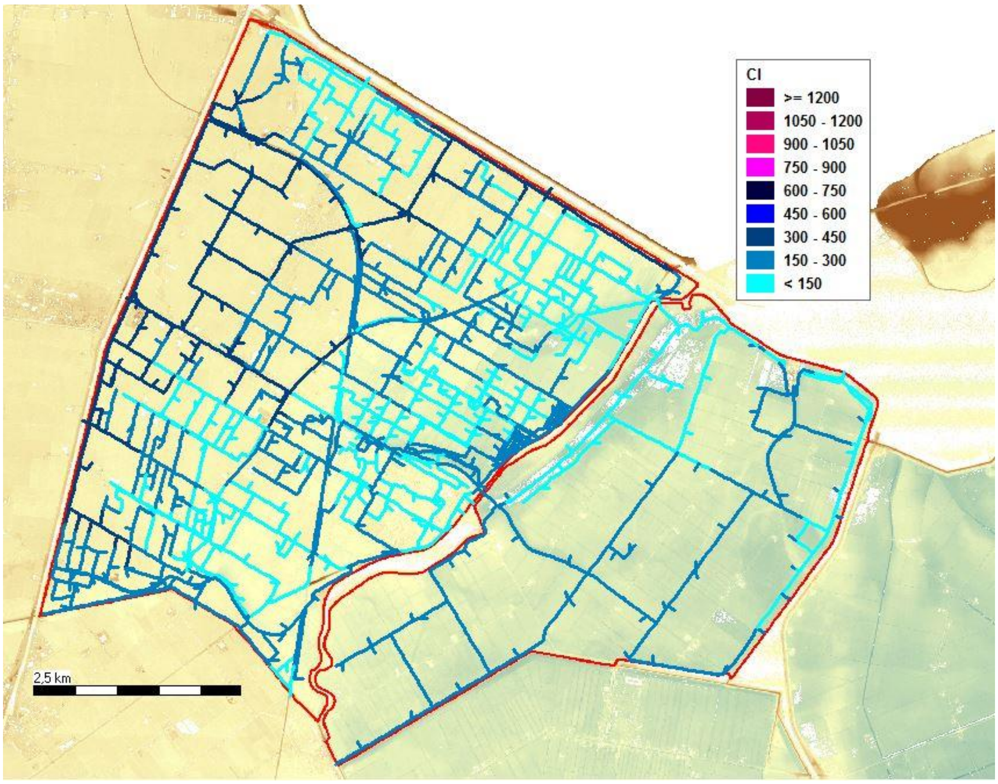

Figure VI -2. Chloride concentration at the end of 6 month (after flushing event) in fine model

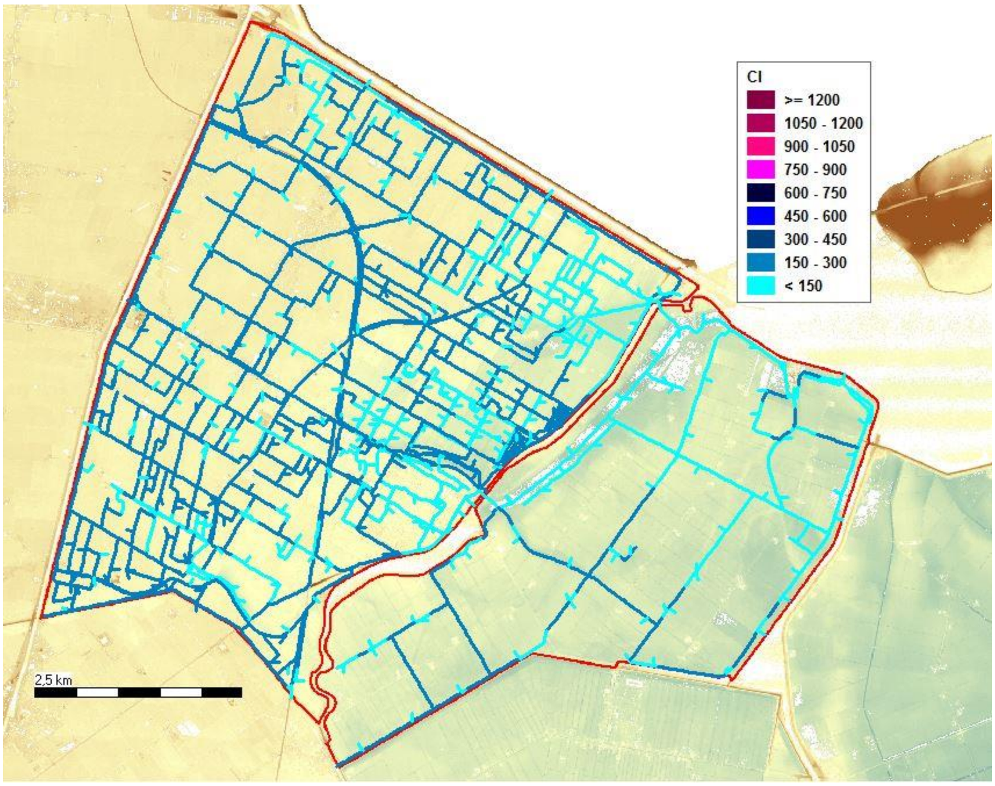

Figure VI -3. Chloride concentration at the end of 9 month (after flushing event) in fine model

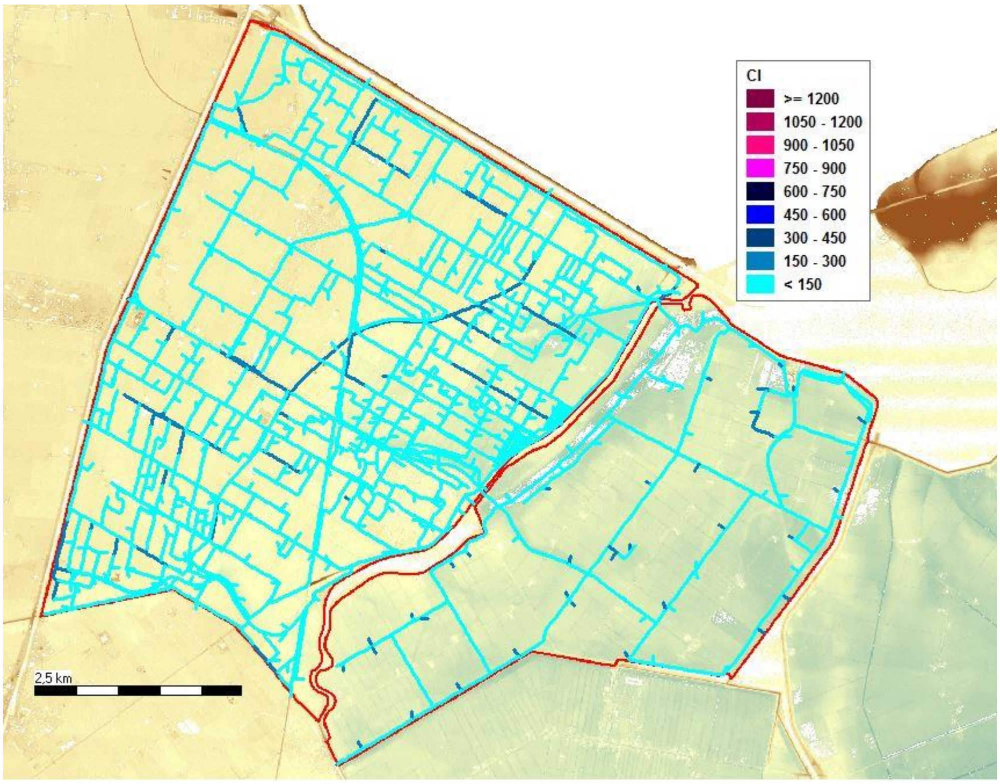

Figure VI -4. Chloride concentration at the end of 12 month (after flushing event) in fine model

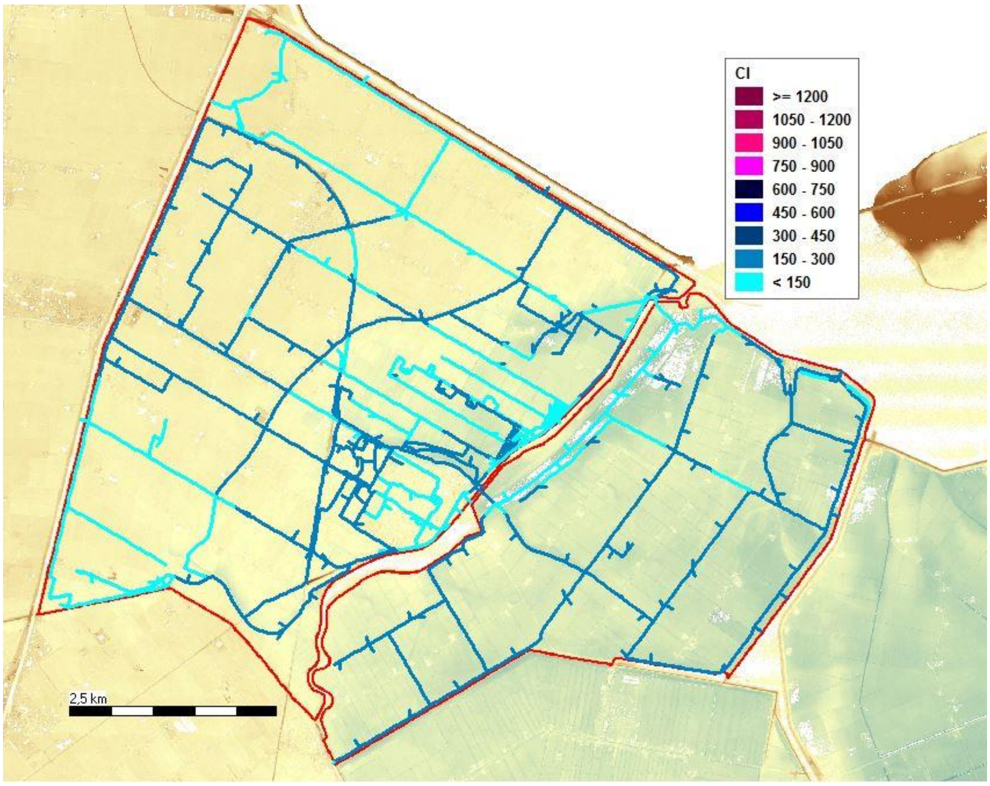

Figure VI -5. Chloride concentration at the end of 3 month (after flushing event) in coarse model

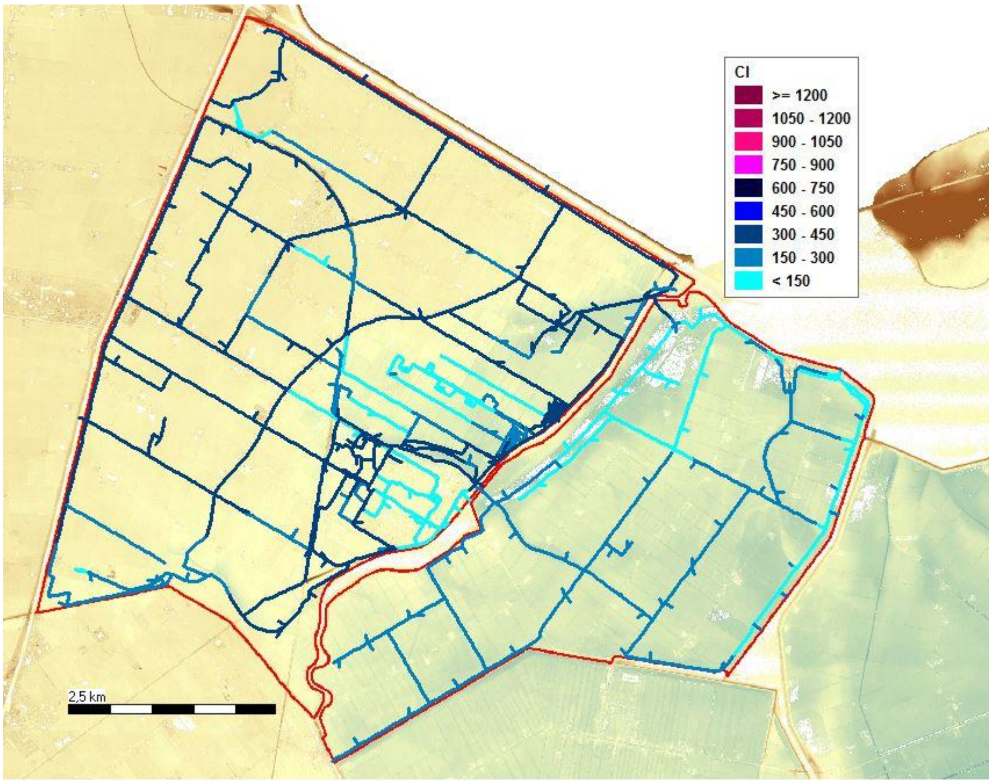

Figure VI -6. Chloride concentration at the end of 6 month (after flushing event) in coarse model

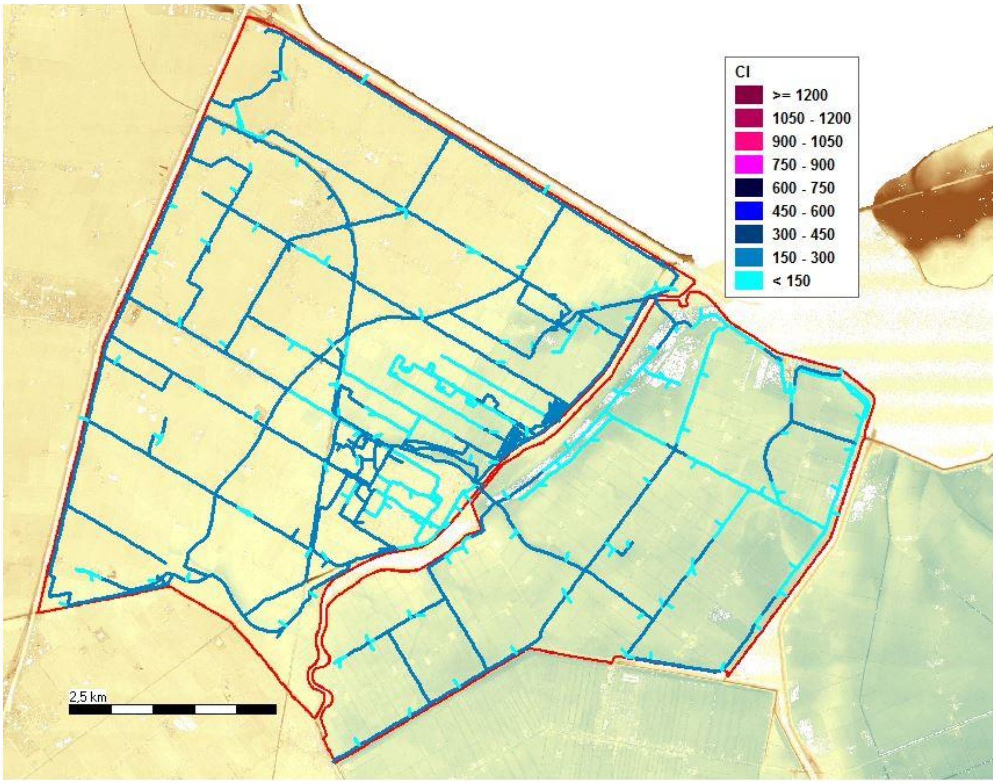

Figure VI -7. Chloride concentration at the end of 9 month (after flushing event) in coarse model

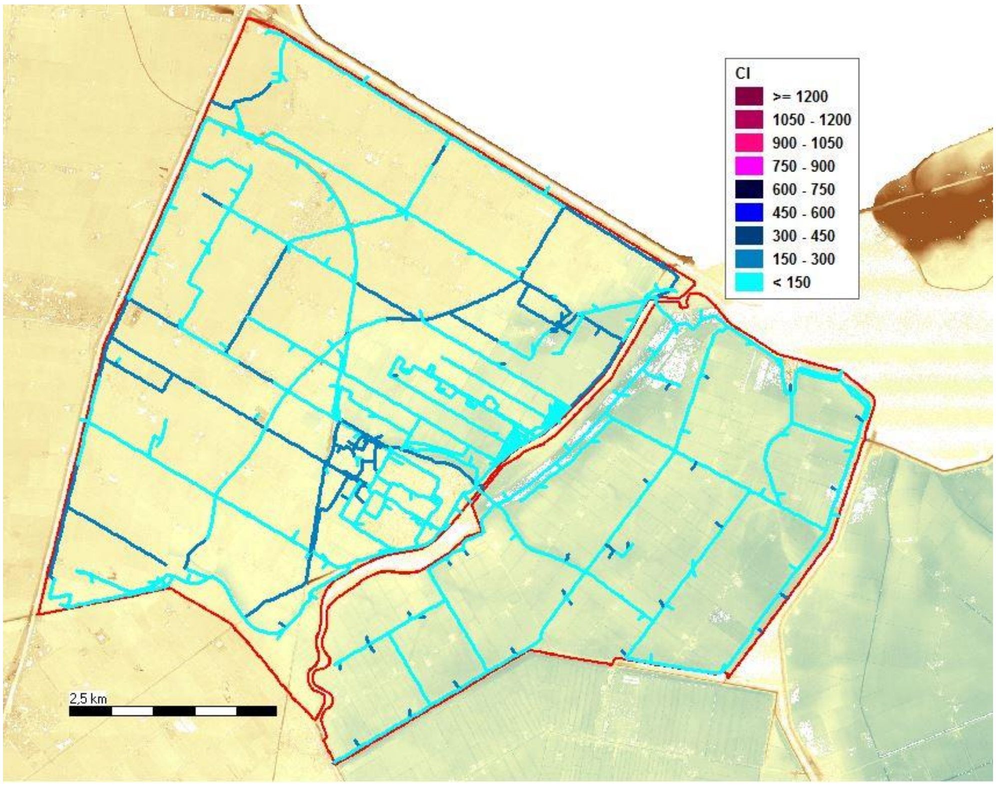

Figure VI -8. Chloride concentration at the end of 12 month (after flushing event) in coarse model