Surface water hydrology for the Cascade model – Study area “Drentsche Veenkoloniën”

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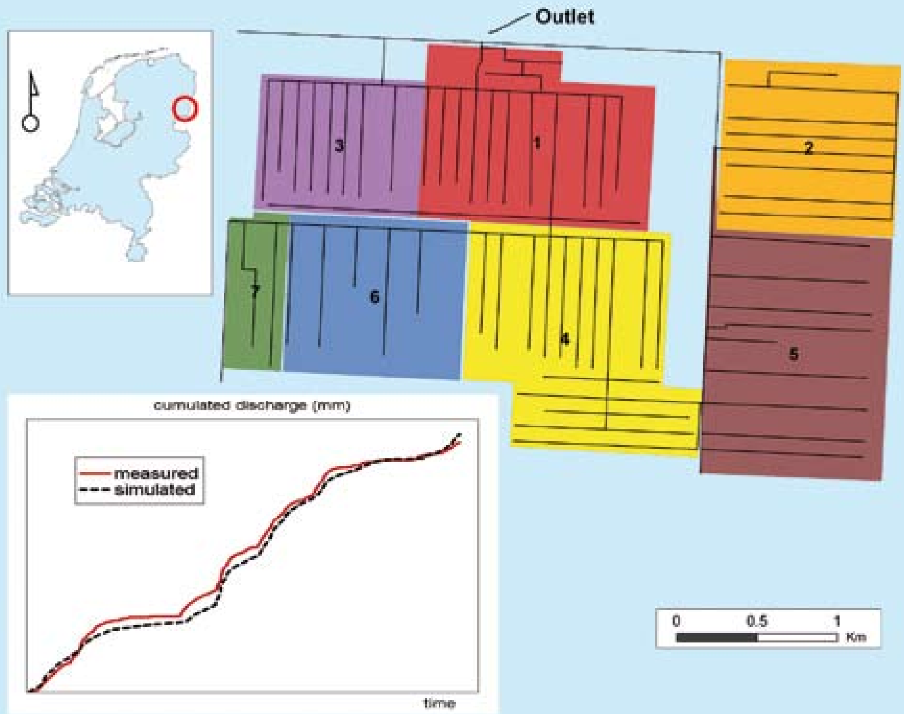

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ABSTRACT

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The hydrological module of the model instrument Cascade describes kinetics of surface water flow in a 10 km² catchment with a single outlet. Discharge measurements are available for calibration. The soil hydrological model SWAP is used to generate a description of drainage and infiltration. The SWQN model is used to simulate surface water flow in a detailed network representing the surface water channels and water management stuctures. The major terms of the surface water balance are drainage from the soil and the pump discharge at the outlet. Kinetics of cumulated discharge simulated at the outlet corresponds with cumulated discharge measured at the drainage pump. Model performance is also tested with a special simulation including a period of prolonged drought.

Keywords: surface water hydrology, SWAP, SWQN, Cascade, model, calibration, pesticide

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Contents

Preface

In the year 2004 a project was started to develop a model instrument named Cascade that could be used for accurate assessments of pesticide exposure concentrations in surface water at different scale levels. The development of this model instrument is funded by the Dutch Ministry of Agriculture, Nature and Food Quality. This document describes the hydrological module of Cascade, and the simulated surface water hydrology.

The authors want to thank Michel Jeuken (currently employed at the Netherlands Environmental Assessment Agency /MNP) and Robert Smit (WUR-Alterra) for their help with the surface water model SWQN, and Joop Kroes (WUR-Alterra) for his help with the soil hydrological model SWAP. Also, Han te Beesd (WUR-Alterra) is gratefully acknowledged for delivering the digital files with the discharge measurements and meteorological data from the region of the study area.

Roel Kruijne, February 2007

Summary

In the year 2004 a project was started to develop a model instrument for accurate assessments of pesticide exposure concentrations at different scale levels. This document describes the hydrological module of the model instrument Cascade and the simulated surface water hydrology.

The hydrological module describes the kinetics of surface water flow in a 10 km^2 catchment, located in the Netherlands in the south-eastern part of Drenthe. This study area represents a large part of the Dutch agricultural area. The dominant crop is potatoes. The network of surface watercourses has a single outlet and external water can be supplied during periods of drought. The area is divided into 7 water management control units called subareas. Discharge measurements at 5 locations including the outlet were available from a regional hydrological study that was conducted in the years 1992-1994.

The SWQN model simulates surface water flow for a schematisation built of nodes and sections which is called the surface water map. This surface water map is digitised based on the topographical map (TOP10-vector; scale 1 : 10 000). The water level is simulated in the nodes located at both ends of these sections. Additional inputs of SWQN are; (i) properties of nodes and sections, (ii) definition and control settings of water management structures like weirs and pumps, (iii) boundary conditions at nodes and structures, and (iv) initial conditions. The SWQN model produces output on a daily basis.

The soil hydrological model SWAP is used to generate a description of drainage flow towards the surface water and infiltration from the surface water into the soil profile. The SWAP model is parameterised with local meteorological data for the period of discharge measurement. Crop transpiration and soil evaporation parameters are based on the literature. Drainage parameters and the boundary condition for seepage flow are based on national and regional hydrological model studies.

The results obtained with SWAP are carefully interpreted, based on expert judgment, results from other model studies, the discharge measurements, and the local groundwater levels observed. It is concluded that the soil water balance terms are plausible, considering both the cumulated amounts and the relative contributions of these terms to the balance during the meteorological seasons of the year and especially during the crop season. The simulation with SWAP results in acceptable input for the surface water model SWQN.

The catchment area consists of 7 subareas with different water management target levels. At the scale level of these subareas a different fit was obtained. These differences can be explained by heterogeneous soil hydrological conditions, the estimated distribution of the area drained, and the accuracy of the discharge measurements.

Surface water hydrology
A correct surface water balance is produced; the simulation error = 0.2% The major terms of the surface water balance are the lumped drainage from the soil and the pump discharge at the outlet. The minor input terms are the direct precipitation onto the water surface and external supply. The minor output terms are the evaporation from the surface water and infiltration to the soil.

It is concluded that the kinetics of the cumulated discharge simulated at the outlet of the study area corresponds with the measured discharge of the drainage pump. Both lines of cumulated discharge coincide during periods of high discharge and during periods of low discharge. The total simulated discharge at the outlet exceeds the measured discharge with 0.5%. At locations within the study area, the fit of the simulated discharge to the measured discharge is less good. It is shown that this different fit may be caused by heterogeneous boundary conditions to surface water flow (e.g. seepage). This lack of fit may also be caused by aspects of water management that are not accounted for in the model, by measurement errors, and by the estimated area drained per node.

The period of discharge measurement coincides with two years representing the 93rd and 97th percentile in a time series of annual precipitation from the local KNMI-weather station Klazienaveen. As a consequence of these high precipitation amounts, there is practically no external supply of surface water simulated. For this reason, the performance of the SWQN model is tested with a special simulation based on artificial meteorological data including a period of prolonged drought.

It is concluded that the parameterised SWQN model can produce an acceptable simulation of surface water flow during such a period of prolonged drought. In accordance with the requirements formulated, during periods of discharge at the outlet there is no external supply of water simulated. Also, during periods of external water supply there is no discharge simulated at the outlet. The water supplied is further distributed within the area via the structures that are included in the surface water network for this purpose.

Based on these results it can be expected that the SWQN model parameterised for the study area can simulate surface water dynamics for a long-term series of meteorological years.

1 Introduction

1.1 Background and problem

The prediction of concentrations in surface water is a part of pesticide registration procedures at the EU and national level. With the introduction of the EU-Water Framework Directive, criteria for surface water quality refer to specific types of surface water bodies. As a consequence, exposure concentrations need to be predicted at different locations in the catchment area. Both the peak concentrations and the change in time of the exposure concentrations are of interest, when the aquatic effects need to be predicted as well.

In the year 2004 a project was started to develop a model instrument that could be used for accurate assessments of pesticide exposure concentrations at different scale levels. This document describes the hydrological module of the model instrument Cascade, and the simulated surface water hydrology.

1.2 Aim and procedure

The purpose of the project is to investigate the relation between the exposure concentration in field ditches and the exposure concentration in a regional watercourse (e.g. at the outlet of a 5-10 km^2 catchment area).

An existing catchment was selected based on the following criteria;

1. The dominant land use is arable crops
2. The surface water system has a hierarchic structure and a single outlet
3. Watercourses are (semi-)permanent during dry periods
4. Availability of information on soil- and surface water system balances

Spray drift is the only entry route of pesticides into the surface water considered in this version.

1.3 Readers guide

In Chapter 2 the model instrument "Cascade" is presented, with a brief description of its components and the required data. In Chapter 3 the study area is described together with the inputs of the surface water module. The parameterisation of the soil hydrological model SWAP is described in Appendix 3. The resulting description of drainage flow towards the surface water is discussed in Appendix 4. In Chapter 4 the input for the SWQN model for simulating surface water flow dynamics is described. The results are discussed in Chapter 5 and the conclusions are given in Chapter 6.

2 Overview of the model structure

The components of the model instrument are discussed in this chapter. A schematic presentation of the concept is shown in Figure 1.

The major components of the instrument are;

1. Geographic data (land use map and surface water map)
2. A surface water module
3. A Drift Calculator
4. A pesticide fate module

Geographic data

The geographic data used within the model instrument are organised in a land use map and a surface water map. In principle, each parcel with an agricultural crop is explicitly defined in the land use map and each (semi-)permanent field ditch that can receive a pesticide input is explicitly defined in surface water map.

The spatial pattern of agricultural crops was extracted from the national land use database (LGN4) and was stored as a polygon theme in ArcView. Each parcel corresponds with a single record in the attribute table of this polygon theme. In the LGN4, a parcel is defined by parcel ID, area, perimeter, and land use class. Other attributes may be added, such as the width of a buffer along the perimeter of the parcel.

The surface water map was digitised based on the topographical map (TOP10-vector; scale 1 : 10 000) and was stored as a polyline theme in ArcView. Each record in the attribute table corresponds with a section defined in the input of the surface water module SWQN. The polyline represents the centerline of the schematised watercourse.

Surface water module SWQN

A description of surface water flow is generated with the model SWQN. This hydrological module uses a schematisation built of nodes and sections (referred to as the land use network; Figure 1). Nodes are defined by a node ID, a pair of coordinates, and a reference level. Sections are defined by a section ID, a node connected at both ends, and length.

The definition of the land use network in the input of the hydrological module is based not only on the hydraulic requirements of the model SWQN, but also on the shape and size of parcels with agricultural crops. Additional inputs of SWQN are; (i) some properties of nodes, sections, and hydraulic structures, (ii) boundary conditions at nodes and hydraulic structures, and (iii) initial conditions.

The model SWQN produces output on a daily basis, such as water levels in nodes, discharges in sections, and several water balance files. Post-processing of SWQN-output has the following purposes;

1. Calculate for each section the average daily depth and width of the water layer.
2. Check the hydrological output of the model SWQN.

A time step of 1 day in the description of surface water flow is accepted for this version of the model instrument.

Drift module

The drift module searches in the wind direction for surface watercourses in the vicinity of a parcel with a crop treated. The current version is an Avenue script that operates in ArcView, with a default deposition curve and some user defined input. The procedure uses an internal segmentation of sections; these segments are no part of the surface water map.

The distance from the crop edge to the surface water is measured in the wind direction, using the polygon of the parcels on the land use map and the centerline of the sections on the surface water map. The drift percentage is calculated based on (i) the width of a buffer defined along the perimeter of the sprayed field, (ii) the cross-sectional dimensions of the section, (iii) the width of the water layer, and (iv) the deposition curve selected. Note that the width of the water layer in the section can either be a constant value, or the daily average calculated from the SWQN output.

The amount of drift is calculated, based on the average drift percentage and the area of surface water per segment. Finally, the amount of drift at individual segments is aggregated per section. The output of this module defines the pesticide entries to the surface water per section and per time step.

The drift module contains a number of deposition curves, defining the drift percentage as a function of distance. These curves were derived from experimental field data (IMAG). Each curve applies to a certain combination of wind angle, crop type, and application technique. By definition, the use pattern refers to all input data related to the crop treated and the application technique.

Fate module

The fate module describes the behavior of pesticides in the surface water system. The modeled system consists of a water layer representing the volume of surface water and a sediment layer. Pesticides are simulated to leave the water layer by volatilisation across the water-air interface or by transport across the boundaries of the water layer.

Pesticide transformation in the watercourse system is described by first-order kinetics and is depending on temperature. Sorption of pesticide to sediment or to suspended solids and sorption to macrophytes are instantaneous.

The fate module may require a more detailed network of nodes and sections than the surface water module SWQN does. For this reason, an interface between the surface water module and the fate module is needed, which has the following tasks;

1. Convert the land use network of nodes and sections into a network for the fate module (referred to as the fate network; Figure 1)
2. Convert the SWQN output into a description of surface water flow for the fate module
3. Convert the output of the drift module into pesticide entries per node of the fate network.

A spray drift entry is defined as a pulse. Spray drift is the only entry route considered in this version; other pesticide entry routes might be included in future versions. Additional inputs of the fate module are (i) pesticide properties, (ii) air temperature, (iii) macrophyte density, (iv) suspended solids, and (v) sediment properties.

The fate module generates exposure concentrations at all locations in the surface water network of the fate module. Other output may be a concentration reduction map, a substance balance, or a report.

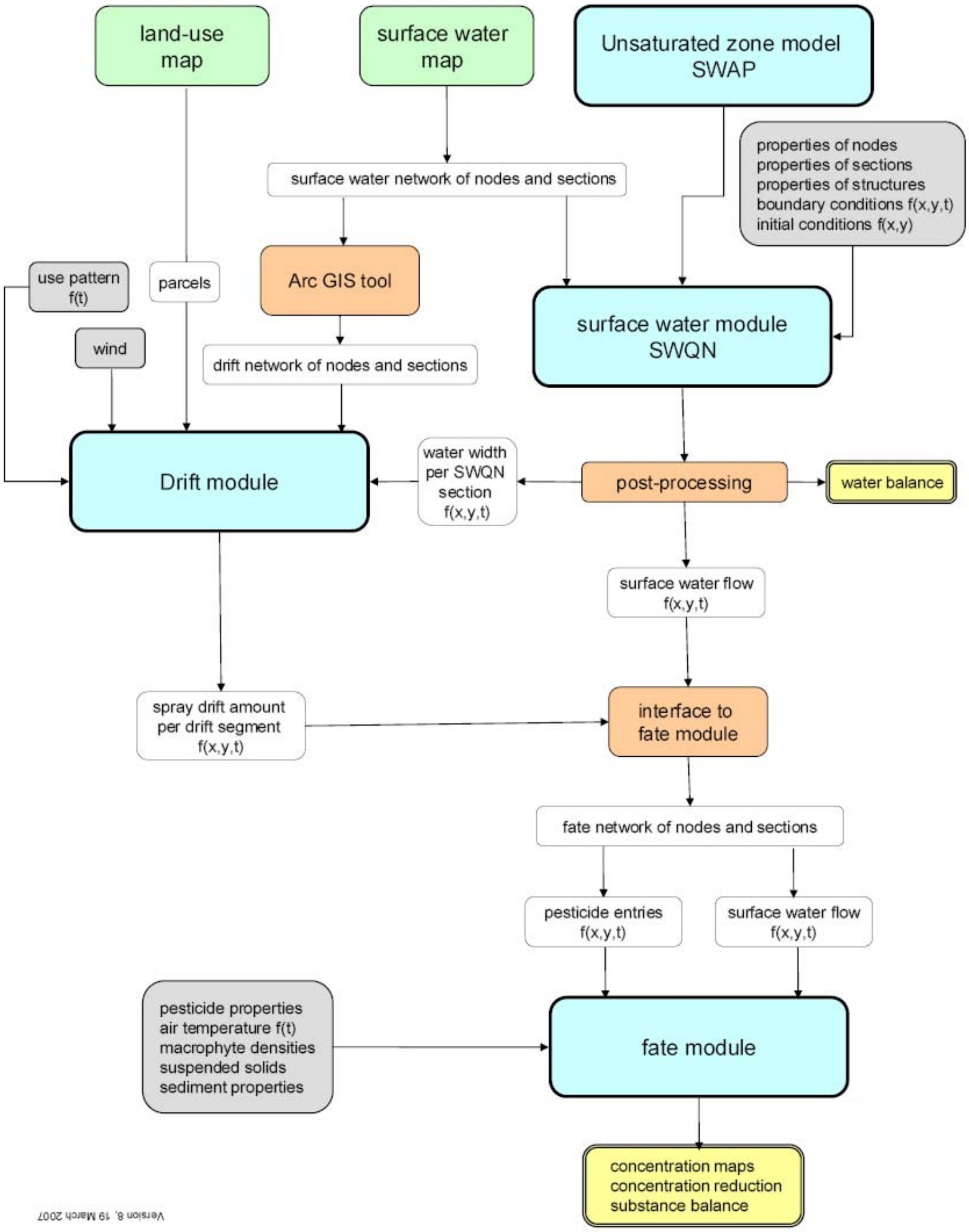

Figure 1: Components of the model instrument Cascade for the prediction of pesticide exposure concentrations at regional scale.

3 The study area

This chapter describes the data that were used to create the land use map and surface water map of the study area, and to parameterise the surface water module (Chapter 4).

3.1 Introduction

A catchment area was sought in order to have a realistic case for developing the 1st version of the model instrument. The selection criteria were;

1. The dominant land use is arable crops
2. The surface water system has a hierarchic structure and a single outlet
3. Watercourses are (semi-)permanent during dry periods
4. Availability of information on the soil- and surface water system

A suitable study area was found in the 'Drentsche Veenkoloniën' (Figure 2). The dominant crops are potatoes, sugar beet and cereals. The 10 km^2 area is a polder, where the surface water network is used both for drainage and for supply of water.

A regional model of the groundwater and surface water systems was developed by (Van Walsum et al., 1998). This model was built for scenario analysis aimed at the conservation of the nature reservate Bargerveen, located at the south of the study area. Surface water hydrology in this 137 km^2 region was intensively measured during the period Nov.'92 – Dec.'94.

Figure 2: Aerial photograph of the study area.

3.2 Collected data

3.2.1 Land use

The land use map of the study area was extracted from the Land use Database of the Netherlands LGN4, which is based on satellite images from the year 1999/2000 (www.lgn.nl). This map covers the rural area excluding the urban zones, as can be seen in (Figure 3).

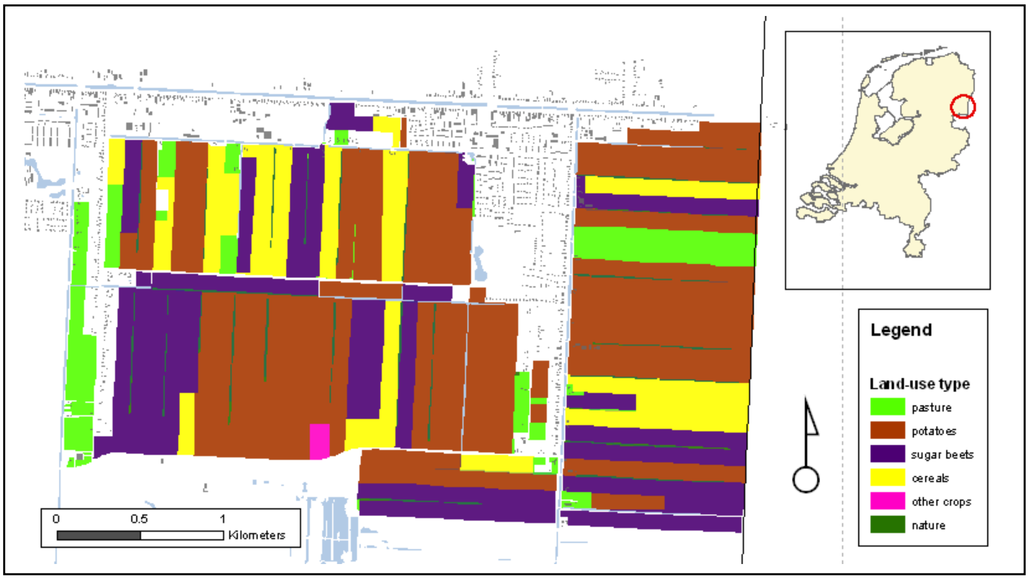

Figure 3: Land use map of the study area (according to the LGN4; based on satellite images of the year 2000).

Each record in the attribute table extracted from the LGN4 represents a polygon with a legend class number, referred to as a parcel. The land use map of the study area has 5 types of agricultural land use. The number of parcels and total area per class are given in Table 1.

Table 1: Number of records and total area per land use type (LGN4). Each record refers to an individual parcel.

Land use	Number of records	Area (ha)
Pasture	46	61
Potatoes	28	366
Sugar beets	23	197
Cereals	16	114
Other crops	1	3
Total agricultural land use	114	740
Nature	30	16
Total (rural area)	144	755

The distribution of parcel size in Figure 4 shows that part of the records with agricultural land use represent very small parcels. The median area of 114 parcels with agricultural land use equals 3.4 ha.

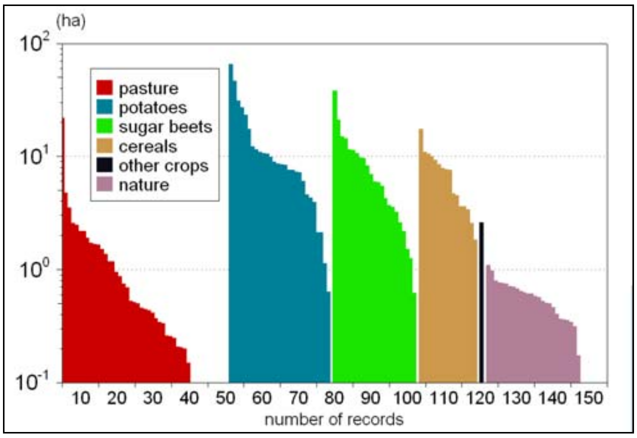

Figure 4: Distribution of parcel size per land use type. Only parcels with an area > 0.1 ha are shown.

3.2.2 Surface water

The schematisation of the surface water network is based on topographical maps (TOP10-vector; Topografische Dienst). This library of topographical maps is based on aerial photographs of the years 1991 to 1997. Surface water with a width < 6 m is defined as a polyline, whereas an area of surface water with a width > 6 m is defined as a polygon (Figure 5). The TOP10-vector contains separate data layers with the centerlines of field ditches, small channels, and large channels. Another data layer contains the polygons of water bodies. The density of watercourses equals 6.5 km/km^2. Note that a part of the field ditches has a width > 6 m.

Figure 5: Map with the surface water in the study area (according to TOP10-vector; Topografische Dienst).

The surface water system consists of 7 water management control units called subareas (Figure 6). The water level in these subareas is controlled by means of a weir, a drainage pump, or a gate for water supply. These gates are called inlet weirs. Each subarea has two target levels; a low water level during winter and a higher water level during summer. The location and type of these devices and the target surface water levels were obtained from the regional hydrological study (van Walsum et al., 1998).

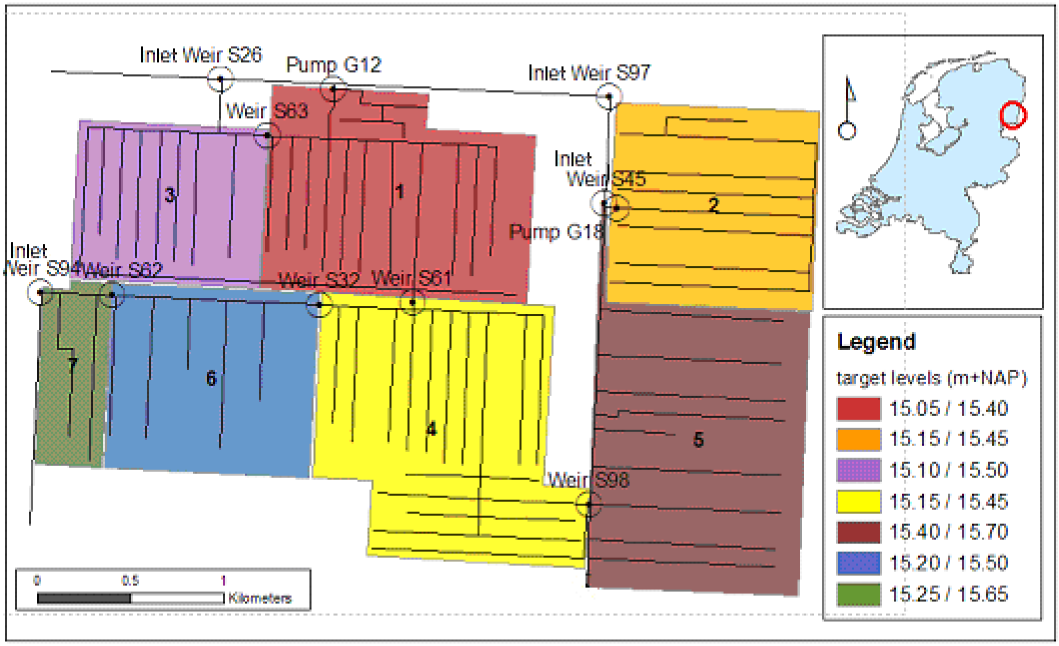

Figure 6: Map with water management subareas, weirs, drainage pumps and inlet weirs. The legend shows the target levels (low / high; according to van Walsum et al., 1998).

Figure 7 shows the subareas, with the direction of flow during periods of discharge indicated by solid lines. The subarea and device numbers correspond with those in Figure 6. Subarea 2 discharges to Subarea 5 by means of a drainage pump (G-18). Subarea 5 discharges to Subarea 4, and then to Subarea 1. The drainage pump G-12 is the outlet of the entire study area. The discharge was measured at the outlet (G-12), at the pump between Subarea 2 and 5 (G-18), and at the weirs between Subarea 7 and 6 (S-62), 6 and 4 (S-32), and 3 and 1 (S-63).

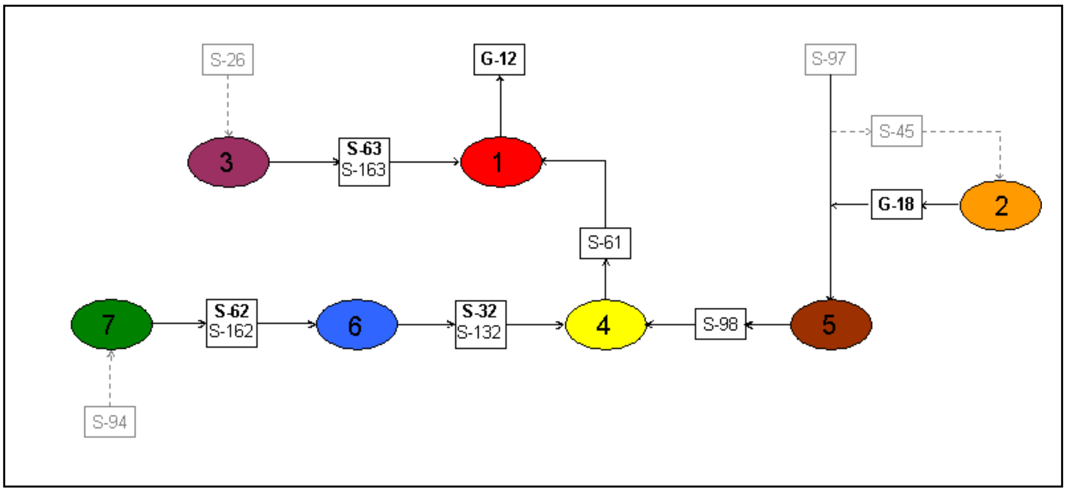

Figure 7: Schematic presentation of surface water flow towards the outlet of the study area. Structure codes in bold indicate the locations where the discharge was measured; i.e. the outlet (G-12), at the pump between Subarea 2 and 5 (G-18), and at the weirs between Subarea 7 and 6 (S-62), 6 and 4 (S-32), and 3 and 1 (S-63).

There was no information available on the period of water supply and the volumes of water supplied to the study area. Figure 8 shows the assumed distribution of surface water within the study area during periods of water supply, based on (Van Walsum et al., 1998). External water can be supplied through an inlet weir to Subareas 3 (S-26), 5 (S-97), and 7 (S-94). Inlet Weir S-45 is used to supply water to Subarea 2. Within the area, the water supplied can be distributed from Subarea 7 towards 6 and 4. Likewise, water can be distributed from Subarea 3 to 1.

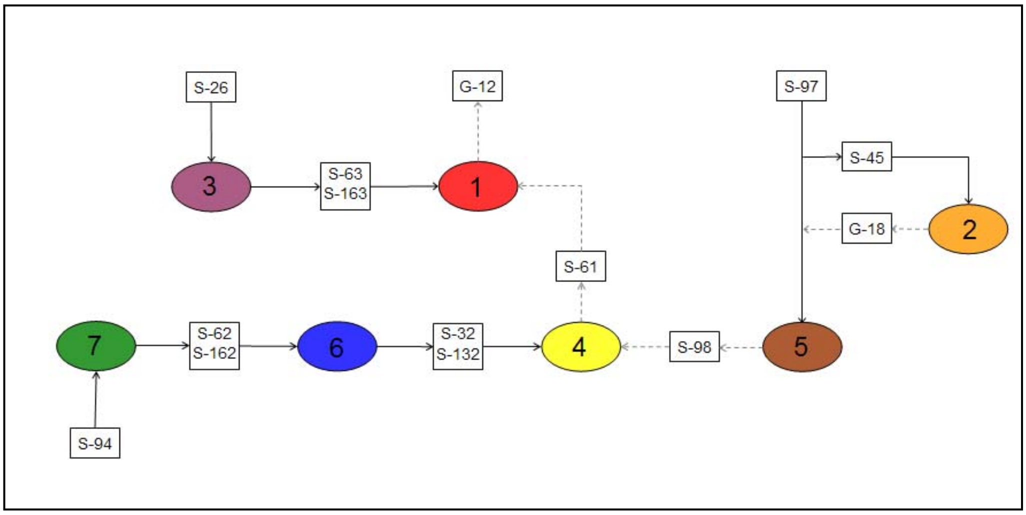

Figure 8: Schematic presentation of surface water flow during periods of external supply. External water can be supplied with an inlet weir to Subarea 3 (S-26), 5 (S-97), and 7 (S-94). Inlet Weir S-45 is used for supply to Subarea 2.

3.2.3 Discharge measurements

During the period Nov.'92 – Dec.'94, the surface water level was recorded on a daily basis at 26 locations, and on a weekly basis at another 100 locations (van Walsum et al., 1998). The corresponding discharge was calculated using the discharge characteristic of the device. Time series of weekly discharges were completed using multiple linear regression analysis. Figure 9 shows an example with the weekly observations and the continuous discharge at Weir S-62.

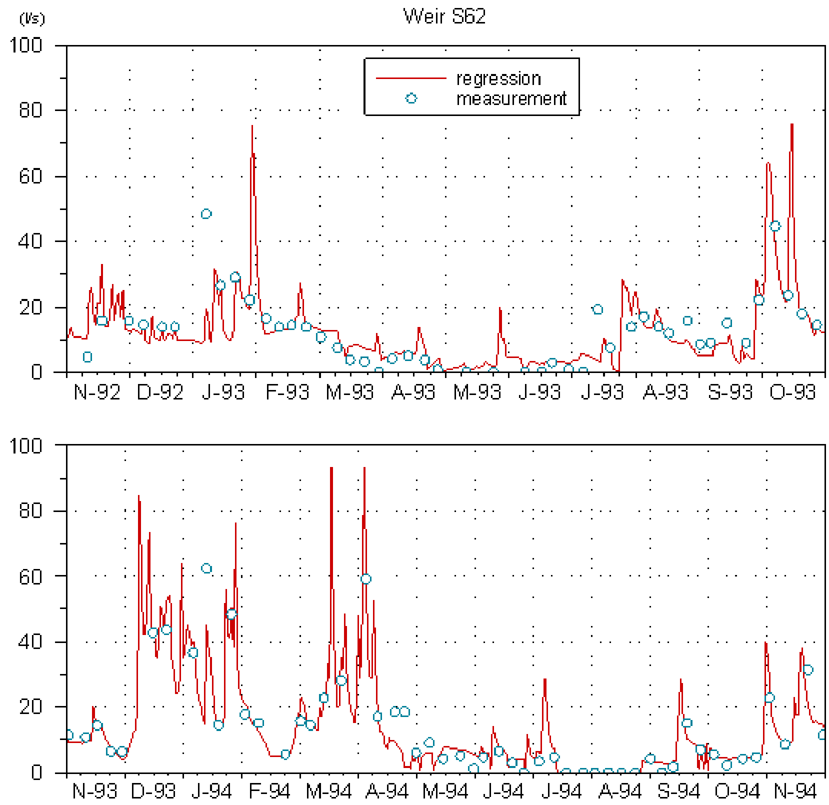

Figure 9: Time series of daily discharge at Weir S-62, based on weekly discharge measurements at Weir S-62 and multiple linear regression analysis of daily discharge measurements at other locations (Van Walsum et al., 1998).

Time series of discharge are available for 3 weirs and 2 drainage pumps within the study area (Table 2). The catchment area equals the sum of the drained subareas. At Weir S-62, the discharge of Subarea 7 was measured; at Weir S-32 the discharge of Subareas 7 and 6; at Weir S-63 the discharge of Subarea 3. At drainage pump G-18 the discharge of Subarea 2 was measured, and at drainage pump G-12 the discharge of the entire study area.

The cumulated discharge was converted to specific discharge based on the estimated catchment area per subarea (Table 2, Figure 10).

Table 2: Cumulated discharge measured at 3 weirs and 2 drainage pumps (November 1st, 1992 - December 1st, 1994), including the estimated catchment area and the corresponding discharge (in mm)

Structure	Discharge (10^6 m^3)	Interval (d)	Catchment (ha)	discharge (mm)	measurement error (%)
Weir S-32	1.35	7	123	1100	15
Weir S-62	0.86	7	33	2600	15
Weir S-63	0.75	7	95	790	20
Pump G-12	9.87	1	897	1100	20
Pump G-18	1.62	1	112	1450	25

Van Walsum et al. (1998) estimated the relative error of the discharge measurements at each location, based on the type of structure, the flow conditions observed and the measurement frequency (Table 2).

The differences that can be seen in Figure 10 will be discussed in Chapter 5.

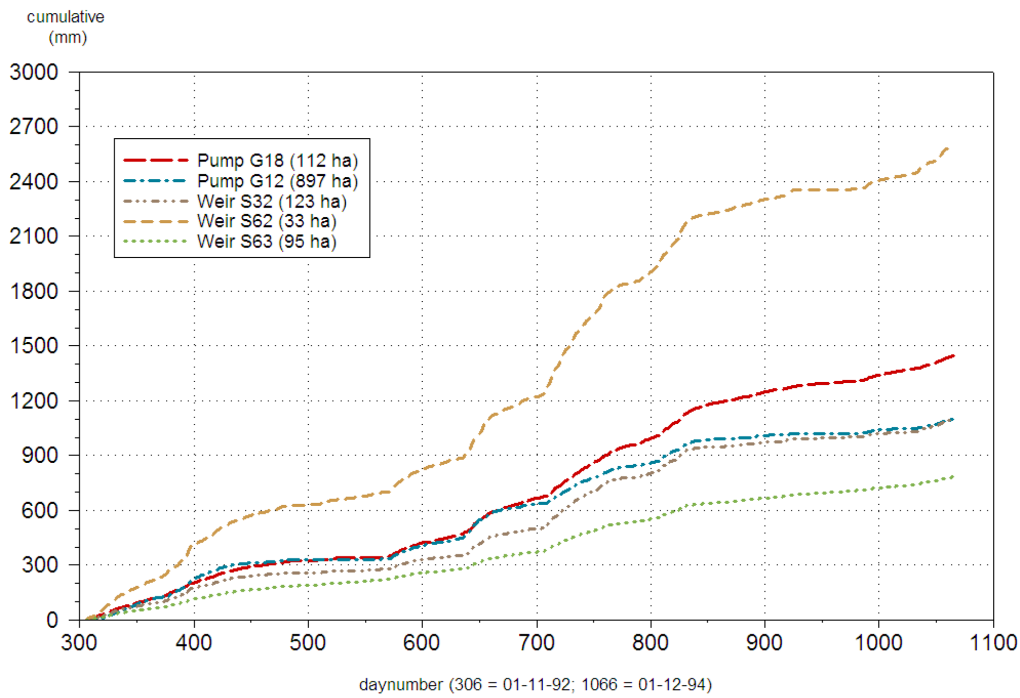

Figure 10: Cumulated discharge per unit area, measured at 2 drainage pumps and 3 weirs (van Walsum et al., 1998). The estimated catchment area of each device is given in Table .

3.2.4 Field elevation

Field elevation data were obtained from a national elevation map with a resolution of 100 m. Figure 11 shows a contour map, obtained by interpolation between the points of the elevation map with a resolution of 100 m.

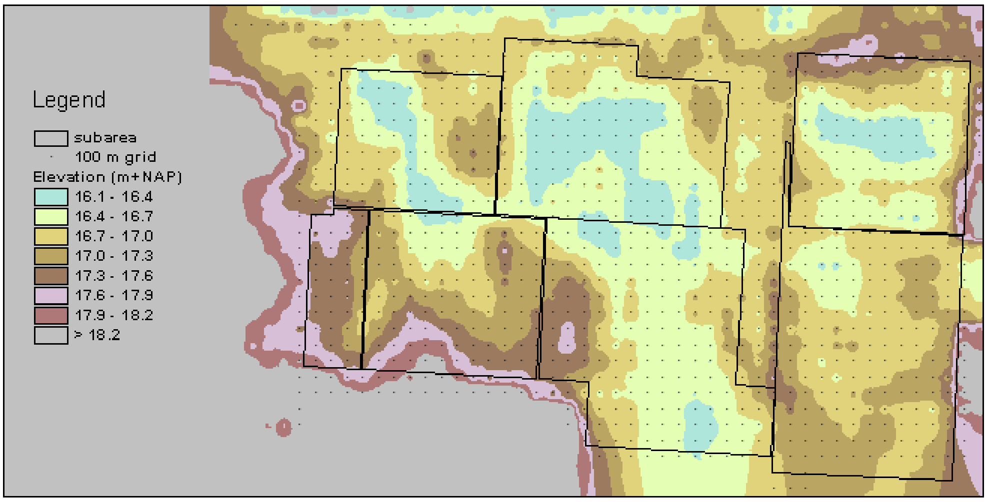

Figure 11: Elevation map of the study area (obtained by interpolation between elevation points at a 100m grid).

Except in the south-western part of the area (Subarea 6, 7) there is no clear direction of slope. The average elevation of the study area is 16.8 m above reference level NAP. The average elevation of each subarea is calculated using the elevation points of the 100 m grid (Table 3). Also included in the table are the target water levels of the subareas. In the Subareas 1 to 5, the lower target water level is 1.4 to 1.6 m below the average elevation of these subareas. In the south-western part of the area, where the elevation is higher, the lower target water level is 1.9 m below the average elevation in Subarea 6 and 2.3 m below the average elevation in Subarea 7.

Table 3: Average field elevation and target water levels of the subareas

Subarea (Figure 6)	Average elevation (m+NAP)	Target water level winter (m+NAP)	Target water level summer (m+NAP)
1	16.45	15.05	15.40
2	16.61	15.15	15.45
3	16.70	15.10	15.50
4	16.72	15.15	15.45
5	16.88	15.40	15.70
6	17.10	15.20	15.50
7	17.54	15.25	15.65

3.2.5 Observed groundwater levels

Observation wells at 14 locations were retrieved from a national database with (historic) data on groundwater levels (DINO). Some wells were rejected because of their location or filter depth. Other wells had insufficient observations, or the observations showed no fluctuation during the period of discharge measurement.

Four observation wells were selected with 30 observations available within the period of discharge measurement. The location of these wells is shown in Figure 12.

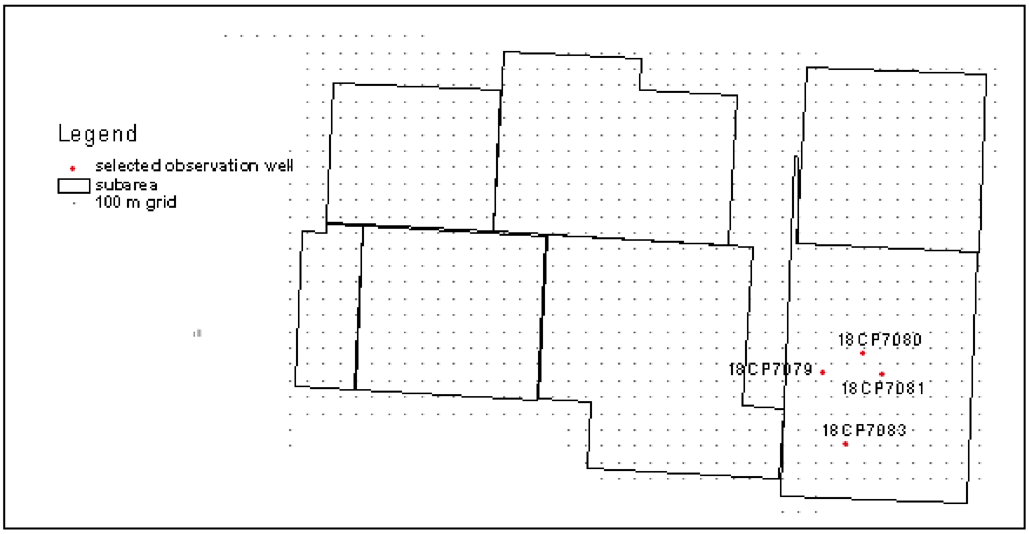

Figure 12: The location of groundwater observation wells within Subarea 5.

The groundwater depth observed at these wells is plotted in Figure 13 (in m-ss). The data are included in Appendix 2. Although the difference between the levels observed at the same day can be rather large (up to 0.5 m), the fluctuation can be compared with the simulated groundwater table.

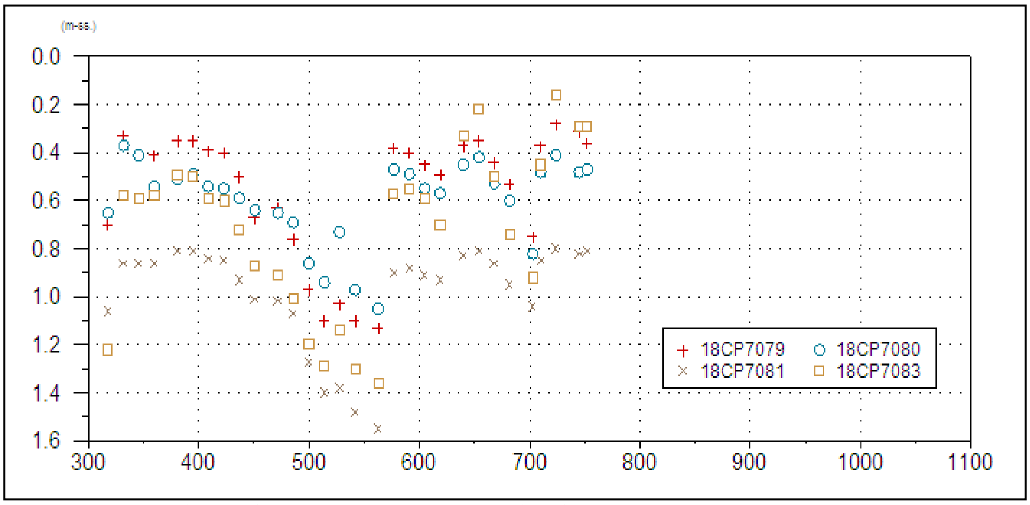

Figure 13: Observed groundwater levels within the period of discharge measurement (DINO).

3.2.6 Soil hydrology

The surface water module requires a description of drainage flow, precipitation and direct evaporation. These daily inputs should be representative for the area considered. Drainage flow towards the surface water system was generated with the soil hydrological model SWAP version 3.1.4. It was decided to parameterise SWAP for a single, representative soil column. The simulated crop was potatoes. Corresponding with the period of discharge measurement, the simulation period starts at November 1st, 1992 and ends at December 1st, 1994.

Details on the parameterisation of SWAP are given in Appendix 3. In summary;

- Local meteorological data: precipitation measured at the weather station Klazienaveen and reference evapotranspiration according to Makkink at the weather station Hoogeveen.
- Crop parameters: The maximum possible evapotranspiration for potatoes, using one crop factor based on decade values during the growing season (Feddes, 1987) and a so-called crop factor for bare soil evaporation during the remaining part of the year. The leaf area index as a function of crop development stage is based on STONE version 3.0 (Clevering and Van Bakel, 2006).
- A soil evaporation reduction function according to (Boesten and Stroosnijder, 1986).
- One soil profile was used. Profile data and soil water retention characteristics were obtained from an overlay with the hydrologic schematisaton of the nutrient fate model STONE version 2.0 (Kroon et al., 2003).
- Drainage parameters were taken from the hydrologic schematisation of STONE version 2.0 (Kroes et al., 2002; Kroon et al., 2003).
- The flux from the regional groundwater system was estimated using maps of the hydraulic head in the 2nd aquifer (Van Walsum et al., 1998)
- Surface water levels and surface water management data were based on Van Walsum et al. (1998)

SWAP was run with an extended drainage routine in order to simulate the interaction between the soil water and the surface water, including periods of prolonged drought, when the groundwater table drops below the surface water level. This drainage routine of SWAP calculates a surface water balance of the secondary drainage system (Kroes et al., 2003). The terms of the generated surface water balance include;

- Drainage flow towards the surface water (m d^{-1})
- External supply (m d^{-1})
- Infiltration from the surface water into the soil (m d^{-1})
- Discharge (m d^{-1})
- Storage (m)

The groundwater table simulated with SWAP was compared with the observed groundwater levels. The lumped sum of (net) drainage flow towards the surface water was converted to input of the surface water model SWQN (Section 4.1.2).

The soil hydrology simulated with the SWAP model is presented in Appendix 4. It is concluded that the calculated soil water balance terms are plausible, considering both the cumulated amounts and the time course of these balance terms during the meteorological seasons of the year and during the crop season. The results were carefully interpreted, based on expert judgment and/or comparison with local groundwater levels observed.

It is also concluded that the simulated drainage and infiltration flux gives a good description of the interaction between the soil water and surface water system in the study area.

4 Surface water flow

The model SWQN version 1.16 is used to generate the description of surface water flow in the study area. In Section 4.1, the concept of the schematisation of the surface water network and the required model input are described. The parameterisation of the model is described in Section 4.2. The results are presented in Chapter 5.

4.1 The model SWQN

The surface water model SWQN uses a dynamic link library (DLL) for computing water levels and flows in a network of open watercourses. The model SWQN is developed at WUR-Alterra (Smit and Siderius, 2007; Dik and Jeuken, 2007) and has an interface with the nutrient-fate model NUSWA-Lite. An example of recent application is the EUROHARP project.

The model SWQN requires the following input;

1. a network of nodes and sections
2. parameters of nodes
3. parameters of sections
4. boundary conditions
5. parameters of structures
    - structure definition
    - description of surface water management
6. initial conditions

4.1.1 Properties of nodes and sections

The surface water system is schematised as a network of nodes and sections. The nodes are the basic elements where the water level is computed. Each node is connected to one or more other nodes. A connection between two nodes represents an open watercourse and is called a section in SWQN. One can also define special types of sections representing a structure (pump, weir, undershot gate, culvert), or representing a transition to a watercourse with different cross-sectional dimensions.

In SWQN a node is defined by;

1. node ID,
2. location (a set of coordinates), and
3. bottom level.

Additional input per node describes (i) the maximum water level, (ii) the initial water level, and (iii) the precipitation district number.

In SWQN a section is defined by;

1. Section ID,
2. node ID at both ends (begin node and end node), and
3. length.

Additional input per section describes (i) the bottom width at both ends, (ii) the side slope at both ends, and (iii) the flow resistance coefficients at both ends and for both flow directions.

Table 4: Definition of nodes and sections in SWQN

Parameter	*Per node or section*	*Remark*
Node ID	Node	Input SWQN
Location (coordinate pair; m)	Node	Input SWQN
Bottom level (m+NAP)	Node	Input SWQN
Maximum water level (m+NAP)	Node	Input SWQN
Initial water level (m+NAP)	Node	Input SWQN
Precipitation district number	Node	Input SWQN
Section ID	Section	Input SWQN
Begin Node ID	Section	Input SWQN
End Node ID	Section	Input SWQN
Length (m)	Section	Input SWQN
Bottom width (m) *	Section	Input SWQN
Side slope factor (-) *	Section	Input SWQN
Flow resistance coefficients *	Section	Input SWQN
Water level at end of time step (m+NAP)	Node	Output SWQN
Water depth at end of time step (m)	Node	Output SWQN
Discharge per time step (m^3/s)	Section	Output SWQN

* at the begin and at the end of the section

The location of a node coincides with the intersection point of the centerlines of the connected sections. There is no difference between the begin node and the end node of a section. By definition, the direction of flow from the begin node towards the end node has a positive sign, and the opposite direction of flow has a negative sign. Depending on a user defined switch, the resistance coefficients can either be specified according to Chezy or according to Manning.

According to the definitions in Table 4 (i.e. when the model is run with the option BottomDepthLocation = 1), sections connected to the same node have equal bottom level at the location of that node. Figure 14 shows 3 nodes connected with 2 sections in a longitudinal cross-section. The vertical axis shows the elevation (in m above reference level) and the horizontal axis shows the distance (in m chainage, starting at Node 1).

The model calculates the slope of each section based on the difference between the bottom level of the nodes at both ends and the section length. The model assigns some other properties to the nodes, based on the input per node and section;

- The representative area of surface water per node is calculated based on the water width corresponding with the maximum water level, times half the length of the connected sections (as shown in Figure 14). This representative area is used for calculating the evaporation – and precipitation boundary conditions at the node (Section 4.1.2).
- The storage capacity of each node is calculated based on the representative area, the side slope factor of the connected sections, and the maximum water level at the node.

The actual volume of water stored at each node is calculated depending on storage capacity, in- and outgoing flows, and the boundary conditions.

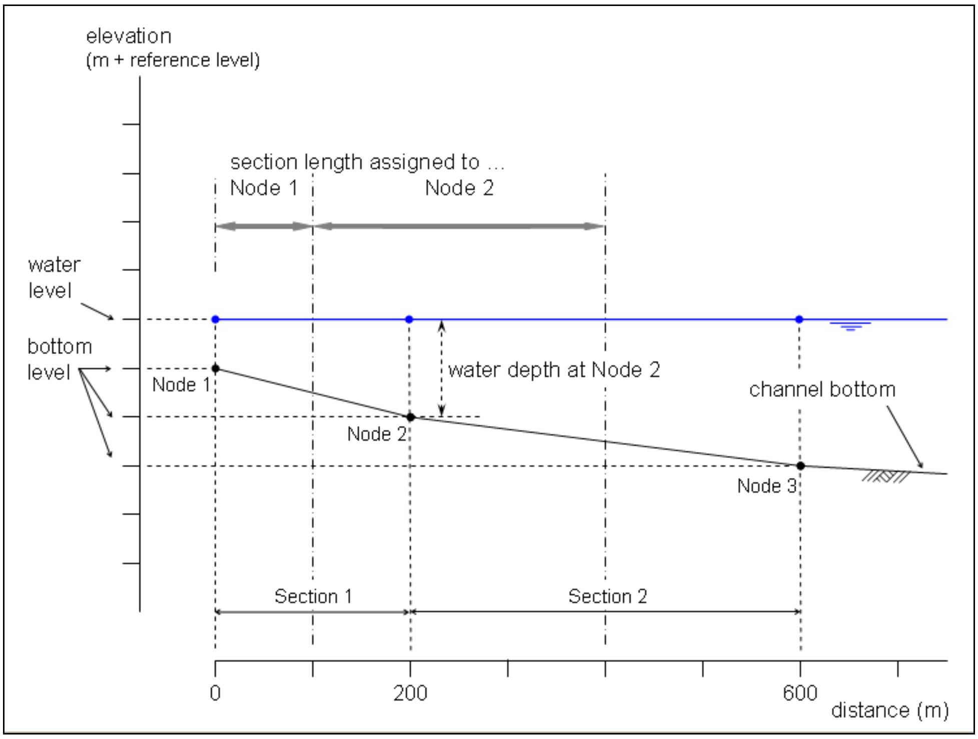

Figure 14: Illustration of the concept of nodes and sections in SWQN. An arbitrary watercourse is schematised starting with sections of 200 and 400 m length. The bottom level of the channel and the (initial) water level are defined at the nodes (in m above reference level). The model assigns half the length of the connected sections to the nodes (see text). The water depth refers to the vertical distance between the bottom level and the water level (in m).

Additional output per section can be derived with a post-processing programme (Appendix 5). Part of these outputs were used to present the results of the SWQN model per section;

- Average water level at end of time step (m+NAP)
- Discharge (m3/d)
- Average water depth at end of time step (m)
- Average wet cross-section at end of time step (m2)

- Average water volume at end of time step (m3/d)
- Average width of the water body at end of time step (m)
- Average flow velocity (m/d)
- Residence time (d)

4.1.2 Boundary conditions

All input for SWQN is defined on a daily basis. The following boundary conditions are defined at the nodes of the schematisation;

1. Drainage,
2. Precipitation, and
3. evaporation.

Flow boundary
The flow boundary condition in SWQN represents the drainage flow towards the surface water (positive sign) or the infiltration of surface water into the soil (negative sign). This model input is specified as a volume of water per time step, and can be prepared using the simulation results of a soil hydrological model;

$$Q_d = q\, A\, 10^4/86400 \qquad \text{Eq. 4-1}$$

With;

Q_d	flow boundary at the node (m^3s^{-1})
q	aeric flux representing the lumped sum of runoff, drainage, seepage into the surface water, and infiltration from the surface water into the soil (m d^{-1})
A	surface area assigned to the node (ha)

The area *A* in Eq. (4-1) can be regarded as the catchment area of the node. This area will depend on local conditions to drainage flow and on the distance between the nodes of the schematisation. The factor $10^4/86400$ in Eq. (4-1) is used to convert from (ha m d^{-1}) to (m^3s^{-1}).

Precipitation
The precipitation boundary condition is specified as a layer of water per time step in (m d^{-1}). In large areas, a distinction between precipitation districts can be made. The model calculates the precipitation volume (m^3s^{-1}) based on the representative area of the nodes (Section 4.1.1).

Evaporation
For each precipitation district, the evaporation boundary condition is specified as a layer of water per time step (flux) in (m d^{-1}). The model calculates the volume of water evaporated (m^3s^{-1}) based on the representative area of the nodes (Section 4.1.1).

Level boundary
A level boundary can be defined at any node of the schematisation. The water at the node will be at a constant level, during the period specified in the SWQN input file SWQN_LevelBoundary.CSV (Appendix 1).

4.1.3 Structures

Several types of structures may be defined;

- a pump,
- a weir,
- an undershot gate, or
- a culvert.

For each type of structure, separate input files are required for constants (structure definition), and for time-dependent parameters describing the surface water management.

In the surface water map of the study area no undershot gates and culverts are used; all structures except the drainage pumps are defined as a weir. The mode of control depends on the purpose of the structure, as will be explained in Sections 4.2.4.1 (pumps) and 4.2.4.2 (weirs).

Except the SWQN-input file with runtime options, all input files of SWQN are ASCII-files with comma separated values (CSV). An overview of input and output files of SWQN is included in Appendix 1.

Pumps
A pump is defined in SWQN by the following input;

1. Pump ID
2. Section ID
3. a linear relation between the difference in water level at both sides of the device and the discharge (referred to as a stage discharge relationship; Eq. 4.2)

$$Q_{pump} = A\,(h_{downstream\ side} - h_{upstream\ side}) + B \qquad \text{Eq. 4.2}$$

with;

Q_{pump}	pump discharge (m^3s^{-1})
h	surface water level (m+NAP)
A	pump coefficient (m^2s^{-1})
B	pump constant (m^3s^{-1}).

These parameters are read from the input file SWQN_PumpDefinition.CSV.

The user may select one of the following modes of pump control;
1. variable discharge
2. start - and stop water level at the begin node of the section (upstream side)
3. start - and stop water level at the end node of the section (downstream side)

The user can define any number of periods with alternating modes of pump control, or with different start- and stop levels. The begin- and end date of these periods are read from the input file SWQN_PumpControl.CSV, together with the other control parameters.

Weirs
A weir is defined in SWQN by the following input;
1. Weir ID
2. Section ID
3. initial - and maximum crest width (m), or;
4. maximum -, minimum - and initial crest level (m+NAP)
5. free flow resistance (for each direction; $m^{1.5}s^{-1}$)
6. submerged flow resistance (for each direction; $m^{1.5}s^{-1}$)

The user may select one of the following modes of weir control;
1. fixed crest width,
2. fixed crest level,
3. target level at the begin node (variable crest level)
4. target level at the end node (variable crest level)

The mode of control and the corresponding parameters are time-dependent; the user can define subsequent periods with different modes of weir control. The begin- and end date of these periods are read from the input file SWQN_WeirControl.CSV, together with the other control parameters.

4.1.4 Model output

The model produces the following types of output;
1. an interface with NUSWA-Lite
2. water balances
3. water depth and water level per node
4. discharge per section

The interface with NUSWA-Lite is a binary file with network layout, state variables and water balances. Almost all the other output is written to ASCII-files with comma separated values (CSV).

Table 5 contains an overview of the water balance files produced by SWQN.

Table 5: Water balance output of SWQN (See also ***Appendix 1****).*

File	Description
SWQN_OutBalance.csv	Water balance per time step for each node; • water level at end of time step, • volume at start and at end of time step, • internal flow discharge at each connection (max. = 4), • flow boundary discharge, • level boundary discharge, • precipitation boundary discharge, • evaporation boundary discharge, • absolute - and relative balance error.
SWQN_OutBalanceYearly.csv	Yearly water balance for each node; • internal flow discharge, • flow boundary discharge, • level boundary discharge, • precipitation boundary discharge, • evaporation boundary discharge, • storage change, • balance error.
SWQN_OutTotalBalance.csv	Daily water balance for whole network; • volume at start and at end of time step, • internal flow discharge at each connection (max. = 4), • flow boundary discharge, • level boundary discharge, • precipitation boundary discharge, • evaporation boundary discharge, • absolute - and relative balance error.
SWQN_OutTotalBalanceYearly.csv	Yearly water balance for whole network; • flow boundary discharge, • level boundary discharge, • precipitation boundary discharge, • evaporation boundary discharge, • storage change, • balance error.

The daily water level and water depth at each node are written to separate output files. The water level is defined in meters above reference level. The water depth is defined as the difference between the water level and the bottom level of the node (in m). In addition, an output file is created with the daily discharge at each section (in m^3s^{-1}).

4.2 Parameterisation of the model

The purpose of this section is to describe the procedure to schematise the surface water network and to prepare the input data of the hydrological module.

4.2.1 Network schematisation

The schematisation of the surface water network was created in ArcGIS, using map layers with the geometry of surface watercourses and parcels (Chapter 3) as a base map.

The aerial photograph in Figure 15 shows a detail of Subarea 2, located in the north eastern part of the study area (Figure 6), with the corresponding schematisation of the surface water network. Two field ditches are connected to the channel at the right hand side. This channel is connected to a second channel at the bottom side. A drainage pump is located at the downstream end of this second channel (i.e. at the left hand side in the figure).

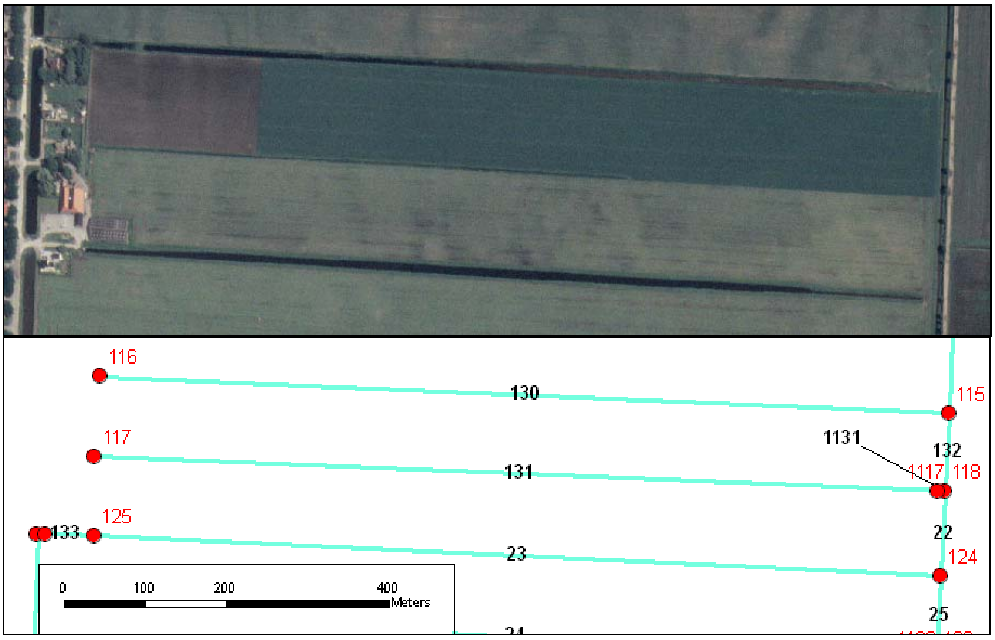

Figure 15: Aerial photograph with part of the corresponding schematisation of the surface water network. Nodes are indicated with red bullets and sections with blue lines. Node ID's are indicated in red and Section ID's in black. The drainage pump is represented by Section 133. (the inlet weir of Subarea 2 is not shown)

A node was created at both ends of a watercourse; one at the upstream end and one at the point of connection with other watercourses. Also, nodes were created at locations where the dimensions of a watercourse change, or at the location of a structure. Field ditches and other watercourses in the study area may have different depths. These watercourses were parameterised using section types with specific cross-sectional dimensions, as will be explained in Section 4.2.2.

The shallow ditch at the center of Figure 15 (Section 131) is connected to a watercourse of greater depth. In order to schematise this connection, a section was created between the Sections 131 and 22. The length of this Section 1131 created between Nodes 1117 and 118 equals 10 m. Figure 16 shows the bottom level at the nodes along the pathway of Sections 131, 1131, and 124. It is assumed that the watercourses in the study area have a zero slope. Hence, the bottom level in the nodes at both ends of a watercourse is the same. The difference between the bottom level of Nodes 1117 and 118 equals 0.75 m, i.e. the difference between the channel bottom of section types III and I (Table 6).

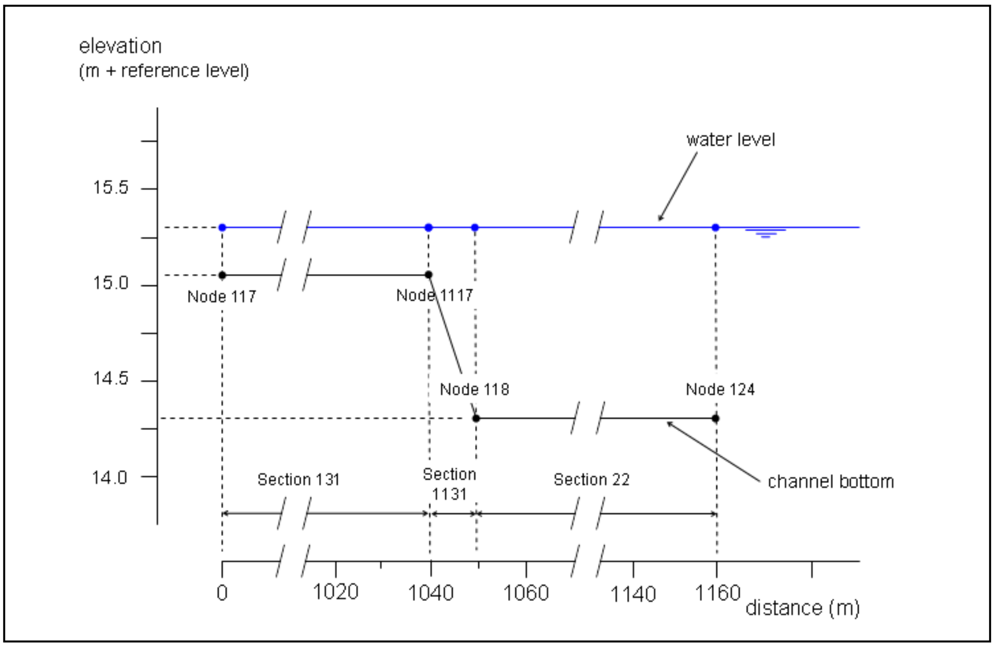

Figure 16: Side view with the nodes connecting Sections 131, 1131 and 22 (see also Figure 15) The difference between the bottom level of Nodes 1117 and 118 is determined by the channel bottom of Sections 131and 22.

The procedure explained in this paragraph was followed at each connection of watercourses having different bottom depths.

4.2.2 Properties of nodes and sections

A pair of coordinates and a unique ID were generated for each node by running a script in ArcView. The script stores the results in the attribute table of the point theme. These coordinates and ID's were copied to the input file SWQN_NodesDefinition.CSV. Also, the length and a unique ID were generated for each section. The ArcView script stores the results in the attribute table of the line theme. These attributes were exported to the input file SWQN_SectionsDefinition.CSV.

The average elevation of the subarea is used to prepare additional inputs, i.e. the bottom level, the maximum water level and the initial water level at the nodes. Each node and each section is assigned to one of the subareas in the study area (Figure 17). A section is created at the boundary between subareas, because the bottom level changes at these locations. The begin node of these sections at the boundary between subareas is assigned to the subarea at the upstream side, and the end node to the subarea at the downstream side. The section at the boundary between subareas is assigned to the subarea at the upstream side.

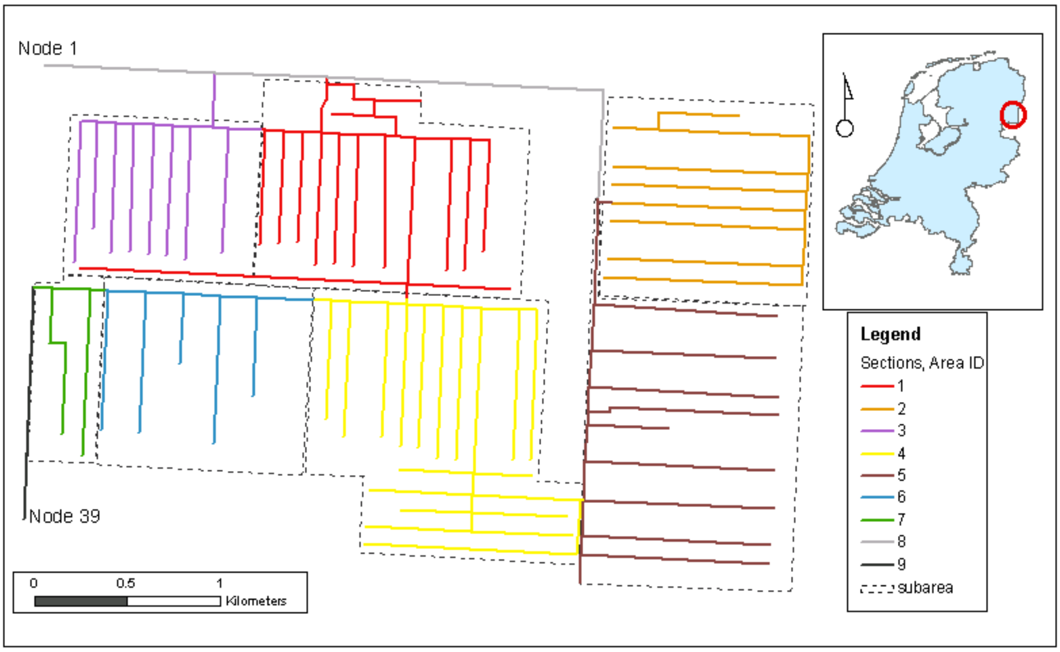

Figure 17: The Area ID of sections on the surface water map corresponds with the subarea numbers 1 to 7. Area ID 8 and 9 refers to sections located outside the catchment area.

Section Types

It was decided to define 4 types of sections with different cross-sectional dimensions and flow resistance coefficients. The section parameters were estimated for each type, based on the topographical map and expert judgment (Table 6). A map with these section types is shown in Figure 18. Sections representing an open watercourse have equal dimensions at both ends, and equal resistance coefficients at both ends and for both directions of flow (excluding the 10 m sections added to the surface water map at locations where the bottom level changes).

The concept of the model SWQN assumes constant resistance coefficients.

Table 6: Parameters of section types.

Section type		Bottom width (m)	Bottom depth (m-ss.)	Side slope h:v (-)	Resistance coefficient (Manning) ($m^{1/3}s^{-1}$)	Bottom slope ($m\ m^{-1}$)	Maximum water depth (m)
I	Small ditch	0.5	1.25	1	10	0	1.0
II	Medium ditch	1	1.5	1	20	0	1.2
III	Large ditch	2	2	1.25	30	0	1.6
IV	Main channel	3	2.5	1.5	40	0	2.0

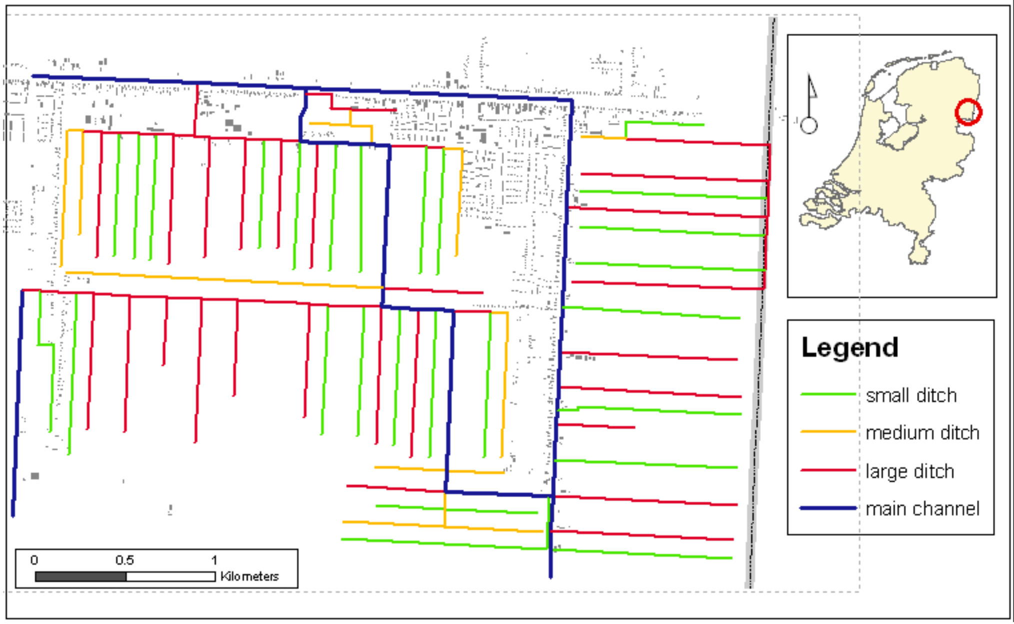

Figure 18: Map with section types according to Table 6.

Bottom Levels
In SWQN, the bottom level is part of the node definition. By assuming that the water depth in small ditches = 0,10 m when the water level is at lower target level, the bottom level at each end node can be derived from the section type and the target level in the subarea;

$$BL_{EndNode(S)} = LowerTargetLevel - y + (BD_{Type\ I} - BD_{EndNode(S)}) \qquad \text{Eq. 4-3}$$

With;

$BL_{EndNode(S)}$	the bottom level at the end node (m+NAP)
LowerTargetLevel	the lower target level in the subarea (m+NAP)
y	the assumed water depth in small ditches, when the water level is at lower target level (0.10 m)
$BD_{Type\ I}$	the bottom depth of section type I (m-ss.)
$BD_{EndNode(S)}$	the bottom depth at the end node (m-ss.)

For example, in Subarea 2 the lower target level = 15.15 m+NAP. The bottom level at the end node of a medium ditch (type II) = 15.15 – 0.1 + (1.25 – 1.5) = 14.80 m+NAP. The bottom level of the end node = 15.05 m+NAP in a small ditch, 14.30 m+NAP in a large ditch, and 13.80 m+NAP in a main channel.

At a begin node located at the tail end of a channel, the bottom level equals the bottom level at the end node of the section.

Maximum water level
The maximum water level at the nodes equals the average elevation of the subarea (Table 3). Outside the catchment area, the average surface elevation is not derived

from the elevation map. At these nodes (Area 8 and 9; Figure 17) the maximum water level was estimated = 17.6 m+NAP. Note that the maximum water level is only used in SWQN for calculating the volumes of direct precipitation and evaporation from the surface water.

Initial water level

The initial water level at the nodes is set = 0,5 m below the average elevation of the subarea (Table 3). At the nodes located outside the catchment area the initial water level = 17.1 m+NAP.

Drained area per node

The drained area per node is needed in order to prepare the flow boundary input at the nodes. The estimation of the drained area per node is based on expert judgment; drainage flow towards the surface watercourse will depend on soil properties, topography, and the density of watercourses. In addition, the distance between the nodes of the schematisation plays a role. The area drained to the nodes outside the catchment area was set equal to zero.

Figure 19 shows a map of the estimated drained area per node. The total drained area of all nodes = 897 ha.

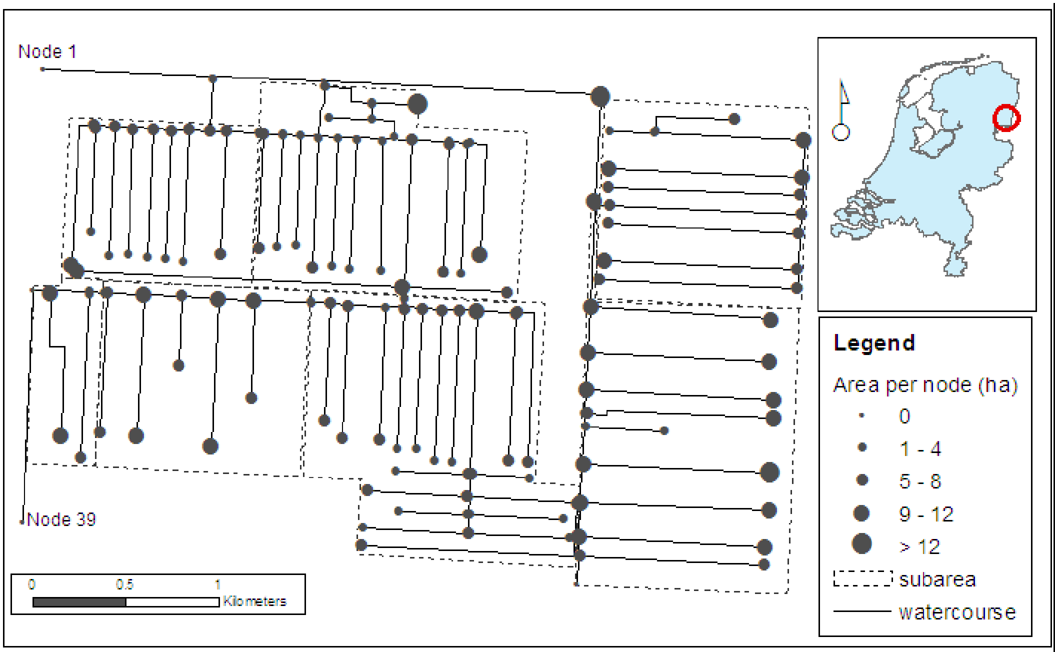

Figure 19: Map with the drained area per node, used for calculating the flow boundary of the surface water model

4.2.3 Boundary conditions

Flow boundary

The cumulated drainage flux simulated with SWAP is fitted to the measured discharge by adapting the area drained per node (Eq. 4.1). The total area of the nodes located within a subarea is represented in the discharge at the subarea outlet (i.e. the weir or pump). The total area of the nodes within all 7 subareas represents the catchment area drained via the pump G-12. The accuracy of the estimated catchment area is approximately 10%. This applies both to the individual subareas and to the study area as a whole.

In Figure 20, the cumulated drainage flux is plotted together with the discharge measured at 2 drainage pumps and 3 weirs (discharge per unit area; in mm). The cumulated net drainage flux simulated with SWAP = 1056 mm. The cumulated net drainage flux fits the best to the discharge from Subarea 7 and 6 measured at Weir S-32 and to the discharge from the entire study area measured at drainage pump G-12. The discharge from Subarea 2 measured at Pump G-18 is higher, whereas the discharge from Subarea 3 measured at Weir S-63 is lower. These differences can be explained by heterogeneous soil hydrological conditions. This heterogeneity can not be described with the single soil column that was used to parameterise SWAP. Other factors that may contribute to this different fit are the estimation of the area drained per node, and the accuracy of the discharge measurements.

It can be seen in Figure 20 that the discharge measured at Subarea 7 (Weir S-62) deviates with a factor 2 from the discharge measured at the other locations. This deviation can't be explained and is regarded as non-representative. Note that the size of Subarea 7 is only 4% of the study area.

It can be concluded that the kinetics of the flux simulated with SWAP corresponds quite well with the measured discharge. This applies both to periods of high discharge (e.g. Nov. 1992 – March 1993 / daynr. 300 – 450) and to periods of zero or negligible discharge (e.g. June - July 1993 / daynr. 520 – 570). The best fit of the simulated drainage flux per unit area to the measured discharge is obtained at the scale of the entire catchment.

Considering both the cumulated amount and the fluctuation of drainage flow within the period of discharge measurements, it can be concluded that the simulation with SWAP resulted in acceptable input for the surface water model SWQN.

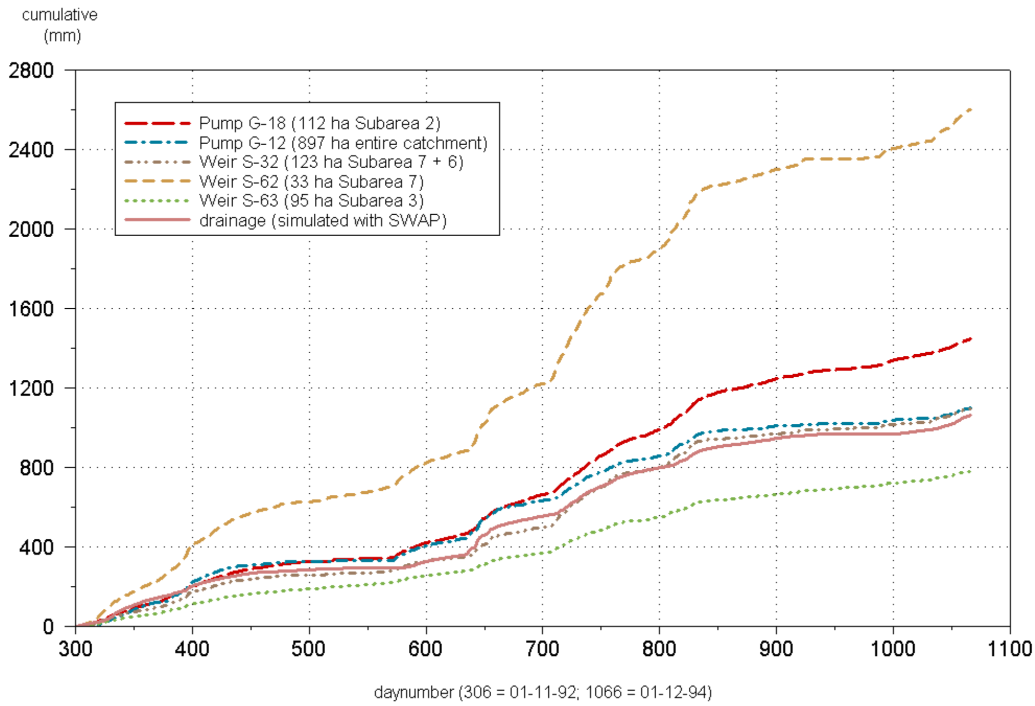

Figure 20: Cumulated drainage flux simulated with SWAP version 3.1.4. and the discharge measured at 2 drainage pumps and 3 weirs (in mm)

The cumulated difference between the net and gross drainage flux is only 4 mm; i.e. the simulated infiltration of surface water into the soil profile. The net drainage flux simulated with SWAP is converted to the flow boundary Q_d (Eq. 4.1).

Precipitation and evaporation boundaries

The daily precipitation and evaporation fluxes were taken from the meteorological input data of the soil hydrological model SWAP. Because the contribution of direct evaporation from the water surface to the surface water balance is rather small, Makkink evapotranspiration data were taken as an approximation of the open water evaporation (Table 12). The entire study area is considered as one precipitation district.

Level Boundary

A level boundary was defined at Nodes 1 and 39 (Figure 19), in order to maintain a constant water level at the channels outside of the area drained by Pump G-12. These channels serve as a reservoir for the external supply of water to the area during periods of drought, or when the target water levels are raised.

Table 7: Level boundary at the reservoirs for external supply

Node ID	*Water level (m + NAP)*
1	15.8
39	16.3

4.2.4 Parameters of water management structures

The parameters and control settings of the water management structures serve to maintain the target levels in the subareas, during periods of discharge and periods of external supply.

The following requirements were formulated;
1. During prolonged periods of discharge at the outlet there is no external supply of water
2. During prolonged periods of external supply of water there is no discharge at the outlet

These requirements apply to the individual subareas and to the catchment as a whole. The structures for maintaining the target water levels in the area are adjusted at fixed dates;
- The low target level (Winter Peil/WP) is raised at April 1st.
- The high target level (Zomer Peil/ZP) is lowered at October 1st.

The periods of low target level coincide with the period of reduced evaporation and crop water use. In line with common water management practice in this type of polder areas, it is assumed that external supply of water is only possible during periods of high target level (coinciding with the growing season of the crop).

The schematisation of the surface water includes 2 drainage pumps and 12 weirs. The function of a weir can be related to;
1. the discharge of surplus water
2. the external supply of water
3. the distribution of external water within the area

4.2.4.1 Pumps

The water level in Subarea 2 is managed with drainage pump G-18, whereas the Pump G-12 serves as the outlet of the entire area (897 ha). For both pumps, the discharge dependent pump characteristic is set equal to zero; so the pump discharge is independent of the head difference (Section 4.1.3). At Pump G-18, the pump constant = 0.125 m^3s^{-1}. Given the size of the drained area (112 ha), this corresponds with a discharge capacity of 10 mm d^{-1}. At Pump G-12, the pump constant = 1.25 m^3s^{-1}. This corresponds with a discharge capacity of 12 mm d^{-1}.

The pump definition and control parameters are given in Table 8. For reference, the target water levels and Node ID at both sides of the structure are included in the table.

The operation of the pump is controlled by means of a start - and stop water level at the upstream side (parameter SelectControlPump = 2). When the water level in the node at the upstream side is above start level, the pump is started. The pump will stop as soon as the water level has reached the stop level. At both pumps, the start level is set at 0.05 m above target level, and the stop level at 0.01 m below target level.

Table 8: Pump definition and control parameters at the outlet of Subarea 2 (G-18) and the entire catchment (G-12).

Structure Code	G-18		G-12	
Section_ID	133		138	
Area_ID downstream side	5		8	
Area_ID upstream side	2		1	
Node_ID upstream side	125		111	
Node_ID downstream side	1125		1111	
Pump coefficient A	0.0		0.0	
Pump constant B	0.125		1.25	
Water management period	WP	ZP	WP	ZP
SelectControlPump	2	2	2	2
Target Level downstream	15.15	15.45	15.05	15.40
StartLevel	15.20	15.50	15.10	15.45
StopLevel	15.14	15.44	15.04	15.39

4.2.4.2 Weirs

The weir definition and control parameters are given in Tables 9, 10 and 11. For reference, the target water levels and Node ID at both sides of the structure are included in these tables.

Discharge of surplus water

There are 5 weirs defined for discharge of surplus water;

1. Weir S-62 (Section 76) to Subarea 6,
2. Weir S-32 (Section 144) to Subarea 4,
3. Weir S-63 (Section 142) to Subarea 1,
4. Weir S-98 (Section 47) to Subarea 4, and
5. Weir S-61 (Section 78) to Subarea 1.

These structures serve as an automatic weir, with the simulated discharge depending on the water level at the upstream side (parameter SelectControlWeir = 3; Table 9). The crest of the weir is adjusted by the model, within the range defined by parameters MaxCrestLevel and MinCrestLevel. The maximum crest level is equal to the higher target level at the upstream side, whereas the minimum crest level is set 0,2 m above the bottom level at the node upstream. When the water level at the upstream side is above the target level, water may flow towards the end node. When the water level at the upstream side is below the target level, no water can flow towards the end node.

Table 9: Definition and control parameters (weirs for discharge of surplus water)

Structure Code	S-62		S-32		S-63		S-98		S-61	
Section_ID	76		144		142		47		78	
Area_ID upstream	7		6		3		5		4	
Area_ID downstream	6		4		1		1		1	
Node_ID upstream	35		29		139		13		40	
Node_ID downstream	1035		1029		1139		1013		1040	
MaxCrestLevel	15.65		15.50		15.50		15.70		15.45	
MinCrestLevel	14.45		14.40		14.30		13.90		13.80	
InitCrestLevel	15.65		15.50		15.50		15.70		15.45	
Water management period	WP	ZP	WP	ZP	WP	ZP	WP	ZP	WP	ZP
SelectControlWeir	3	3	3	3	3	3	3	3	3	3
Target Level upstream	15.25	15.65	15.20	15.50	15.10	15.50	15.40	15.70	15.15	15.45
Target Level downstream	15.20	15.50	15.15	15.45	15.05	15.40	15.05	15.40	15.05	15.40
CrestLevel (fixed)	-	-	-	-	-	-	-	-	-	-
TargetLevel BeginNode	15.25	15.65	15.20	15.50	15.10	15.50	15.40	15.70	15.15	15.45
TargetLevel EndNode	-	-	-	-	-	-	-	-	-	-

External supply of water

During periods of low target level, these weirs have no function. The weir crest is set at a fixed level above the target level at the upstream side (parameter SelectControlWeir = 2; Table 10). This treshold is needed in order to prevent unwanted entrance of surface water.

During periods of high target level, external water can be supplied to the area at 4 locations;

1. Inlet weir S-94 (Section 114) to Subarea 7,
2. Inlet weir S-26 (Section 121) to Subarea 3,
3. Inlet weir S-97 (Section 31) to Subarea 5, and
4. Inlet weir S-45 (Section 145) from Subarea 5 to Subarea 2.

During periods of high target level, these structures serve as an automatic weir with the simulated discharge depending on the water level at the downstream side (parameter SelectControlWeir = 4). When the water level at the downstream side is below the target level at the end node (parameter TargetLevelEndNode), the weir starts to discharge and water may flow towards the end node. The water level at the downstream side will start to rise and when the target water level of the subarea is reached at the end node, the water demand is met and the flow across the weir will stop.

The difference between the target level at the end node (parameter TargetLevelEndNode) and the higher target level at the downstream side of the weir = 0.05 m. This treshold is needed in the model in order to retain the water being supplied. Without this treshold, the water supplied can leave the subarea via the weir at the outlet to the next subarea.

The crest level during periods of high target level is set 0.02 m above the higher target level at the upstream side for the Inlet Weir S-94 and 0.05 m above this level for the other Inlet Weirs.

Table 10: Definition and control parameters (weirs for external supply of water)

Structure Code	S-94		S-26		S-97		S-45	
Section_ID	114		121		30		145	
Area_ID upstream	9		8		8		5	
Area_ID downstream	7		3		5		2	
Node_ID upstream	38		3		4		5	
Node_ID downstream	1038		1003		140		1124	
MaxCrestLevel	16.32		15.85		15.85		15.75	
MinCrestLevel	15.65		15.50		15.70		15.40	
InitCrestLevel	16.32		15.85		15.85		15.75	
Water management period	WP	ZP	WP	ZP	WP	ZP	WP	ZP
SelectControlWeir	2	4	2	4	2	4	2	4
Target Level upstream	16.30	16.30	15.80	15.80	15.80	15.80	15.40	15.70
Target Level downstream	15.25	15.65	15.10	15.50	15.40	15.70	15.15	15.45
CrestLevel (fixed)	16.32	-	15.85	-	15.85	-	15.75	-
TargetLevelBeginNode	-	-	-	-	-	-	-	-
TargetLevelEndNode	-	15.60	-	15.45	-	15.65	-	15.40

Figure 21 shows a detail of the surface water map at the boundary between Subarea 5 and 2, with the Node ID, Section ID, the Pump G-18 and the Weir S-45. This configuration is needed in the model because two functions cannot be combined in one structure; i.e. the discharge of surplus water via the drainage pump and the supply of water to the subarea.

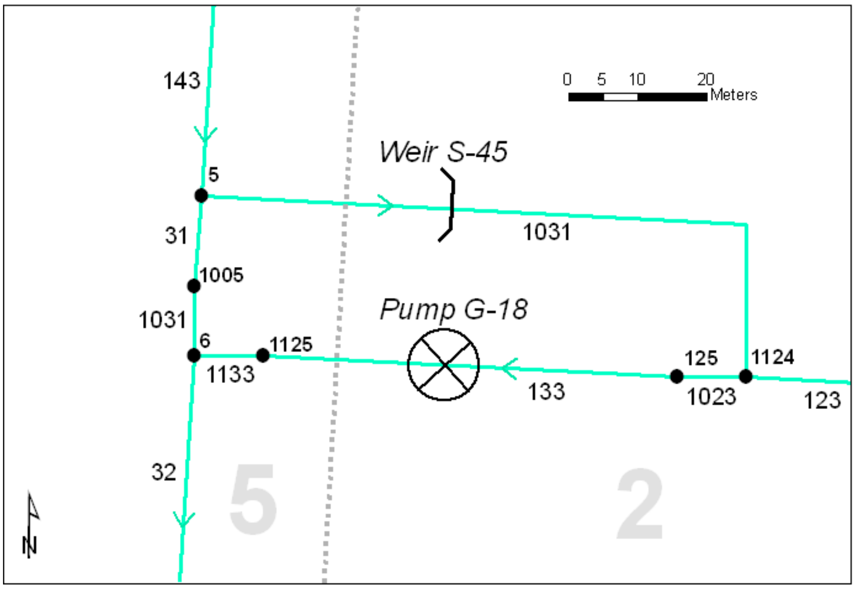

Figure 21: Detail of the surface water map at the boundary between Subarea 5 and 2, with the nodes (Node ID in bold case), sections (Section ID in normal case), drainage pump G-18 and Weir S-45.During periods of high target level water may be supplied to Subarea 2 via the Weir S-45.

Distribution of external water within the area

Distribution of external water within the area is controlled at 3 locations with a seperate weir;

1. Weir S-162 (Section 3076) from Subarea 7 to Subarea 6,
2. Weir S-163 (Section 3144) from Subarea 6 to Subarea 4, and
3. Weir S-132 (Section 3142) from Subarea 3 to Subarea 1.

Figure 22 shows a detail of the surface water map at the boundary between Subarea 7 and 6, with the Node ID, Section ID, and the Weir S-162 located in a virtual bypass of the channel defined as the Weir S-62. This configuration is needed in the model because two functions cannot be combined in one structure; i.e. discharge of surplus water regulated by the water level upstream, and distribution of external water within the area regulated by the water level downstream.

The same configuration is also used at Weir S-63, with Sections 2142, 3142 (Weir S-163) and 4142 forming the virtual by-pass, and at Weir S-32, with Sections 2144, 3144 (Weir S-132) and 4144 forming the virtual by-pass (see also Table 11).

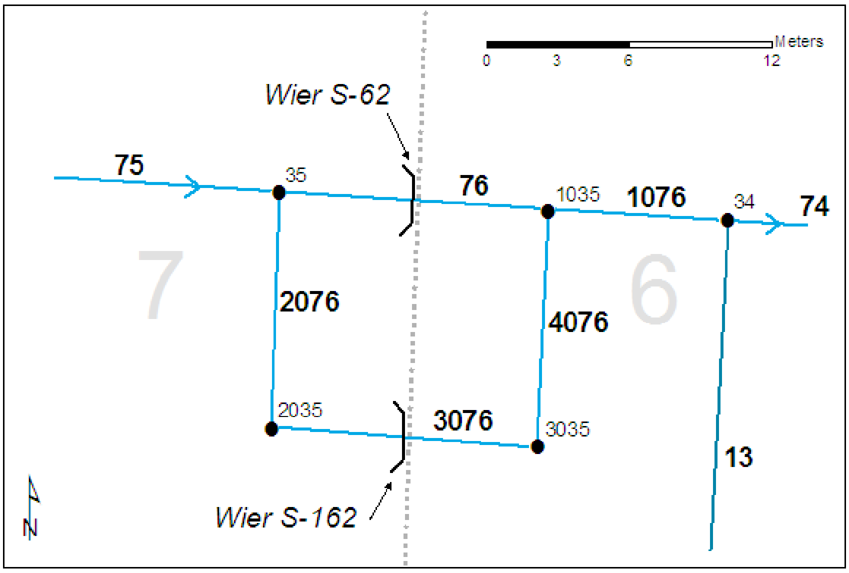

Figure 22: Detail of the surface water map at the boundary between Subarea 7 and 6, with nodes (Node ID in normal case) and sections (Section ID in bold case). Weir S-62 serves as an automatic weir with the crest level depending on the water level at the upstream side (Subarea 7). During periods of high target level, Weir S-162 may serve as an automatic weir for water supply, with the crest level depending on the water level at the downstream side (Subarea 6).

During periods of high target level, the Weir S-162 (Section 3076) may serve as an automatic weir for water supply, with the crest level depending on the water level at the downstream side (Subarea 6). The supply through Weir S-162 will continue as long as the water level at the downstream side (i.e. in Node 3035) is below the target level.

Note that the stop level of Pump G-18 is chosen above the target level at the end node of Inlet Weir S-45, in order to prevent the pump from operating while water is being supplied to the subarea. Accordingly, the stop level of Pump G-12 is chosen above the target level at the end node of Inlet Weir S-163.

Table 11: Definition and control parameters (weirs for distribution of external water within the area)

Structure Code	S-162		S-163		S-132	
Section_ID	3076		3142		3144	
Area_ID upstream	7		3		6	
Area_ID downstream	6		1		4	
Node_ID upstream	2035		2139		2029	
Node_ID downstream	3035		3139		3029	
MaxCrestLevel	15.75		15.60		15.60	
MinCrestLevel	15.55		15.40		15.40	
InitCrestLevel	15.30		15.15		15.25	
Water management period	WP	ZP	WP	ZP	WP	ZP
SelectControlWeir	2	4	2	4	2	4
Target Level upstream	15.25	15.65	15.10	15.50	15.20	15.50
Target Level downstream	15.20	15.50	15.05	15.40	15.15	15.45
CrestLevel (fixed)	15.30	-	15.15	-	15.25	-
TargetLevelBeginNode	-	-	-	-	-	-
TargetLevelEndNode	-	15.45	-	15.35	-	15.40

The parameterisation of the water management structures was tested with a special times series of the flow boundary based on SWAP simulations with artificial meteorological data (Appendix 6).

5 Results and discussion

In this chapter, some results of the surface water model SWQN are shown. These are; the cumulated discharge for the entire simulation period (Section 5.1), the surface water balance (Section 5.2), and some detailed results in Sections 5.3 and 5.4.

The following requirements were formulated;

- An acceptable fit of the lines of simulated discharge.
- A correct surface water balance; i.e. the simulation error is negligible compared to the balance total, so that all water is accounted for
- During prolonged periods of discharge at the outlet there is no external supply of water to the area
- During prolonged periods of external supply of water there is no discharge at the outlet
- A plausible simulation of surface water state and flow within the area.

5.1 Cumulated discharge

In Figure 23, the discharge measured at the drainage pumps is plotted with the discharge simulated at SWQN Sections 133 and 138, expressed in mm per unit of drained area. For the entire period, the cumulated discharge simulated at Section 133 is about 300 mm less than the measurement at Pump G-18 (-20%). The cumulated discharge at Section 138 exceeds the measurement at Pump G-12 with some 5 mm (0.5%).

Both during periods of zero discharge and during periods of high discharge, the lines of cumulated discharge simulated at the outlet (Section 138) and of cumulated discharge measured at Pump G-12 almost coincide. The simulation was fitted by the area drained per node; the estimation error is approximately 10% (Section 4.2.2).

Starting at November 1st, 1993 (daynr. 671), the discharge per unit drained area measured at Pump G-18 is higher than the discharge per unit drained area measured at Pump G-12. This continues during the summer of 1994, also when Pump G-12 has zero discharge. This deviation starting at November 1st, 1993, may be caused by the water management (adjustment of the pump and the inlet device), or by a change in boundary conditions to surface water flow.

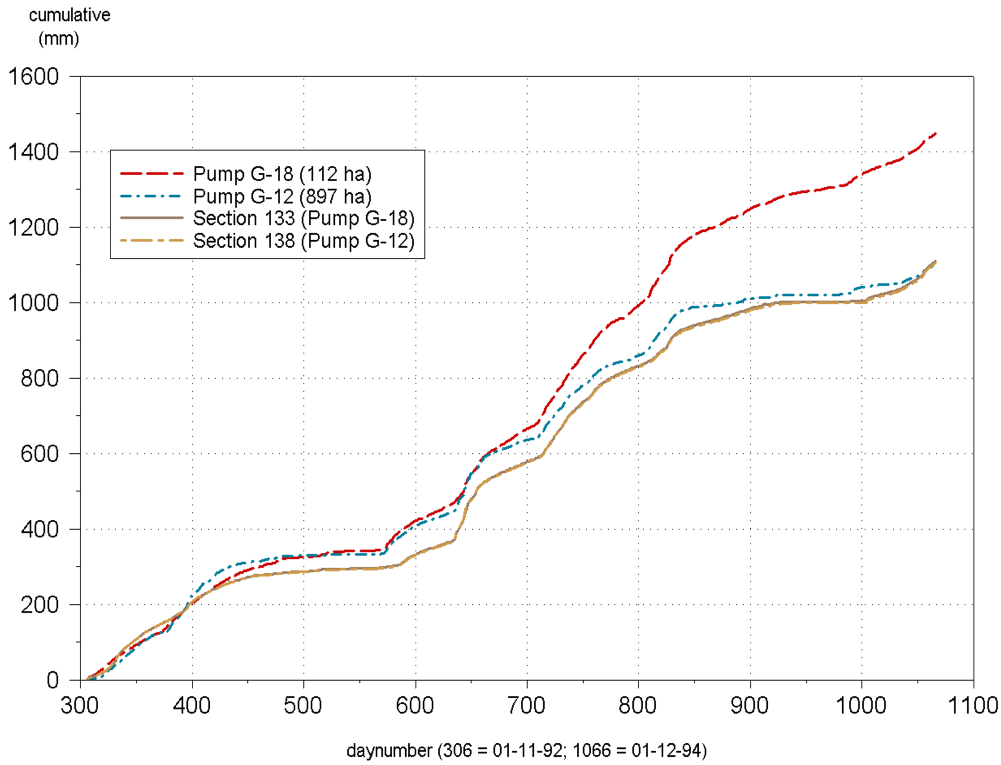

Figure 23: Measured discharge of the drainage pumps G-18 and G-12, and simulated discharge of SWQN-sections 133 and 138 (cumulated discharge per unit of drained area; in mm)

It is concluded that the kinetics of the discharge simulated at the outlet of the study area corresponds with the line of cumulated discharge measured during the entire 761-days simulation period. The simulated discharge from the study area exceeds the measured discharge with 0.5%. Within the study area, the fit of the cumulated simulated discharge to the cumulated measurement is less good than for the entire study area. This can be caused by a combination of factors not accounted for in the model parameterisation, such as: (i) heterogeneous boundary conditions to surface water flow, (ii) water management practice, (iii) measurement errors, (iv) deviations from the estimated area drained per node.

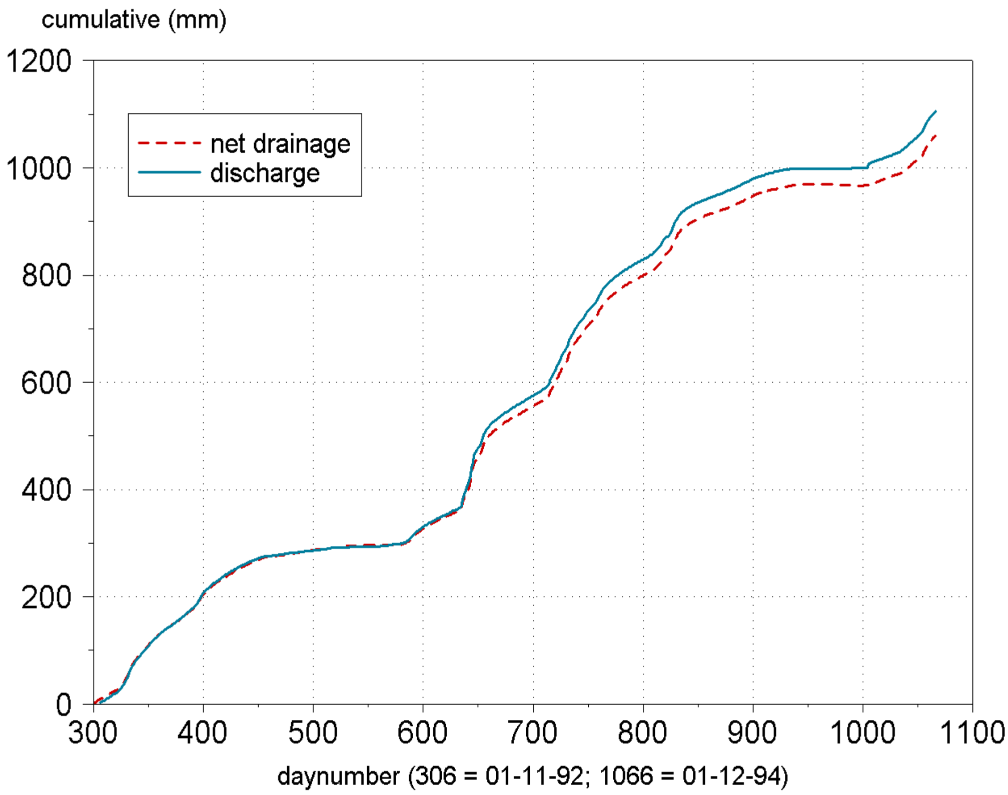

Figure 24: Cumulated lines of the net drainage flow towards the surface water and the discharge simulated at the outlet of the area

Figure 24 shows the cumulated lines of the net drainage flow towards the surface water and the discharge simulated at the outlet (Section 138; Pump G-12). It can be concluded from these two lines that the kinetics of the discharge from the entire area is dominated by drainage flow towards the surface water, during the period of discharge measurements.

During periods of prolonged drought the influence of external supply will become more important. This was shown with the simulations based on artificial meteorological input data (Appendix 6).

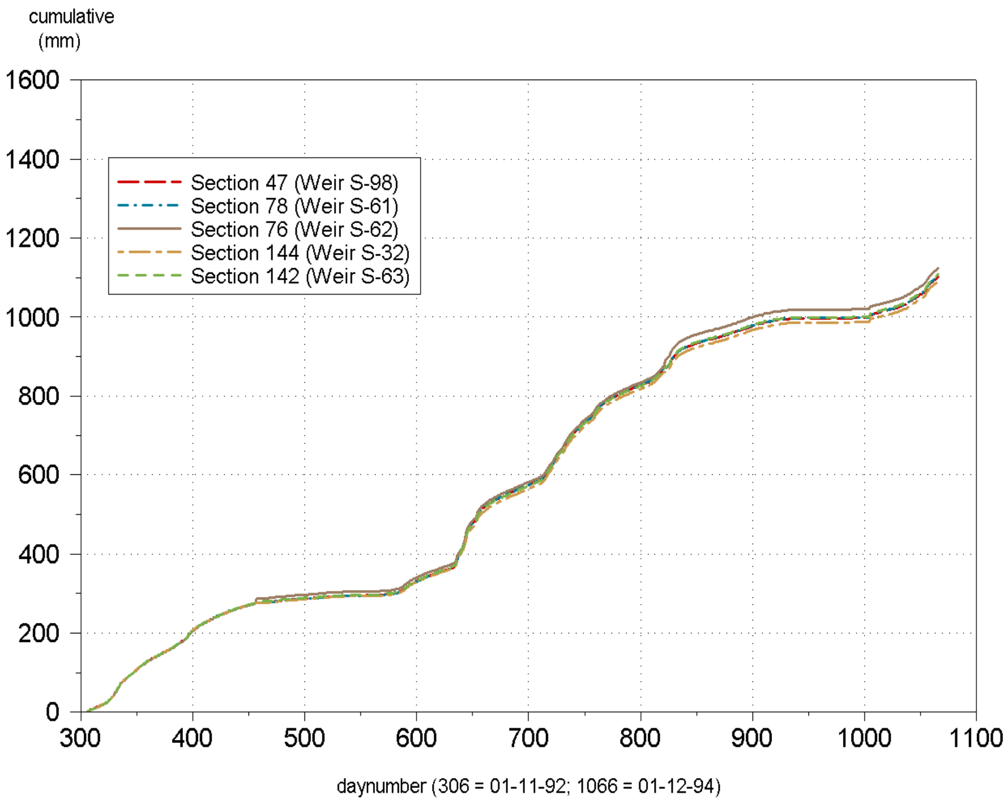

Figure 25: Cumulative discharge simulated at the boundaries between Subareas showing equal discharge per unit of drainaed area (in mm)

The cumulative discharge simulated at the boundaries between subareas is shown in Figure 25. These lines almost coincide, as can be expected based on the uniform flow boundary originating from a single soil column and the limited amount of water supplied to the area. It can be concluded that the discharge at the boundaries between subareas is consistent.

5.2 Surface water balance of the entire area

Table 12 shows the surface water balance of the 897 ha study area for the entire simulation period (in 10^6 m^3). The direct precipitation onto the water surface and evaporation from the water surface are based on a total channel length within the catchment = 60 247 m.

The amount of drainage from the soil corresponds with the lumped drainage term in the soil water balance. This surface water balance term contributes with 91% to the balance total. The amount of surface water infiltrating to the soil corresponds with the lumped infiltration term in the soil water balance (Appendix 4, Table 4.4). The discharge at the outlet (Section 138; Pump G-12) equals 9.92 10^6 m^3; (95% of the balance total).

The external supply of surface water to the area through the Inlet Weirs S-97 (Section 30), S-94 (Section 114) and S-26 (Section 121) equals 0.09 10^6 m^3. This small amount is explained by the amount of precipitation during the simulation period. The years 1993 and 1994 represent the 93rd and 97th percentile in the time series of annual precipitation from the KNMI-weather station Klazienaveen (period 1971 – 2000).

Table 12: Surface water balance of the entire catchment area (897 ha). (Simulated with SWQN version 1.16)

Surface water storage (10^6 m^3)		3 years	
Final	0.139	daynr final	1066
Initial	0.144	daynr initial	306
Change	-0.004	period (days)	761
Error	-0.001		
In-Out-Change	0.021		
Surface water balance components (10^6 m^3)			
In		Out	
Precipitation	0.84	Evaporation	0.44
Drainage from soil	9.48	Infiltration to soil	0.03
Supply	0.09	Discharge	9.92
Total	10.40	Total	10.39

SWQN Run 47, based on SWAP Run pgb10

The change in storage (the retention in the entire area) is negligible. The difference of the surface water balance (Total In – Total Out – Storage change) is 0.021 10^6 m^3 or 0.2% of the balance total. So, it can be concluded that all the water is accounted for and that the 761-days balance of the surface water in the study area is correct.

The cumulated lines of the major terms of the surface water balance are shown in Figure 26. The minor terms of the surface water balance are shown in Figure 27; i.e. precipitation onto the water surface, direct evaporation from the water surface, infiltration to the soil, and external water supply.

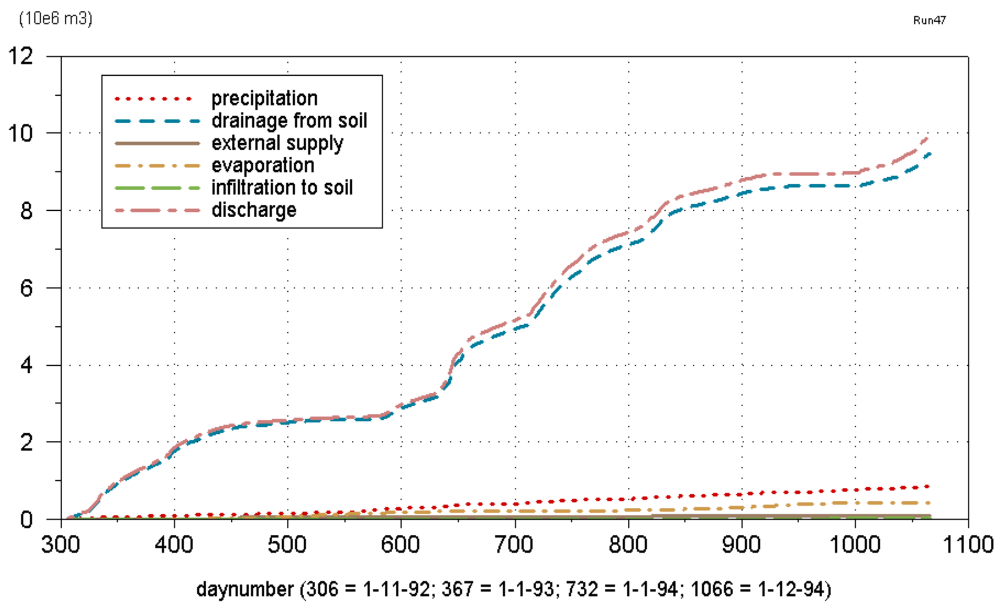

Figure 26: Cumulated terms of the surface water balance (in 10^6 m^3)

In line with the simulation of soil hydrology, precipitation measured at the weather station Klazienaveen was used for calculating direct precipitation onto the water surface. Also, the reference evapotranspiration according to Makkink measured at the weather station Hoogeveen was used for calculating evaporation from the water surface. Both terms of the surface water balance are calculated based on the actual area of surface water during the simulation period. The line of cumulated external supply shows the volume of water that is added to the surface water system at April 1st; i.e. the day when the target water level is raised (daynr. 457, 822).

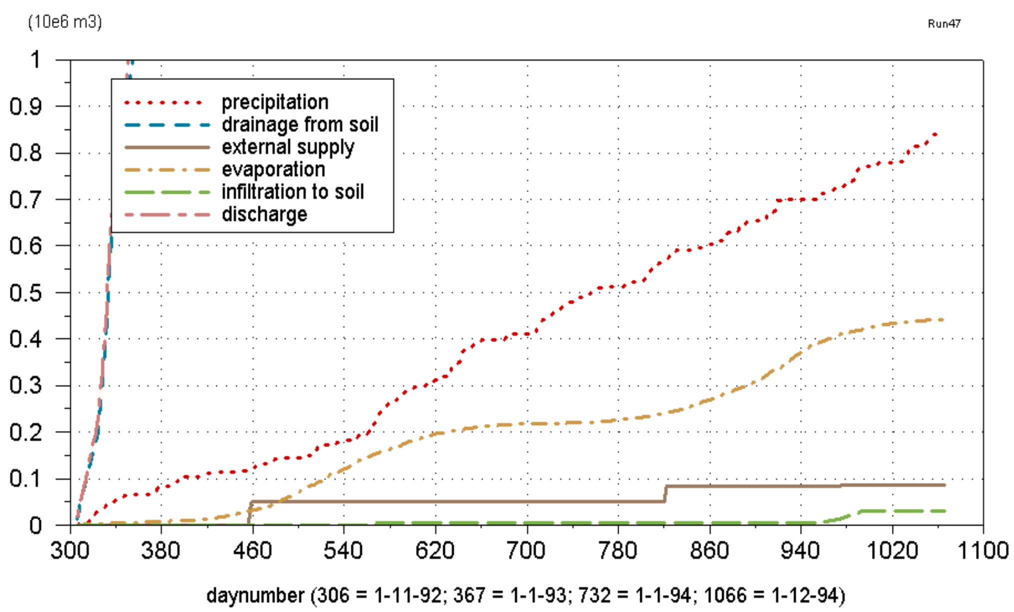

Figure 27: Detail of Figure 26 (Cumulated terms of the surface water balance (in 10^6 m^3)

5.3 State and discharge per section (Subarea 2)

In this section some results of the simulations in Subarea 2 are shown. The purpose is to give an idea about the dynamics of surface water flow and the dimensions of the surface water body at distinct locations. A post-processing programme was used for transformation of standard SWQN output per node into the required output per section (Appendix 5).

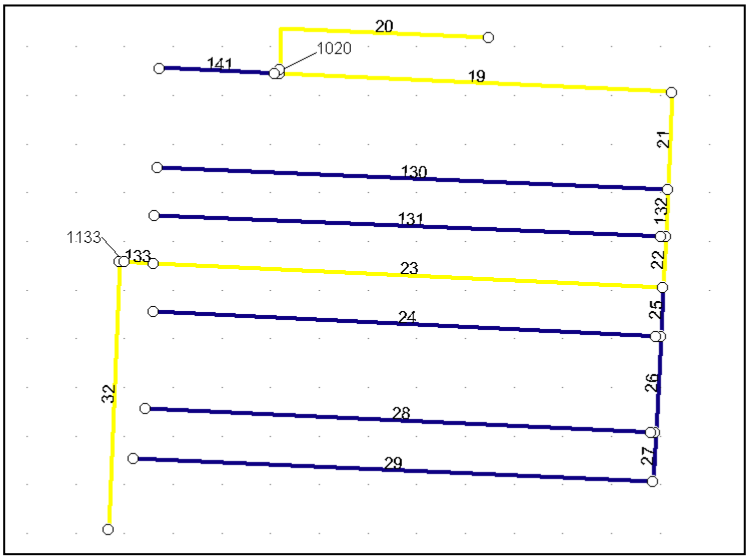

Figure 28: Map with the section numbers of Subarea 2. Section 133 represents the drainage pump G-18. Section 32 represents the main channel at the downstream side of the pump, which is located in Subarea 5.

The graphs of Figure 29 to Figure 33 show the daily output during the period from March 10, 1994 to April 29, 1994 (day number 800 – 850), for some sections along the pathway indicated yellow on the map of Figure 28

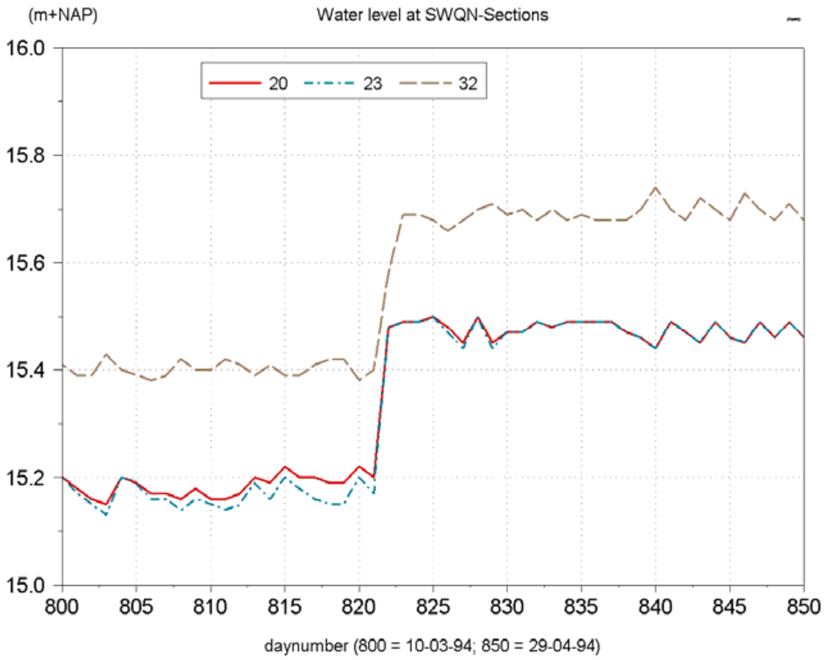

Figure 29: Simulated water level in Sections 20, 23 in Subarea 2 and 32 in Subarea 5.

Figure 29 shows the water level in Sections 20, 23 in Subarea 2 and 32 in Subarea 5. At April 1st, 1994 (daynr. 822), the target water level in Subarea 2 is raised from 15.15 to 15.45 m+NAP. From that day on, the water level in Subarea 2 fluctuates between 15.50 and 15.44 m+NAP, i.e. the start and stop level of Pump G-18.

The water level in Section 32 is controlled by the Weir S-98 between Subarea 5 and 4. The crest is raised from 15.40 to 15.70 m+NAP (and remains at this fixed level until October 1st).

Figure 30: Simulated water depth in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5.

Figure 30 shows the water depth in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5. Section 20 is a small ditch (Type I); Sections 19 and 23 are large ditches (Type III). The Section 32 is a main channel (Type IV; the cross-sectional dimensions are given in Table 6). It can be seen in the figure that the water depth in these ditches increases in accordance with the adjustment of the target water level.

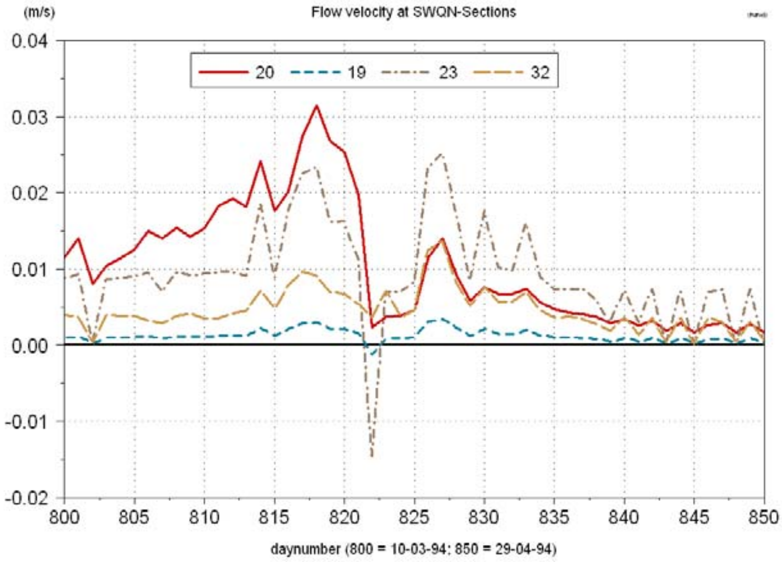

Figure 31: Simulated flow velocity in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5 (in m/s).

Figure 31 shows the flow velocity simulated in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5. It can be seen in the figure that the flow velocity in these sections varies with; i) the cross-sectional dimensions, and ii) the distance to the pump. The flow velocity in Section 20 (a small ditch; Type I) is higher than in Section 19 (a large ditch; Type III). The flow velocity in Section 23, which is located at the downstream side of the drainage pump, is higher than in Section 19. Both sections have the same cross-section, but the flow in Section 23 comes from the entire subarea, whereas the flow through Section 19 originates from the tail end of 2 channels (Sections 141 and 20; Figure 28).

A design criterion for the maximum allowable flow velocity in fine sandy soils and peat soils = 0.15-0.30 m s^{-1} (page 787, Cultuurtechnische Vereniging, 1988). The flow velocity shown in Figure 31, which represents the average velocity on a daily basis, should remain below these values. It can be seen that the maximum flow velocity = 0.03 m s^{-1}.

At April 1st, 1994 (daynr. 822), the water that is used to raise the target level is supplied through Inlet Weir S-45 and enters Subarea 2 via Section 23. This causes the negative sign of the flow velocity in Section 23 (this flow is directed from the end node towards the begin node).

During the period from daynr. 840 to 850 the flow velocity in the sections of Subarea 2 is determined by the operation of the Pump G-18.

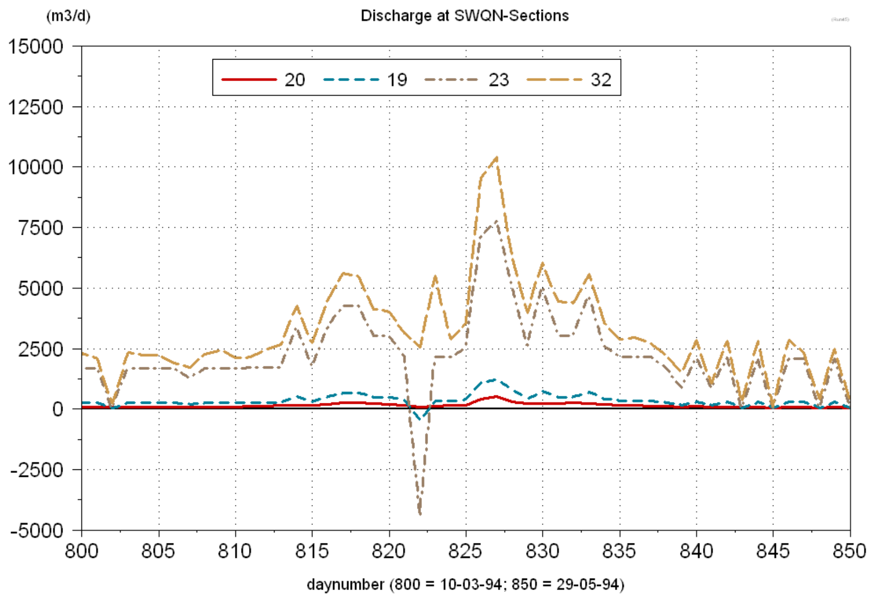

Figure 32: Simulated discharge in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5 (in m^3/d).

Figure 32 shows the simulated discharge in Sections 20, 19, 23 in Subarea 2 and 32 in Subarea 5 (in m^3 d^{-1}). It can be seen that the discharge increases in downstream direction of flow. The capacity of Pump G-18 equals 0.125 m^3 s^{-1} (10800 m^3 d^{-1}). The 7500 m^3 d^{-1} discharge simulated in Section 23 at daynr. 827 corresponds with an average flow velocity = 0.025 m s^{-1} or 2250 m d^{-1}. When the pump discharges at maximum capacity, the flow velocity in Section 23 will be equal to 10800 / 7500 * 0.025 = 0.036 m s^{-1}. So, it can be concluded that the flow velocity in the supply channel (Section 23) will remain well below the design criterion at all circumstances.

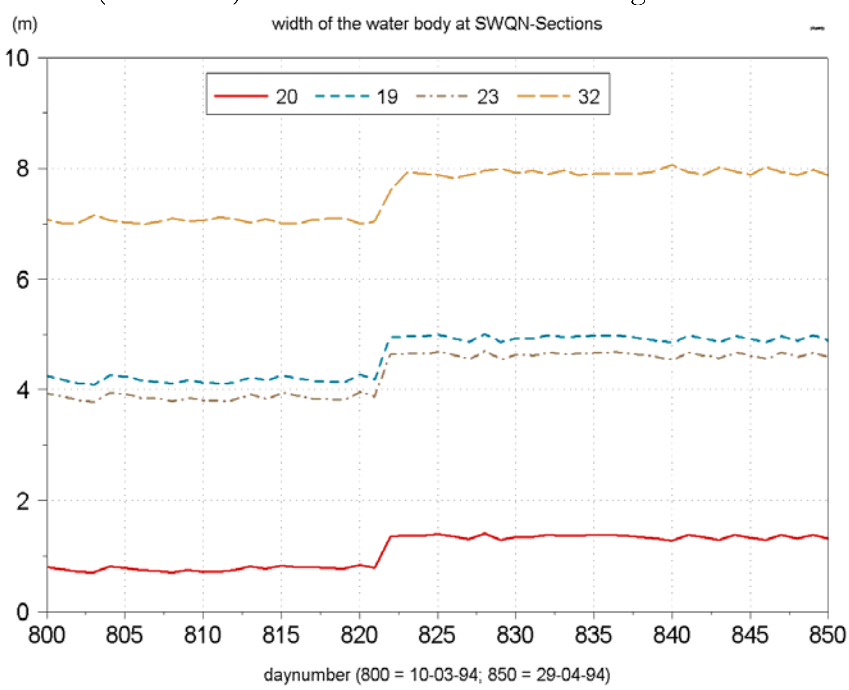

Figure 33: Simulated width of the water body in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5 (in m).

Figure 33 shows the width of the water body in Sections 20, 19, 23 in Subarea 2 and Section 32 in Subarea 5 (in m).

It can be seen in the figure that the water width simulated in the small channel (Section 20) increases from approximately 0.8 m during the period of low target level, to 1.3 m during the period of high target level.

In summary, it was shown by these figures with daily output per section in Subarea 2, that the water level in these sections normally fluctuates within the range determined by the operation of the pump. Also, as can be expected from the model parameterisation, the width and depth of the water body increase with the cross-sectional dimensions of the channel, and when the target water level is raised. The discharge and the flow velocity decrease with the size of the channel. It was shown that, given the capacity of the drainage pump, the flow velocity remains well below the maximum flow velocity that is referred to as design criterion for these type of channels.

5.4 Other results

In this section two particular events are illustrated, in order to give an idea about the average residence time in the surface water system. Note that the time step of the output of the SWQN model = 1 day.

Figure 34 shows the water level simulated at the end nodes of the sections defined as Inlet Weir S-94 (Node 1038), Weir S-62 (Node 1035), Weir S-32 (Node 1029) and Weir S-61 (Node 1040), during the period June 3rd, 1993 – October 21st, 1993. It can be seen in the figure that the water level in Subarea 7 and 6 remains almost constant. The fluctuation of the water level in Subarea 1 and 4 is caused by the operation of the drainage pump. Figure 35 shows the daily precipitation, the lumped discharge towards the surface water and the simulated discharge from the drainage pump G-12 (in mm), during the period September 24th, 1993 – October 9th, 1993 (daynr. 633 – 648). The lumped discharge can be regarded as the incoming hydrograph, whereas the pump discharge can be seen as the outgoing hydrograph of the study area.

The 43 mm of precipitation at daynr. 635 is partly discharged at the same day; it can be seen in Figure 35 that the pump discharge exceeds the drainage flux at day 635. The drainage flow resulting from this amount of precipitation is simulated in the next two days, and so is the response of the surface water system. This can be seen from the lumped drainage and the pump discharge at daynr. 636 and 637. At daynr. 636 the input by drainage flow and precipitation exceeds the discharge of the drainage pump, which causes the water level to rise.

The target water level in the area is lowered at daynr. 640. This explains the simulated pump discharge at daynr. 640 exceeding drainage flow by a factor 4.

High amounts of precipitation at daynr. 642 and 643 lead to an increased drainage flow at daynr. 643 and 644. The sum of drainage flow and precipitation exceeds the pump discharge during 3 days, causing the peak water levels at daynr. 644. The response of the surface water system starts at daynr. 643. The duration of 4 days is determined by the pump discharge capacity (12 mm d-1).

It can be concluded from these two events that the simulated response time of the surface water system to incoming soil drainage flow is less than 1 day.

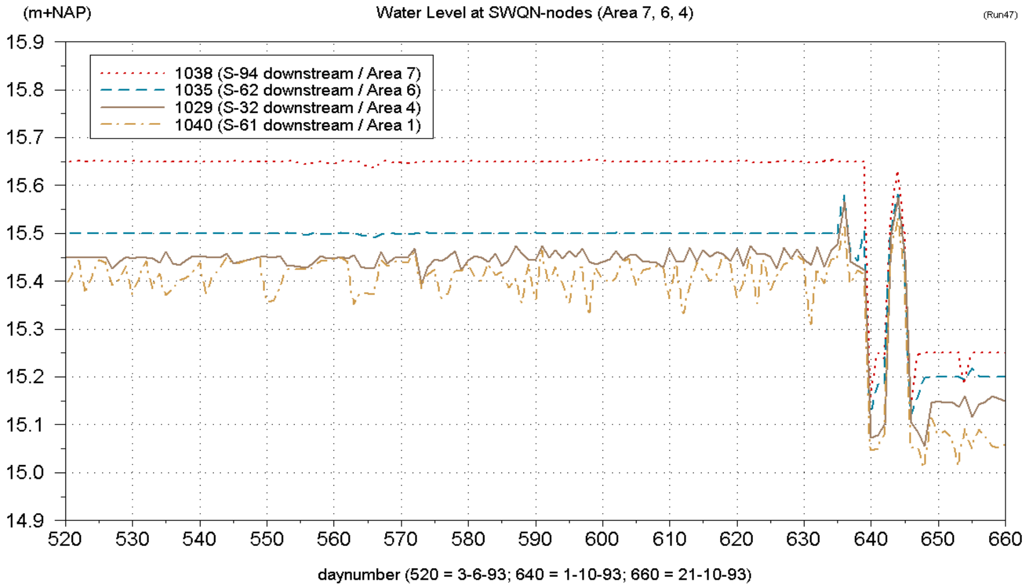

Figure 34 Simulated water level at the end nodes of the sections defined as Inlet Weir S-94 (Node 1038), Weir S-62 (Node 1035), Weir S-32 (Node 1029) and Weir S-61 (Node 1040), during the period June 3rd, 1993 – October 21st, 1993.

The state shown in Figure 34 is also compared with the simulation results based on the artificial meteorological data (Figure 6.6, Appendix 6).

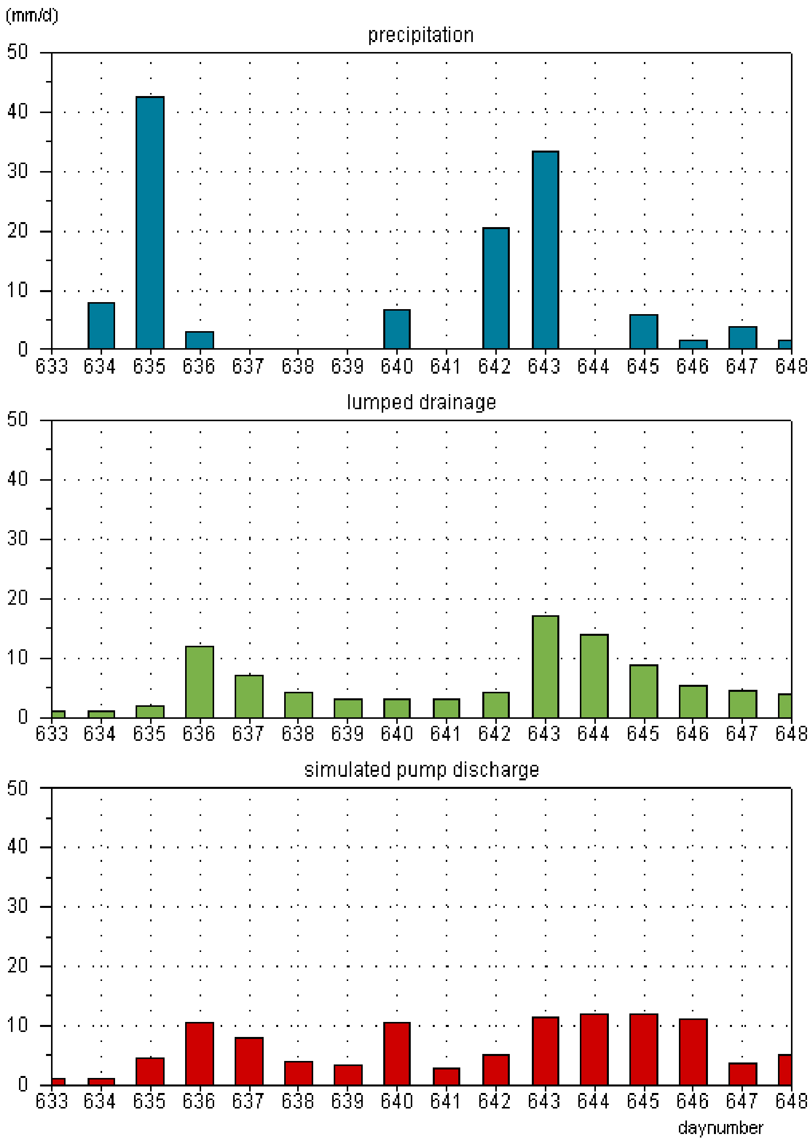

Figure 35: Daily precipitation, lumped net drainage flux towards the surface water, and the discharge simulated at the drainage pump G-12.

6 Conclusions

A suitable study area for the hydrological module of the Cascade model instrument was found in the "Drentsche Veenkoloniën". Conform the selection criteria, the 10 km^2 catchment area has a single outlet. It is located in a polder with the possibility of external water supply. The dominant land use is potatoes. Discharge measurements of 25 months duration are available at 5 locations including the outlet, from a regional hydrological study that was conducted in the years 1992 – 1994 (Van Walsum et al., 1998).

These time series of discharge are used for calibrating the surface water model SWQN. The full parameterisation of the surface water model SWQN is based on local meteorological data, a description of drainage flow and surface water infiltration obtained with the soil hydrological model SWAP, a surface water network that was derived from a topographical map and the information obtained from the regional hydrological study.

Soil hydrology

The simulated soil hydrology meets the following requirements;

- The simulation error of the simulated soil water balance (Total In – Total Out – Storage Change) equals 0.01%; i.e. all water is accounted for in the balance.
- The major terms of the soil water balance are plausible, considering both the cumulated amounts and the relative contributions of these terms to the balance during the meteorological seasons of the year and especially during the crop season.
- The simulated groundwater regime corresponds with the time course of the observed groundwater levels, which means that a plausible fluctuation of the groundwater table is obtained.

Based on the kinetics of simulated drainage flow during periods of high discharge and during periods of low discharge, it is concluded that the simulation with SWAP results in acceptable input for the surface water model SWQN.

The best fit of the simulated drainage flux per unit of catchment area to the measured discharge is obtained at the scale of the 10 km^2 catchment. This fit is obtained by adjustment of the area drained per node. At locations within the study area this fit is less good. These differences within the area may be caused by heterogeneous soil physical and hydrological conditions, the estimated distribution of the area drained per node, and the accuracy of the discharge measurements.

Surface water hydrology

The simulated surface water flow meets the following requirements;

- An acceptable fit of the lines of simulated discharge.
- A correct surface water balance
- During prolonged periods of discharge at the outlet there is no external water supplied to the area
- During prolonged periods of external water supply there is no discharge at the outlet
- A plausible simulation of surface water state and flow within the area.

The kinetics of the cumulated discharge simulated at the outlet shows a good fit to the line of cumulated measured discharge. For the entire simulation period, the simulated discharge at the outlet exceeds the measured discharge with only 0.5%. Within the study area, the fit of the cumulated simulated discharge to the cumulated measurement is less good. This can be caused by a combination of factors not accounted for in the model parameterisation, such as: (i) heterogeneous boundary conditions to surface water flow, as is explained for seepage, (ii) water management practice, (iii) discharge measurement errors, (iv) deviations from the estimated area drained per node.

A correct surface water balance is produced for the entire period of discharge measurement, with a simulation error = 0.2% of the balance total. The major terms of the surface water balance are the lumped drainage from the soil and the pump discharge at the outlet. It is concluded that the kinetics of the discharge at the outlet is dominated by drainage flow towards the surface water.

Because the period of discharge measurements coincides with two wet years, there is almost no external supply of surface water simulated. Based on a special simulation with artificial meteorological data it is concluded that the SWQN model of the study area produces an acceptable simulation of surface water flow during periods of prolonged drought, when external water is supplied to the area.

A plausible simulation of surface water state and flow is obtained. This conclusion is based on daily output per section showing the width and depth of the water body, and on comparison of the flow velocity with the design criterion for these type of channels.

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Appendix 1 SWQN input files and output files

1-1 Description of input files for SWQN

Overview of filenames

File	Description	Source
SWQN_RuntimeOptions.in	Calculation period and output type options	database/manual
SWQN_NodesDefinition.csv	X and Y coordinates, optional	GIS/database
SWQN_SectionsDefinition.csv	Connected nodes, length, etc.	GIS/database
SWQN_WeirsDefinition.csv*	Definition of weirs	manual/database
SWQN_WeirsControls.csv*	Management for weirs	manual/database
SWQN_GatesDefinition.csv*	Definition of gates	manual/database
SWQN_GatesControls.csv*	Management for gates	manual/database
SWQN_CulvertsDefinition.csv*	Definition of culverts	manual/database
SWQN_PumpsDefinition.csv*	Definition of pumps	manual/database
SWQN_PumpsControl.csv*	Management for pumps	manual/database
SWQN_FlowBoundary.csv*	Boundary discharges	SWAP/database/manual
SWQN_LevelBoundary.csv*	Fixed level boudary condition	database/manual
SWQN_PrecEvap.csv*	Direct precipitation and evaporation	database/manual

*optional: only needed if this type of structure exist.

SWQN_RuntimeOptions.in

Section/Name	Description	Default	Unit	Type
[CalculationSettings]				
CalculationID*	Calculation identification message	-	-	C60
StartDay	Day for start of calculation	-	day	I
StartMonth	Month for start of calculation	-	month	I
StartYear	Year for start of calculation	-	year	I
EndDay	Day for end of calculation	-	day	I
EndMonth	Month for end of calculation	-	month	I
EndYear	Year for end of calculation	-	year	I
InitiationDays*	Number of days for initial calculation**	0	day	I
TimestepNumeric*	Internal time step (must be a full divisor of 24 hours)	3	hour	I
ResistanceType*	Resistance formula of Chezy (1) or Manning (2)	2	-	I
BottomDepthLocation*	Bottom depths defined at nodes (1) or sections (2)	1	-	I
OutLayout*	Produce txt-file with schematisation (1=yes, 0=no))	1	-	I
OutBalanceAll*	Produce all balance output (1) or only diviations (2)	1	-	I
DumpDay*	Produce a dump of the dll-IO at the selected day	-1	day	I

*optional **boundary conditions at TimeStart will be applied during this period

SWQN_NodesDefinition.csv

BottomDepthLocation equals 1

Col	Name	Description	Unit	Type
1	NodeID	Could be non-continuous	-	I
2	PrecEvapID	Selection of precipation and evaporation region	-	I
3	NodeX	X co-ordinate	m	R
4	NodeY	Y co-ordinate	m	R
5	Bottomlevel	Bottom level in meters from reference level	m f.r.l.	R
6	MaxLevel	Maximum level in meters from reference level	m f.r.l.	R
7	InitialWaterlevel	Initial water level in meters from reference level	m f.r.l.	R

BottomDepthLocation equals 2

Col	Name	Description	Unit	Type
1	NodeID	Could be non-continuous	-	I
2	PrecEvapID	Selection of precipation and evaporation region	-	I
3	NodeX	X co-ordinate	m	R
4	NodeY	Y co-ordinate	m	R
5	MaxLevel	Maximum level in meters from reference level	m f.r.l.	R
6	InitialWaterlevel	Initial water level in meters from reference level	m f.r.l.	R

SWQN_SectionsDefinition.csv

BottomDepthLocation equals 1

Col	Name	Description	Unit	Type
1	SectionID	Could be non-continuous	-	I
2	BeginNodeID	Begin node	-	I
3	EndNodeID	End node	-	I
4	Length	Length	m	R
5	BottomWidthBegin	Bottom width begin node	m	R
6	BottomWidthEnd	Bottom width end node	m	R
7	SlopeBegin	Slope begin node: ratio between width and height	-	R
8	SlopeEnd	Slope end node: ratio between width and height	-	R
9	ResistBeginPos	Chezy resistance coefficient begin node positive direction	$m^{½}.s^{-1}$	R
10	ResistBeginNeg	Chezy resistance coefficient begin node negative direction	$m^{½}.s^{-1}$	R
11	ResistEndPos	Chezy resistance coefficient end node positive direction	$m^{½}.s^{-1}$	R
12	ResistEndNeg	Chezy resistance coefficient end node negative direction	$m^{½}.s^{-1}$	R

BottomDepthLocation equals 2

Col	Name	Description	Unit	Type
1	SectionID	Could be non-continuous	-	I
2	BeginNodeID	Begin node	-	I
3	EndNodeID	End node	-	I
4	Length	Length	m	R
5	BottomlevelBegin	Bottom level begin node in meters from reference level	m f.r.l.	R
6	BottomlevelEnd	Bottom level end node in meters from reference level	m f.r.l.	R
7	BottomWidthBegin	Bottom width begin node	m	R
8	BottomWidthEnd	Bottom width end node	m	R
9	SlopeBegin	Slope begin node: ratio between width and height	-	R
10	SlopeEnd	Slope end node: ratio between width and height	-	R
11	ResistBeginPos	Chezy resistance coefficient begin node positive direction	$m^{½}.s^{-1}$	R
12	ResistBeginNeg	Chezy resistance coefficient begin node negative direction	$m^{½}.s^{-1}$	R
13	ResistEndPos	Chezy resistance coefficient end node positive direction	$m^{½}.s^{-1}$	R
14	ResistEndNeg	Chezy resistance coefficient end node negative direction	$m^{½}.s^{-1}$	R

SWQN_WeirsDefinition.cvs

Col	Name	Description	Unit	Type
1	WeirID	Could be non-continuous	-	I
2	Section	Equal to SectionID	-	I
3	MaxCrestWidth	Maximum crest width	m	R
4	InitialCrestWidth	Initial crest width	m	R
5	MaxCrestLevel	Maximum crest level	m f.r.l.	R
6	MinCrestLevel	Minimum crest level	m f.r.l.	R
7	InitialCrestLevel	Initial crest level	m f.r.l.	R
8	MuPosFree	Free flow resistance	$m^{1½}.s^{-1}$	R
9	MuNegFree	Free flow resistance	$m^{1½}.s^{-1}$	R
10	MuPosSub	Submerged flow resistance	$m^{1½}.s^{-1}$	R
11	MuNegSub	Submerged flow resistance	$m^{1½}.s^{-1}$	R

SWQN_WeirsControl.csv

Col	Name	Description	Unit	Type
1	Date*	Date for change of setting	date	C10
2	WeirID	ID used in structure definition	-	I
3	SelectControlWeir	1 = Crest width; 2 = Crest level; 3 = Set targetlevel for begin node; 4 = Set target level for end node	-	I
4	CrestWidth	Crest width	m	R
5	CrestLevel	Crest level	m f.r.l.	R
6	TargetlevelBegin	Targetlevel begin node	m f.r.l.	R
7	TargetlevelEnd	Targetlevel end node	m f.r.l.	R

* date formats ‘yyyy-m-d’ and ‘d-m-yyyy’ are both accepted

SWQN_GatesDefinition.cvs

Col	Name	Description	Unit	Type
1	GateID	Could be non-continuous	-	I
2	Section	Equal to SectionID	-	I
3	SillLevel	Sill level	m f.r.l.	R
4	InitialOpeningLevel	Initial opening level	m f.r.l.	R
5	MaxOpeningLevel	Maximum opening level	m f.r.l.	R
6	InitialOpeningWidth	Initial opening width	m	R
7	MaxOpeningWidth	Maximum opening width	m	R
8	MuPosFree	Free flow resistance	$m^{½}.s^{-1}$	R
9	MuNegFree	Free flow resistance	$m^{½}.s^{-1}$	R
10	MuPosSub	Submerged flow resistance	$m^{½}.s^{-1}$	R
11	MuNegSub	Submerged flow resistance	$m^{½}.s^{-1}$	R
12	MuPosWeir	Weir flow resistance	$m^{1½}.s^{-1}$	R
13	MuNegWeir	Weir flow resistance	$m^{1½}.s^{-1}$	R

SWQN_GatesControl.csv

Col	Name	Description	Unit	Type
1	Date*	Date for change of setting	date	C10
2	GateID	ID used in structure definition	-	I
3	SelectControlGate	1 = Opening level, 2 = Opening width, 3 = Targetlevel begin node, 4 =Targetlevel end node, 5 = Both 3 and 4	-	I
4	OpeningLevel	Opening level	m f.r.l.(?)	R
5	OpeningWidth	Opening width	m	R
6	TargetlevelBegin	Targetlevel begin node	m f.r.l.	R
7	TargetlevelEnd	Targetlevel end node	m f.r.l.	R

* date formats ‘yyyy-m-d’ and ‘d-m-yyyy’ are both accepted

SWQN_CulvertsDefinition.cvs

Col	Name	Description	Unit	Type
1	CulvertID	Could be non-continuous	-	I
2	Section	Equal to SectionID	-	I
3	Number	Parallel culvert number	-	I
4	Type	1 = Rectangular, 2 = Round	-	I
5	Length	Length	m	R
6	Radius/Width	Depending on type chosen type	m	R
7	Radius/Height	Depending on type chosen type	m	R
8	SillLevel	Sill level	m f.r.l.	R
9	BottomLevel	Bottom level	m f.r.l.	R
10	Resist	Manning coefficient	m½.s-1	R
11	MuPosFree	Submerged flow resistance	$m^{½}.s^{-1}$	R
12	MuNegFree	Submerged flow resistance	$m^{½}.s^{-1}$	R
13	MuPosSub	Weir flow resistance	$m^{1½}.s^{-1}$	R
14	MuNegSub	Weir flow resistance	$m^{1½}.s^{-1}$	R

SWQN_PumpsDefinition.cvs

Col	Name	Description	Unit	Type
1	PumpID	Could be non-continuous	-	I
2	Section	Equal to SectionID	-	I
3	PumpCharacteristicA	Height dependent variable discharge*	$m^2.s^{-1}$	R
4	PumpCharacteristicB	Fixed discharge*	$m^3.s^{-1}$	R

***** Eq. (6-2)

SWQN_PumpsControl.csv

Col	Name	Description	Unit	Type
1	Date*	Date for change of setting	date	C10
2	PumpID	ID used in structure definition	-	I
3	SelectControlPump	1 = Discharge (variable); 2 = Start and stoplevel for begin node; 3 = Start and stop level for end node	-	I
4	Discharge	Variable discharge	$m^3.s^{-1}$	R
5	StartLevelBegin	Startlevel for begin node	m f.r.l.	R
6	StoplevelBegin	Stoplevel for begin node	m f.r.l.	R
7	StartlevelEnd	Startlevel for end node	m f.r.l.	R
8	StoplevelEnd	Stoplevel for end node	m f.r.l.	R

* date formats ‘yyyy-m-d’ and ‘d-m-yyyy’ are both accepted

SWQN_FlowBoundary.csv

Col	Name	Description	Unit	Type
1	Date*	Date for change of setting	date	C10
2	NodeID	ID used in node definition	-	I
3	Discharge	Inflow or outflow discharge**	$m^3.s^{-1}$	R

* date formats ‘yyyy-m-d’ and ‘d-m-yyyy’ are accepted. ** Multiple discharges on same node and day add up!

SWQN_LevelBoundary.csv

Col	Name	Description	Unit	Type
1	Date*	Date for change of setting	date	C10
2	NodeID	ID used in node definition	-	I
3	Level	Fixed level boundary condition	m f.r.l.	R

* date formats ‘yyyy-m-d’ and ‘d-m-yyyy’ are both accepted

SWQN_PrecEvap.csv

Col	Name	Description	Unit	Type
1	Date*	Date for change of setting	date	C10
2	PrecEvapID	ID for different meteorology regions to select per node	-	I
3	Precipitation	Areal precipitation	$m.d^{-1}$	R
4	Evaporation	Areal evaporation	$m.d^{-1}$	R

* date formats ‘yyyy-m-d’ and ‘d-m-yyyy’ are both accepted

1-2 Description of output files for SWQN

Overview of filenames

File	Description
NuswaLite_Waterbalance.bin	Binary file with network layout and waterbalances for NuswaLite
SWQN_OutBalance.csv	Daily waterbalance for every node
SWQN_OutBalanceYearly.csv	Yearly waterbalance for every node
SWQN_OutDepths.csv	Daily waterdepth (waterlevel minus bottomlevel) for every node
SWQN_OutDischarges.csv	Daily discharges for every section
SWQN_OutLayout.csv	Text-file with network layout
SWQN_OutLevels.csv	Daily waterlevel for every node
SWQN_OutTotalBalance.csv	Daily waterbalance for whole network
SWQN_OutTotalBalanceYearly.csv	Yearly waterbalance for whole network

NuswaLite_Waterbalance.bin

Rec	Field	Name	Description	Unit	Type
1	1	CalcID	Calculation identification message	-	C60
	2	StartYear	Day for start of calculation	day	I4
	3	StartMonth	Month for start of calculation	month	I4
	4	StartDay	Year for start of calculation	year	I4
	5	EndTime	Calculation length in days	day	I4
2	1	NOfNodes (N)	Number of nodes	-	I4
3*	1	NodeID	Node ID	-	I4
	2	BottomArea	Bottom area	m^2	R8
	3	InitialVolume	Initial volume	m^3	R8
	4	NOfConNodes (CN)	Number of connected nodes	-	I4
	5-CN	ConNodID	Connected node ID	-	I4
4**	1	VolAddEnd	Volume at end of timestep	m^3	R8
	2	LevTimEnd	Waterlevel at end of day	m	R8
	3	Vel	Flow velocity	$m.d^{-1}$	R8
	4	FlwBnd	Boundary discharge	$m^3.d^{-1}$	R8
	5	FlwBndP	Precipitation boundary discharge	$m^3.d^{-1}$	R8
	6	FlwBndE	Evapiration boundary discharge	$m^3.d^{-1}$	R8
	7-CN	FlwNodID1-CN	Internal flow discharges	$m^3.d^{-1}$	R8

* One record for every node ** One record for every node and then repeated for every day calculated

SWQN_OutBalance.csv

Col	Name	Description	Unit	Type
1	Date	Date	date	y-m-d
2	Node	Node	-	I
3	LevTimEnd	Waterlevel at end of day	m	R
4	VolAddStrt	Volume at start of timestep	m^3	R
5	VolAddEnd	Volume at end of timestep	m^3	R
6-15	FlwNodID1-10	Internal flow discharges	$m^3.s^{-1}$	R
16	FlwBndH	Level boundary discharge	$m^3.s^{-1}$	R
17	FlwBndQ	Flow boundary discharge	$m^3.s^{-1}$	R
18	FlwBndP	Precipitation boundary discharge	$m^3.s^{-1}$	R
19	FlwBndE	Evapiration boundary discharge	$m^3.s^{-1}$	R
20	AbsErr	Absolute waterbalance error	m^3	R
21	RelVErr	Average volume related waterbalance error	%	R
22	RelQErr	Average discharge related waterbalance error	%	R

SWQN_OutBalanceYearly.csv

Col	Name	Description	Unit	Type
1	Year	Year	-	I
2	Node	Node	-	I
3	InternalFlowDischarge	InternalFlowDischarge	$m^3.y^{-1}$	R
4	FlowBoundaryDischarge	FlowBoundaryDischarge	$m^3.y$	R
5	LevelBoundaryDischarge	LevelBoundaryDischarge	$m^3.y$	R
6	PrecipitationBoundaryDischarge	PrecipitationBoundaryDischarge	$m^3.y$	R
7	EvapirationBoundaryDischarge	EvapirationBoundaryDischarge	$m^3.y$	R
8	StorageChange	StorageChange	m^3	R
9	BalanceError	BalanceError	m^3	R

SWQN_OutDepths.csv

Col	Name	Description	Unit	Type
1	Date	Date	date	y-m-d
2	NodeID	Node ID	-	I
3	Depth	Waterdepth (waterlevel minus bottomlevel)	m	R

SWQN_OutDischarges.csv

Col	Name	Description	Unit	Type
1	Date	Date	date	y-m-d
2	SectionID	Section ID	-	I
3	Discharge	Flow discharge	$m^3.s^{-1}$	R
4	CumDischarge	Cumulative flow discharge (from january 1^{st} to date)	$m^3.s^{-1}$	R

SWQN_OutLayout.csv

Rec	Field	Name	Description	Unit	Type
1	1	NOfNodes (N)	Number of nodes	-	I
2-N	1	NodeID	Node ID	-	I
	2	BottomArea	Bottom area	m^2	R
	3	InitialVolume	Initial volume	m^3	R
	4	NOfConNodes (CN)	Number of connected nodes	-	I
	5-CN	ConNodID	Connected node ID	-	I

SWQN_OutLevels.csv

Col	Name	Description	Unit	Type
1	Date	Date	date	y-m-d
2	NodeID	Node ID	-	I
3	Level	Waterlevel	m f.r.l.	R

SWQN_OutTotalBalance.csv

Col	Name	Description	Unit	Type
1	Date	Date	date	y-m-d
2	VolAddStrt	Volume at start of timestep	m^3	R
3	VolAddEnd	Volume at end of timestep	m^3	R
4-13	FlwNodID1-10	Internal flow discharges	$m^3.s^{-1}$	R
14	FlwBndH	Level boundary discharge	$m^3.s^{-1}$	R
15	FlwBndQ	Flow boundary discharge	$m^3.s^{-1}$	R
16	FlwBndP	Precipitation boundary discharge	$m^3.s^{-1}$	R
17	FlwBndE	Evapiration boundary discharge	$m^3.s^{-1}$	R
18	AbsErr	Absolute waterbalance error	m^3	R
19	RelVErr	Average volume related waterbalance error	%	R

SWQN_OutTotalBalanceYearly.csv

Col	Name	Description	Unit	Type
1	Year	Year	-	I
4	FlowBoundaryDischarge	FlowBoundaryDischarge	$m^3.y$	R
5	LevelBoundaryDischarge	LevelBoundaryDischarge	$m^3.y$	R
6	PrecipitationBoundaryDischarge	PrecipitationBoundaryDischarge	$m^3.y$	R
7	EvapirationBoundaryDischarge	EvapirationBoundaryDischarge	$m^3.y$	R
8	StorageChange	StorageChange	m^3	R
9	BalanceError	BalanceError	m^3	R

Appendix 2 Groundwater level observations (in m-ss.)

daynr. (1 = 1/1/1992)	Observation well code				min	Avg (n = 4)	max	range (max - min)
	18CP7079	18CP7080	18CP7081	18CP7083				
318	0.70	0.65	1.06	1.22	0.65	0.91	1.22	0.57
332	0.33	0.37	0.86	0.58	0.33	0.54	0.86	0.53
346	0.41	0.41	0.86	0.59	0.41	0.57	0.86	0.45
360	0.41	0.54	0.86	0.58	0.41	0.60	0.86	0.45
381	0.35	0.51	0.81	0.49	0.35	0.54	0.81	0.46
395	0.35	0.49	0.81	0.50	0.35	0.54	0.81	0.46
409	0.39	0.54	0.84	0.59	0.39	0.59	0.84	0.45
423	0.40	0.55	0.85	0.60	0.40	0.60	0.85	0.45
437	0.50	0.59	0.93	0.72	0.50	0.69	0.93	0.43
451	0.67	0.64	1.01	0.87	0.64	0.80	1.01	0.37
472	0.63	0.65	1.02	0.91	0.63	0.80	1.02	0.39
486	0.76	0.69	1.07	1.01	0.69	0.88	1.07	0.38
500	0.97	0.86	1.27	1.20	0.86	1.08	1.27	0.41
514	1.10	0.94	1.40	1.29	0.94	1.18	1.40	0.46
528	1.03	0.73	1.38	1.14	0.73	1.07	1.38	0.65
542	1.10	0.97	1.48	1.30	0.97	1.21	1.48	0.51
563	1.13	1.05	1.55	1.36	1.05	1.27	1.55	0.50
577	0.38	0.47	0.90	0.57	0.38	0.58	0.90	0.52
591	0.40	0.49	0.88	0.55	0.40	0.58	0.88	0.48
605	0.45	0.55	0.91	0.59	0.45	0.63	0.91	0.46
619	0.49	0.57	0.93	0.70	0.49	0.67	0.93	0.44
640	0.37	0.45	0.83	0.33	0.33	0.50	0.83	0.50
654	0.35	0.42	0.81	0.22	0.22	0.45	0.81	0.59
668	0.44	0.53	0.86	0.50	0.44	0.58	0.86	0.42
682	0.53	0.60	0.95	0.74	0.53	0.71	0.95	0.42
703	0.75	0.82	1.04	0.92	0.75	0.88	1.04	0.29
710	0.37	0.48	0.85	0.45	0.37	0.54	0.85	0.48
724	0.28	0.41	0.80	0.16	0.16	0.41	0.80	0.64
745	0.31	0.48	0.82	0.29	0.29	0.48	0.82	0.53
752	0.36	0.47	0.81	0.29	0.29	0.48	0.81	0.52
Avg (n = 30)	0.56	0.60	0.98	0.71				0.47

Appendix 3 Soil hydrology – Parameterisation of SWAP

Drainage flow towards the surface water system was generated with the soil hydrological model SWAP version 3.1.4 (Kroes and Van Dam, 2003). The major part of the model parameters were obtained from STONE version 2.0 (Kroon et al., 2003) and the regional hydrological study (Van Walsum et al., 1998).

Overlay with the STONE schematisation

In STONE (Kroes et al., 2002; Wolf et al., 2003), a plot is defined by a unique combination of meteorology, physical and chemical soil conditions, boundary conditions for drainage flow (defined here as local groundwater flow), and the bottom boundary conditions for regional groundwater flow. These bottom boundary conditions describe the interaction of local groundwater with the deep groundwater system.

The schematisation of STONE has a resolution of 6.25 ha (250 x 250 m grid cells) and contains 6405 different plots (Kroon et al., 2003). An overlay was made of this national schematisation and the map of the study area. The results of this 800 ha coverage with grid cells of the STONE schematisation are shown in Table 3.1. Almost 70% of the study area covers the STONE plots 2325 and 2343, whereas the remaining 30% covers (a small part of) miscellaneous plots.

Table 3.1: Representation of STONE plots within the study area (STONE version 2.0).

STONE schematisation		Study area
Plot ID	Plot area (ha)	(ha)
2325	219	219
2343	344	338
other plots (n = 26)	-	244
Total covered area		800

Some 90% of the surface water level control units (subareas) is covered in the STONE schematisation. The dominant plot within this 800 ha coverage is 2434. The boundaries of these seven subareas were obtained from (van Walsum et al., 1998).

According to the Soil Map of the Netherlands, the dominant soil type is peat with loamy sand at the top 0.2 m and peat or muck layers between 0.2 and 1.0 m depth (Figure 3.1). The groundwater regime is Gt III* in 33% and Gt V* in 52% of the study area. The STONE-plot 2325 represents the soils with the relatively shallow groundwater regime (Gt III*), and STONE-plot 2343 represents the soils with the moderately deep groundwater regime (Gt V*).

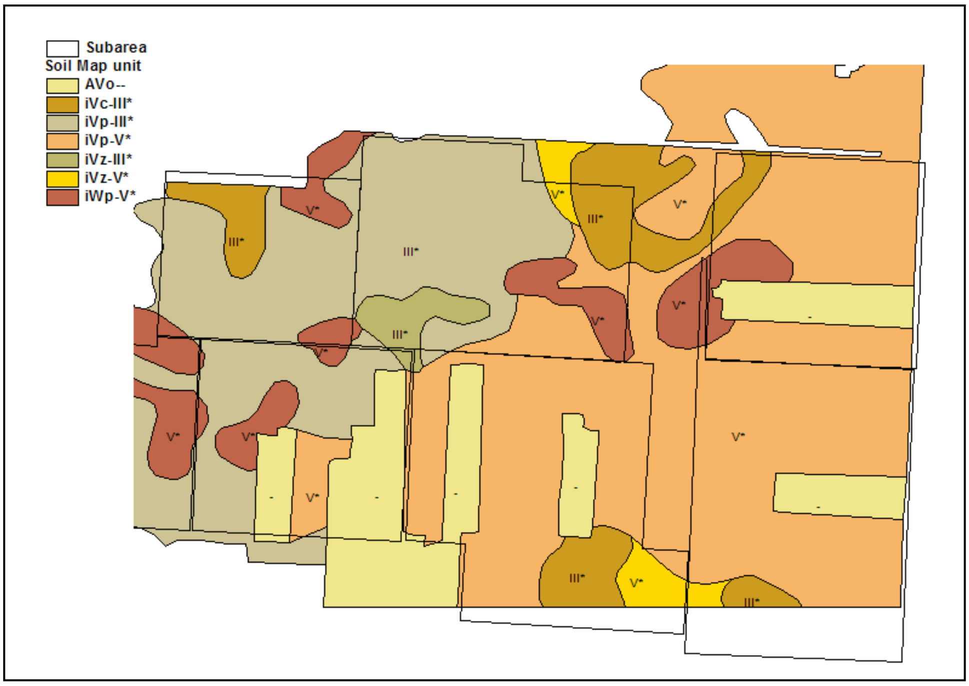

Figure 3.1: Soil map units in the study area; according to the Soil Map of the Netherlands (scale 1:50 000) with the groundwater regime class V, III* (unknown class indicated by "-").*

Meteorology
Daily precipitation was measured at the weather station Klazienaveen. Reference evapotranspiration according to Makkink was measured at the weather station Hoogeveen (Table 3.2).

Table 3.2: Reference evapotranspiration according to Makkink measured at the KNMI-weather station Hoogeveen (during the simulation period starting at November 1st, 1992 and ending at December 1st, 1994).

period	(m)
1992	0.017
1993	0.512
1994	0.537
Total (761 days)	1.066

The SWAP model calculates the maximum evapotranspiration rate based on this reference evapotranspiration rate and a crop factor for the growing season. In the remaining part of the year, a so-called crop factor for bare soil is used.

Evapotranspiration
During the growing season, the maximum evapotranspiration rate is divided in two parts. The maximum crop transpiration rate is calculated based on the crop factor and the leaf area index. The remaining part is the maximum evaporation rate.

The growing season of potato crop starts at April, 20th and lasts until September, 1st. The crop factor = 1.1, i.e. the average of 10 decade-values starting at the 3rd decade of May 9 (Feddes, 1987: page 43). Because the contribution of crop transpiration to the evapotranspiration rate is small during the 1st, the 2nd and the last decade of the growing season, these 3 decade-values were excluded from the average crop factor that represents the entire crop season.

The leaf area index is a function of crop development stage based on STONE version 3.0 (Clevering and Van Bakel, 2006) (Figure 3.2).

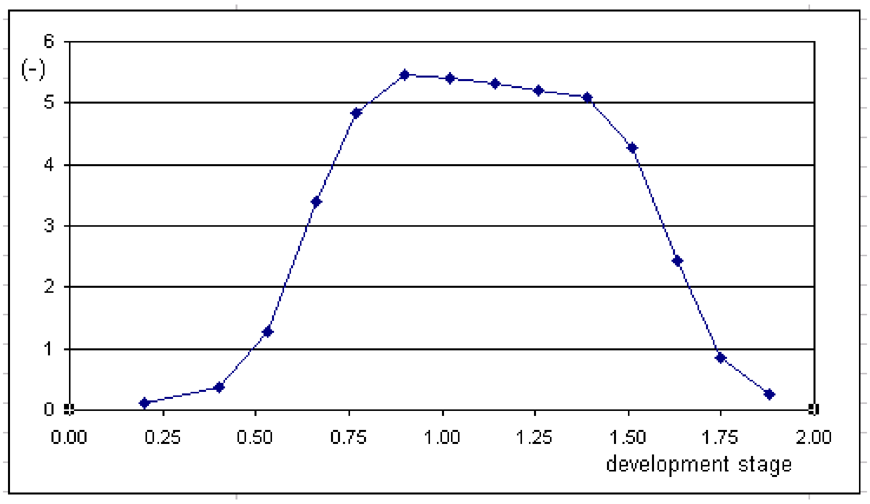

Figure 3.2: Leaf area index for potatoes as a function of crop development stage (based on Clevering and Van Bakel, 2006)

The crop transpiration rate may be reduced by the simulated pressure head conditions in the root zone. The root uptake by the crop is limited at pressure head values above -25 cm, and stops at pressure head values above -10 cm.

Evaporation

The amount of interception water is calculated from daily precipitation and the leaf area index of the crop, using a method applicable to agricultural crops according to Von Hoyningen-Hüne and Braden with coefficient a = 0.25 cm d^{-1} (Kroes and Van Dam, 2006, page 39). Soil evaporation is calculated using an evaporation reduction function with β = 0.79 $cm^{0.5}$ (corresponding with 2.5 $mm^{0.5}$, according to Boesten and Stroosnijder, 1986).

Crop factor for bare soil

Penman (1948) and McIlroy & Angus (1964) found that monthly averages of potential soil evaporation were on average 0.9 times the evaporation of an open water surface. De Bruin (1987) found that the ratio of Penman divided by Makkink reference evapotranspiration for inland weather stations (de Bilt, Eelde and Beek) was 1.35 for March, 1.30 for April, 1.30 for May, 1.17 for September and 0.98 for October (period 1965-1985). Only these months are considered here because they are the most relevant months for the soil evaporation (taking into account the crop period, and the time course of the leaf area index shown inFigure 3.2). The average value of this ratio over these months is 1.2.

Before and after the growing season, the SWAP model calculates the potential evaporation from bare soil as the product of Makkink reference evapotranspiration and a so-called crop factor for bare soil. Based on the above information this so-called crop factor for bare soil was assumed to be equal to 0.9 *x* 1.2 = 1.1.

Soil
Soil profile data were obtained from STONE version 2.0, plot 2343. The soil column has a 0.2 m sandy layer on top of a 0.65 m thick peat layer (Table 3.3). The soil moisture retention characteristics of each horizon were taken according to STONE 2.0 (Soil Physical Unit *BFE* = 5).

Table 3.3: Soil Building blocks with porosity, saturated hydraulic conductivity and organic matter content of the soil profile (STONE version 2.0; Wösten et al, 1988).

Soil Building Block	Layer thickness (m)	Bottom depth (m-ss.)	Porosity (-)	K_{sat} (m/d)	Organic matter (-)
B-02	0.05	0.05	0.43	0.097	0.18
B-02	0.10	0.15	0.43	0.097	0.27
B-02	0.05	0.20	0.43	0.097	0.49
O-16	0.05	0.25	0.89	0.011	0.61
O-16	0.10	0.35	0.89	0.011	0.67
O-16	0.15	0.50	0.89	0.011	0.54
O-16	0.10	0.60	0.89	0.011	0.47
O-16	0.15	0.75	0.89	0.011	0.41
O-02	12.25	13.00	0.38	0.156	0.39

Drainage
Parameters were obtained from STONE version 2.0, plot 2343 (Table 3.4). The bottom depth of the channel (in m-ss.) decreases with the drainage system number. Drainage by means of saturated groundwater flow is distributed among these 3 different systems when the groundwater table is above the water level in the 3rd drainage system (0.75 m-ss.). When the groundwater table is below the water level of the 1st drainage system (1.6 m-ss.), drainage flow stops and surface water can start to infiltrate into the soil.

Table 3.4: Drainage parameters based according to STONE 2.0 (STONE plot 2343), unless indicated otherwise.

Parameter	Drainage system No. 1	2	3
Drain distance (m)	258	1767	298
drainage bottom (m-ss.)	1.60	1.00	0.75
Drainage - and infiltration resistance (d)	458 (*)	735	309

(*) the value according to STONE multiplied by 2 (based on expert judgment)

Regional groundwater
The interaction with the regional groundwater system is described as a constant upward seepage flux = 0.005 mm d^{-1}. This input from the regional groundwater

system was estimated from maps of the pressure head in the 2nd aquifer (Appendix 9 in Van Walsum et al., 1998).

Surface water
The soil hydrological model SWAP was run with an extended drainage routine, in order to simulate the infiltration of surface water into the soil profile during periods of prolonged drought. The daily surface water balance of this extended drainage routine in SWAP includes the following terms;

- Drainage flow towards the surface water (m d^{-1})
- External supply (m d^{-1})
- Infiltration from the surface water into the soil (m d^{-1})
- Discharge (m d^{-1})
- Storage (m)

Infiltration from surface water into the soil is simulated when the groundwater level in the soil profile is below the surface water level. The infiltration represents the demand of water during periods of prolonged drought.

For this extended SWAP simulation of soil hydrology in this single soil column cropped with potatoes, surface water levels need to be defined. This was done by assuming that the height of the weir crest equals the target level of Subarea 5 (the groundwater observation wells are located within this subarea). The water level is raised to 1.18 m-ss at April 1st (16.88 – 15.70 = 1.18 m, with the average elevation of the Subarea = 16.88 m+NAP and the high target level = 15.70 m+NAP) and lowered to 1.48 m-ss at October 1st (16.88 – 15.40 = 1.48 m). Target surface water levels in the subareas were obtained from (van Walsum et al., 1998).

Appendix 4 Soil Hydrology - Results

The simulated soil hydrology should meet the following requirements;

- A correct soil water balance, i.e. all water is accounted for in the balance.
- The major terms of the soil water balance are considered plausible.
- A plausible fluctuation of the groundwater table

Soil water balance

The soil water balance for the entire simulation period is shown in Table 4.1. The 761 days simulation period starts at November 1st, 1992 and ends at December 1st, 1994. The final storage, initial storage, and the water balance components are model output. The difference of the simulated soil water balance (Total In – Total Out – Storage Change) equals 0.0002 m or 0.01% of the balance total. So, all water is accounted for and the 761-days soil water balance is correct.

Table 4.1: Soil water balance of a 1m² soil column (profile depth = 13 m).

Water storage (m)		Period	
Final	5.2026	daynr final	1066
Initial	5.1752	daynr initial	306
Change	0.0274	Nr of days	761
In-Out-Change	0.0002		

Water balance components (m)

In		Out	
Precipitation	2.0313	Interception	0.0547
		Actual transpiration	0.3788
		Actual soil evaporation	0.5557
Lumped infiltration	0.0038	Lumped drainage	1.0564
Seepage (upward)	0.0381		
Total	2.0732	Total	2.0456

Balance terms

The amount of surface water infiltrated into the soil is limited to 4 mm. This can be explained by the high amount of rainfall; the years 1993 and 1994 represent the 93rd and 97th percentile in the time series of annual precipitation from the KNMI-weather station Klazienaveen (period 1971 – 2000).

The constant seepage rate at the bottom of the soil column cumulates to 38 mm. Because seepage can not be directly measured in the field, the seepage rate is often obtained by solving the water balance equation. Van der Gaast et al. (2007) used SWAP to calculate the long-term average seepage rate for a large number of combinations of hydrological conditions, soil physical properties, and meteorology in the Netherlands. The resulting seepage map shows some details of the spatial variability of calculated seepage rates within the study area, with legend class limits ranging from 0.25 mm d^{-1} in downward direction to 1 mm d^{-1} in upward direction. Within this range of long-term average seepage rates, the spatial pattern shows upward seepage in Subarea 1, 3, 6 and 7 and downward seepage in Subarea 2, 4 and 5. This is an example of spatial variability that is not accounted for in the single, representative soil column that was used here.

The evaporation of intercepted rainfall equals 55 mm. The total transpiration of the potato crop during the 2 growing seasons equals 379 mm, and the evaporation from bare soil equals 556 mm. Drainage flow towards the surface water contributes with 50% to the soil water balance.

In Figure 4.1 the cumulated terms of the soil water balance are plotted against time (the evaporation of intercepted rainfall is shown in Figure 4.2).

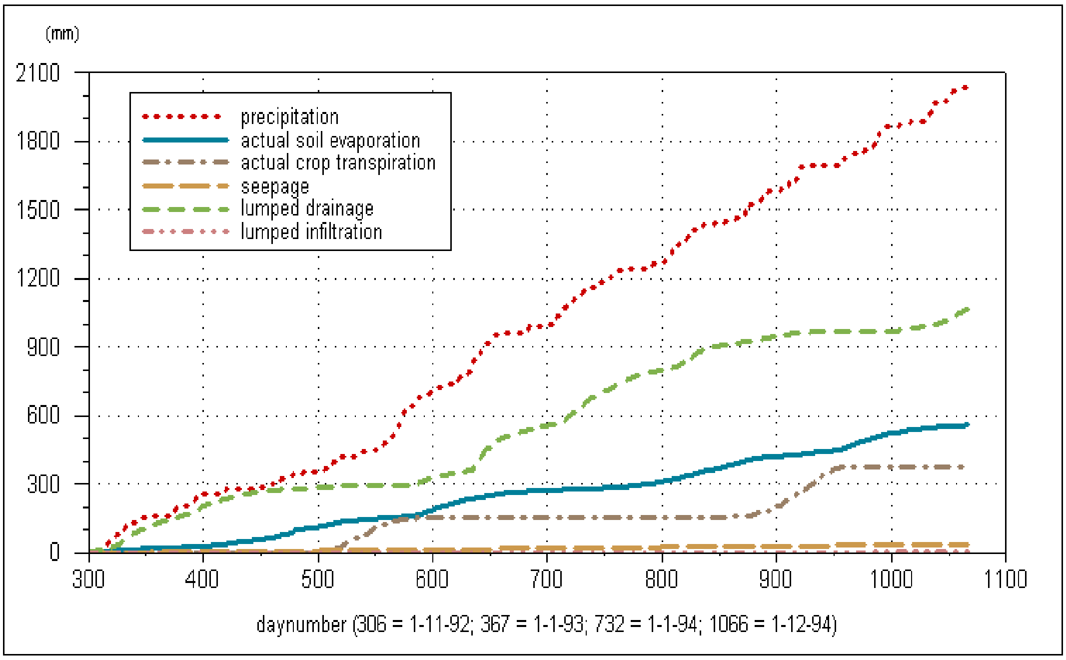

Figure 4.1 Cumulated terms of the soil water balance (in mm; see also Table).

The cumulated actual soil evaporation and actual crop transpiration are plotted in Figure 4.2, together with the maximum soil evaporation, the maximum crop transpiration, and the evaporation of intercepted rainfall. The growing season lasts from April 20th to September 1st (daynr. 476 – 610 in the year 1993, and daynr. 841 – 975 in the year 1994).

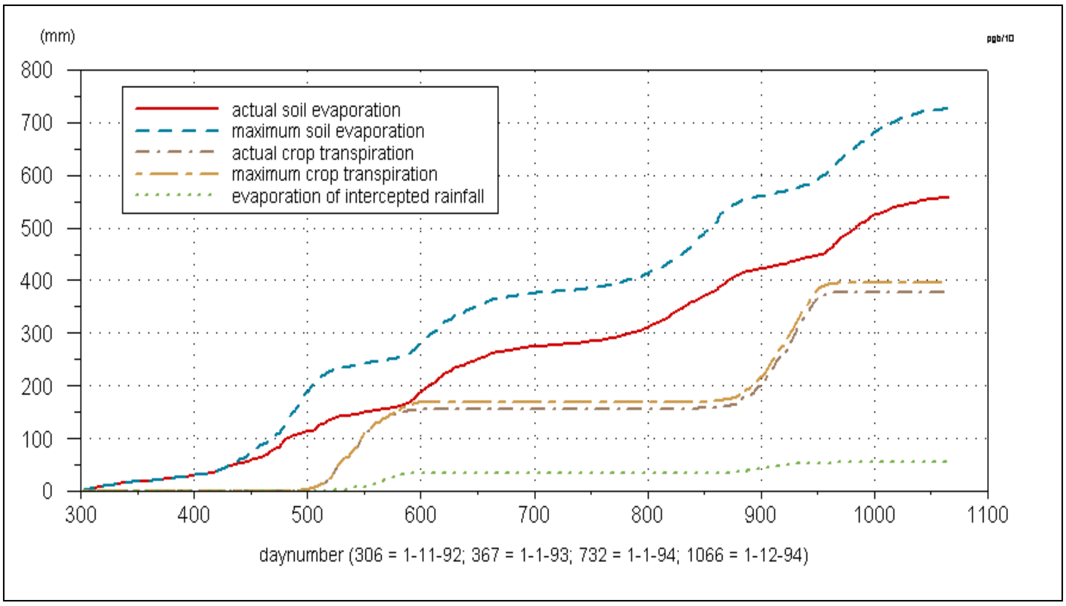

Figure 4.2 The cumulated actual soil evaporation and actual crop transpiration, with the maximum soil evaporation and maximum crop transpiration, and the evaporation of intercepted rainfall (in mm)

The maximum evapotranspiration (ET_{max}) during the entire simulation period equals 1118 mm (529 mm in 1993 and 570 mm in 1994; Table 4.2). The maximum soil evaporation (E_{max}) equals 723 mm (359 mm in 1993 and 345 mm in 1994), and the maximum crop transpiration (T_{max}) equals 395 mm (170 mm in 1993 and 225 mm 1994).

The actual evaporation (E_{act} = 611 mm) is the sum of soil evaporation (E_s) and intercepted rainfall (E_i). It can be seen in Figure 4.2 that the maximum soil evaporation rate is relatively low during winter, and during the growing season when the soil is covered by the crop. The maximum soil evaporation rate starts to rise in March; i.e. some 40 days before the start of the growing season. During this period, the model reduces soil evaporation rate depending on the cumulated maximum soil evaporation during a drying cycle. It can also be seen in Figure 4.2 that during the growing season the evaporation of intercepted rainfall contributes to the actual evaporation. This evaporation term is calculated based on precipitation and the leaf area index of the crop.

The actual crop transpiration (T_{act}) equals 379 mm (157 mm in 1993 and 222 mm and 1994). During the 1st growing season, crop transpiration is reduced because of wet conditions in the root zone. Starting at daynr. 572, these conditions in the root zone last for about 3 weeks. During the 2nd growing season, crop transpiration is reduced because of wet conditions in the root zone as well, but only at a few occasions. As a result, crop transpiration is reduced with 8% during the 1st growing season (1993) and with only 2% during the 2nd growing season (1994).

The actual evapotranspiration (ET_{act}) equals 990 mm (450 mm in 1993 and 521 mm in 1994). These annual amounts of actual evapotranspiration can be compared with simulation results for potatoes grown on soils with a groundwater regime comparable to the one at the study area (Gt V*). Van Bakel et al. (2007) reported a 30-years average evapotranspiration = 460 mm per year. This long-term average value for the evapotranspiration lies in between the annual results obtained for the study area.

The evapotranspiration reduction = 15% in 1993 and 9% in 1994. Depending on the meteorological conditions during the growing season, the evapotranspiration level and the evapotranspiration reduction may vary with the years.

Table 4.2: Maximum and actual evaporation and crop transpiration terms in the study area (for a period of 761 days, in mm). Results obtained with SWAP 3.1.4. (ET_{max} = maximum evapotranspiration, E_{max} = maximum soil evaporation, T_{max} = maximum crop transpiration, E_i = evaporation of intercepted rainfall, E_s = actual soil evaporation, E_{act} = actual evaporation, T_{act} = actual crop transpiration, ET_{act} actual evapotranspiration)

Period	ET_{max}	E_{max}	T_{max}	E_i	E_s	E_{act}	T_{act}	ET_{act}
1992	19	19	0	0	19	19	0	19
1993	529	359	170	35	258	293	157	450
1994	570	345	225	20	279	299	222	521
total (761 days)	1118	723	395	55	556	611	379	990

Groundwater levels
Figure 4.3 shows the simulated groundwater table and the observed groundwater levels, together with the simulated surface water level. It can be seen in the figure that the simulated groundwater table lies within the range of these 4 levels during most of the observation dates, and that the simulated groundwater regime corresponds with the time course of the observed groundwater levels. Since the range of these levels observed is rather large (up to 0.5 m) and the observation period covers only 60% of the discharge measurement period, it can only be concluded that the simulated groundwater regime is plausible.

Infiltrating surface water
Surface water can infiltrate into the soil as soon as the groundwater table drops below the surface water level. This is the case in August and September, 1994 (daynr. 955 to 995).

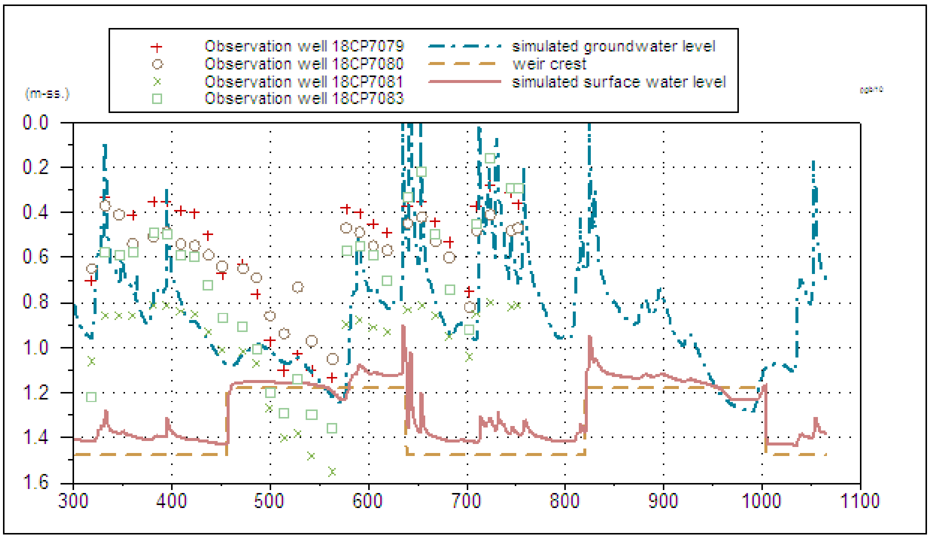

Figure 4.3: The simulated groundwater table and the observed groundwater levels, together with the surface water level simulated with the extended drainage routine in SWAP.

The terms of the surface water balance simulated with SWAP are shown in Table 4.3 (in m per unit area). The infiltration to the soil equals 4 mm. This amount corresponds with a volume of 37 10^3 m^3 for the 897 ha catchment. Note that this balance of the surface water generated with SWAP is no input of the SWQN model. The extended drainage routine can simulate the infiltration of surface water into the soil profile, leading to a realistic simulation of the groundwater table during periods of prolonged drought. The resulting drainage and infiltration fluxes were converted to the flow boundary input at the nodes of the surface water schematisation.

Table 4.3: Balance of surface water reservoir simulated with SWAP (in m per unit area. The balance period = 761 days)

In	(m)	Out	(m)
Drainage from the soil	1.064	Infiltration to the soil	0.004
External supply	0.005	Outflow	1.122
Storage change (increase)	-0.001		
Total	1.123	Total	1.125

Conclusions

The water balance for a representative 1 m^2 soil column cropped with potatoes was simulated for a period of 761 days with a cumulated error < 0.01% of the balance total. The results were carefully interpreted, based on expert judgement, simulation results reported, and comparison with the local groundwater levels observed.

The major soil water balance terms are plausible, considering both the cumulated contributions of these terms to the balance total, and the time course of these terms during the meteorological seasons of the year and especially during the growing season of the crop.

It is expected that the simulated infiltration flux gives a good description of the interaction between the soil water system and the surface water system of the study area, during periods of prolonged drought.

Table 4.4: Annual soil water balances of a 1m² soil column (profile depth = 13 m)

Water storage (m)		Year	1992
Final	5.1870	daynr final	366
Initial	5.1752	daynr initial	306
Change	0.0118	period (days)	61
In-Out-Change	0.0000		
Water balance components (m)			
In		Out	
Rain	0.1596	Interception	0
		Transpiration	0
		Soil evaporation	0.0186
Lumped infiltration	0	Lumped drainage	0.1323
Seepage	0.0031		
Total	0.1627	Total	0.1508

Water storage (m)		Year	1993
Final	5.2282	daynr final	731
Initial	5.1870	daynr initial	367
Change	0.0412	period (days)	365
In-Out-Change	0.0001		
Water balance components (m)			
In		Out	
Rain	0.9740	Interception	0.0346
		Transpiration	0.1572
		Soil evaporation	0.2581
Lumped infiltration	0.0007	Lumped drainage	0.5019
Seepage	0.0183		
Total	0.9930	Total	0.9517

Water storage (m)		Year	1994
Final	5.2026	daynr final	1066
Initial	5.2282	daynr initial	732
Change	-0.0256	period (days)	335
In-Out-Change	0.0001		
Water balance components (m)			
In		Out	
Rain	0.8977	Interception	0.0201
		Transpiration	0.2216
		Soil evaporation	0.2790
Lumped infiltration	0.0031	Lumped drainage	0.4223
Seepage	0.0168		
Total	0.9176	Total	0.9430

SWAP Run pgb10

Appendix 5 Conversion of SWQN output

In order to calculate pesticide entries by spray drift the dimensions and the volume of the water body in a section are needed. A post-processing programme was used for transformation of SWQN output per node into the required output per section, and for calculating some additional flow characteristics. The output of this post-processing programme SWQN_IO is described in Table 5-1. For example; the water level in a section equals the average of the water level in the nodes at both ends. All items shown in the table are calculated for each section and for each day of the simulation period.

Table 5.1: Contents of post-processing output file SWQN_WaterFlow.DAT (1 data record for each time step and each section)

Column		Symbol	units	Remarks
1	Date (SWQN format)		-	
2	day number (1 = 01-01-1992)		-	
3	Section ID (SWQN)		-	
5	Water level	*H*	m+NAP	Average level at the begin node and end node
6	Discharge	*Q*	m^3/d	Unit conversion of SWQN output (from m^3/s)
7	Water depth	*H*	m	Water level *H* minus the average bottom level
8	Wet cross-section	*A*	m^2	$A = h(B + hz)$ With h = water level B = average bottom width z = average side slope (h:v)
9	Water volume	*V*	m^3	$V = A * L$ With L = section length
10	Width of the water body	*B*	m	$b = B + 2zh$
11	flow velocity	*V*	m/d	$V = Q / A$
12	residence time	*T*	D	$t = V / abs(Q)$

In order to be able to plot the total travel time of surface water from a point at the network towards the outlet against time, the residence time of surface water in the sections along the pathway from that point towards the outlet can be cumulated. E.g. the travel time from Node 106 at the beginning of Section 118 towards Node 2 at the end of Section 1138 (Section 138 represents Pump G-12) equals the sum of the residence time in Sections 118, 140, 1140, 122, 138 and 1138 (Figure 5-1).

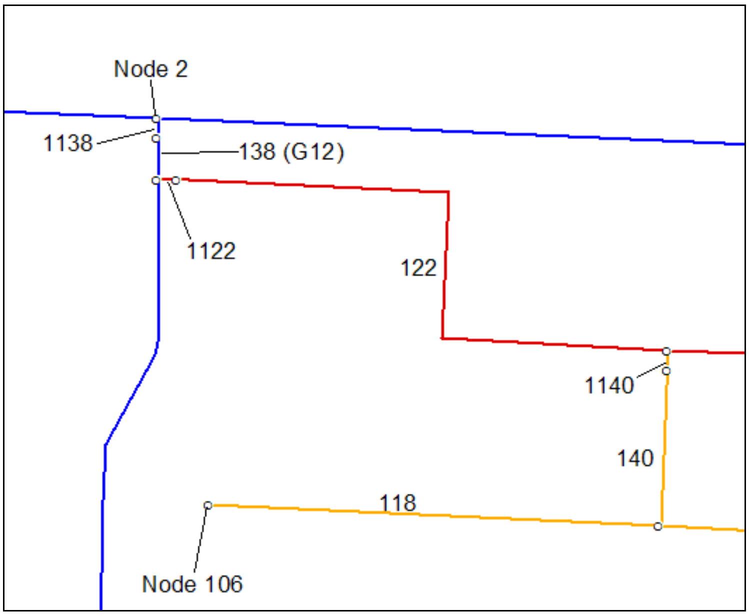

Figure 5.1: Sections of the surface water map near drainage pump G-12. The travel time from Node 106 at the beginning of Section 118 towards Node 2 at the end of Section 1138 (Section 138 represents Pump G12) equals the sum of the residence time in Sections 118, 140, 1140, 122, 138 and 1138.

The post-processing programme SWQN_IO calculates the travel time between any point at the surface water network and the outlet, for each time step.

Appendix 6 Results of a simulation with artificial meteorological input

Introduction

The performance of the parameterised SWQN model was tested with a special simulation of external water supply during a period of prolonged drought. For this purpose, the soil hydrological model SWAP was run with artificial meteorological input.

The simulation period coincides with the discharge measurement period. Daily precipitation and evapotranspiration according to Makkink were taken from the weather station Klazienaveen and Hoogeveen, except for the period between May 1st and July 31st, 1993 (daynr. 487 - 578) when precipitation was set equal to zero.

The cumulated lumped drainage and infiltration fluxes simulated by SWAP are shown in Figures 6-1 and 6.2, together with the other terms of the soil water balance.

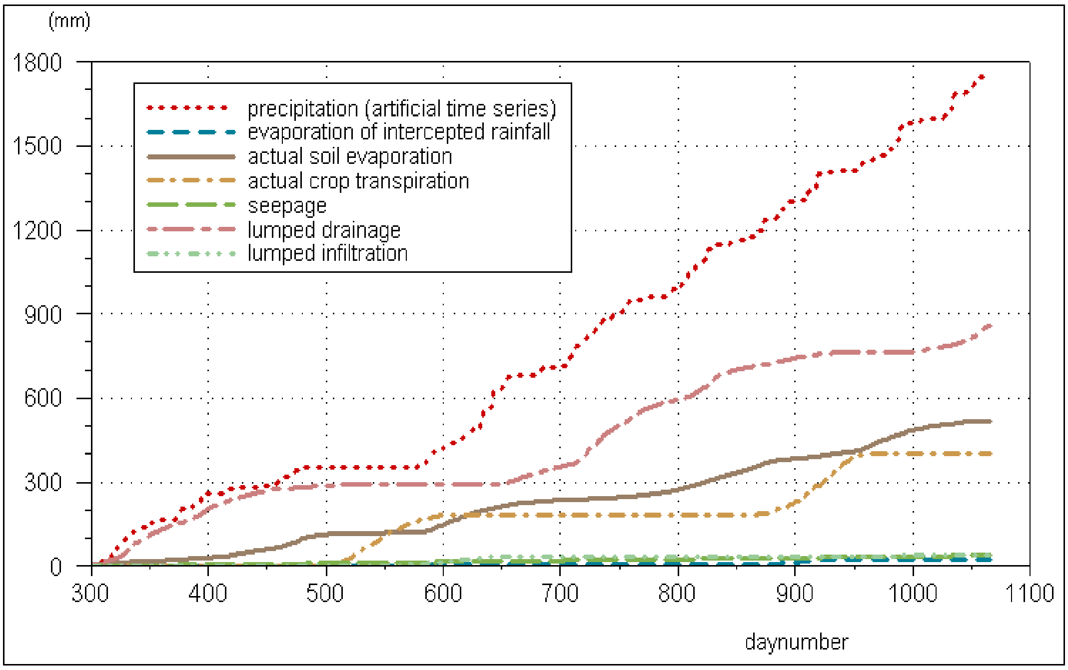

Figure 6.1: Cumulated terms of the soil water balance, based on artificial meteorological data with 3 months of drought (daynr. 487 – 578).

The groundwater table and the surface water level simulated with SWAP are shown in Figure 6.3. Drainage flow occurs when the groundwater level is above surface water level. Surface water infiltrates into the soil when the groundwater level is below the surface water level.

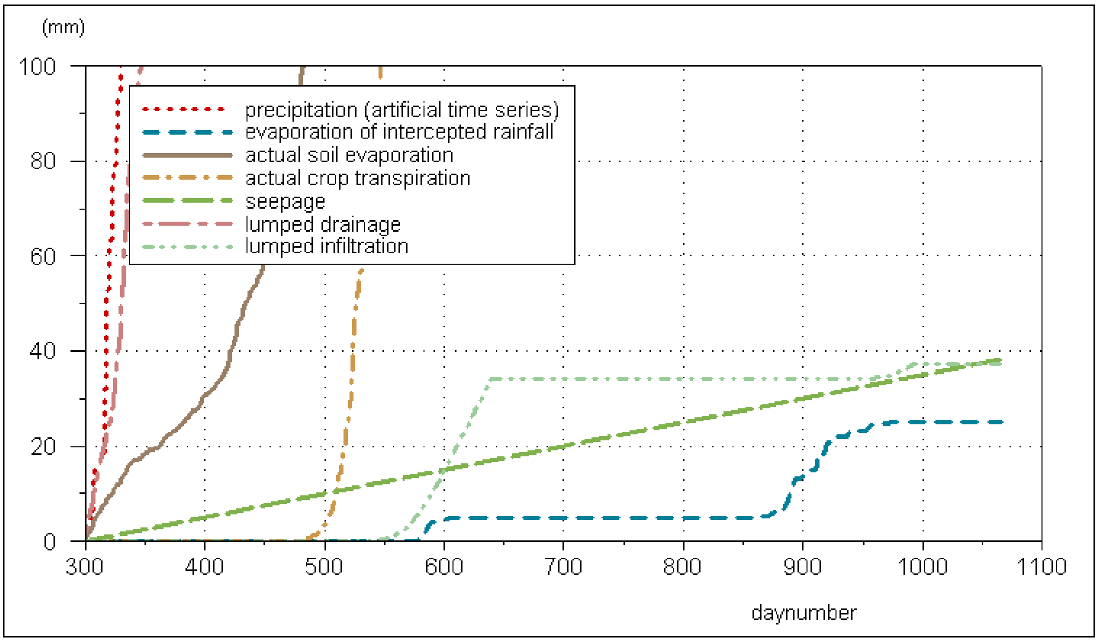

Figure 6.2: Detail of Figure 6.1.

The cumulated infiltration simulated during the period between daynr. 539 and 640 equals 34 mm, as can be seen in Figure 6.2.

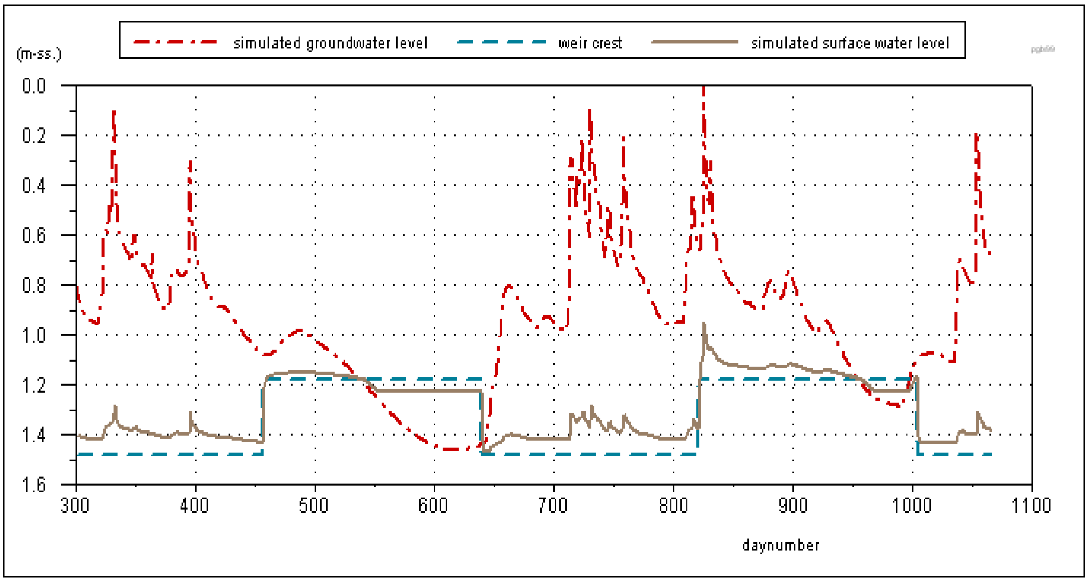

Figure 6.3: The groundwater table and surface water level simulated with SWAP. The crest level of the weir is raised at April, 1st and lowered at October, 1st.

The lumped drainage- and infiltration flux simulated with SWAP was converted to the flow boundary input of the SWQN model. In the next section the simulated discharge at the location of the inlet weirs and at the weirs for distributing the water within the area is presented. See Figures 7 and 8 for the schematised map with the location of these structures and subareas.

Results

Figure 6.4 shows the cumulated discharge per section during the 761-days simulation period (in 1000 m^3). Between daynr. 584 and 631, external water is supplied through the Inlet Weir S-94 (Section 114). Further distribution to Subarea 6 is simulated by the discharge at Weir / by-pass S-162 (Section 3076) and to Subarea 4 at Weir / by-pass S-132 (Section 3144). During this period of external supply there is no discharge simulated at the Weirs S-62 and S-32. This is in agreement with the function of these structures and the requirements formulated (Section 4.2.4).

Note that the volume of water supplied at daynr. 457 and 822 is used to raise the target level in the channels.

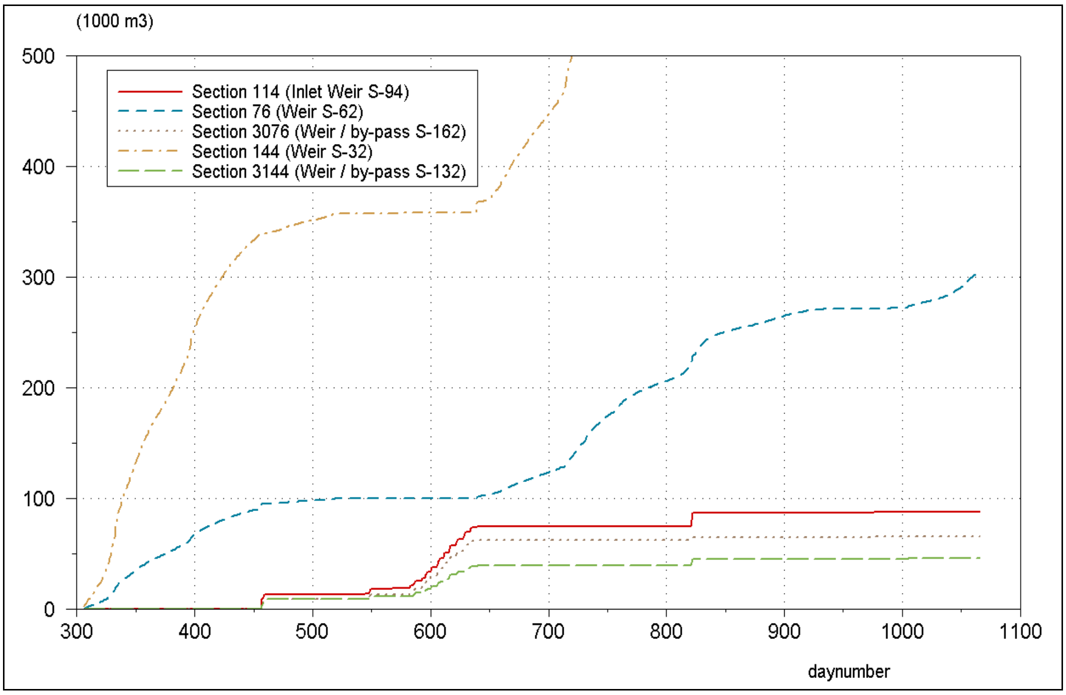

Figure 6.4: Cumulated discharge showing the external water supplied to Subarea 7, and further distributed to Subareas 6 and 4.

Figure 6.5 shows the water level simulated at the end nodes of the sections defined as Inlet Weir S-94 (Node 1038), Weir S-62 (Node 1035), Weir S-32 (Node 1029) and Weir S-61 (Node 1040). At daynr. 539, drainage flow changes into infiltration flow, causing the water level to decrease. Between daynr. 551 and 640, the water level fluctuates between the levels determined by the control parameters defined at the Inlet Weir (S-94) or the Weir / by-pass (S-162, S-132). At daynr. 640, the target level in the subarea is decreased. According to the water management control settings, no external supply of water is possible during periods of low target level.

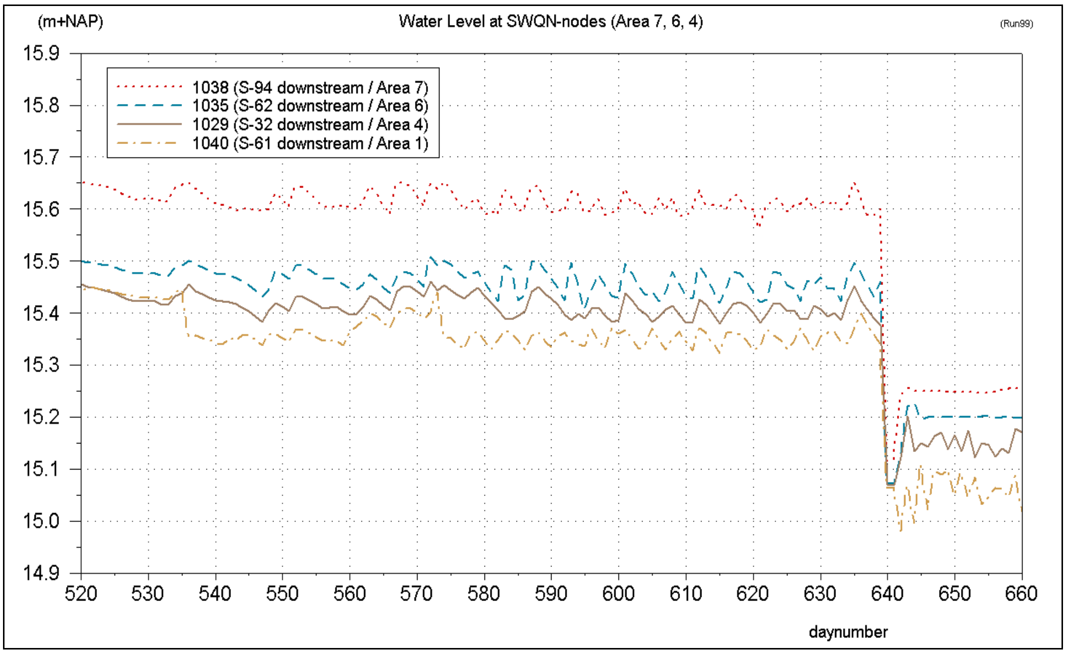

Figure 6.5: The water level simulated at the end nodes of the sections defined as Inlet Weir S-94 (Node 1038), Weir S-62 (Node 1035), Weir S-32 (Node 1029) and Weir S-61 (Node 1040).

Based on comparison of the results shown in Figures 6.5 and 34 it can be concluded that the simulated water levels in these channels show a similar fluctuation above and below the target water levels to the same degree, both during periods of prolonged drought and during periods of excess rainfall.

Figure 6.6 shows the external water supplied to Subarea 3 through the Inlet Weir S-26 (Section 121). Within Subarea 3, the water flow is distributed among two branches; i.e. Section 136 directed towards the western part of Subarea 3 and Section 123 towards Weir S-63 and Subarea 1. The discharge simulated at Section 136 has a negative sign because it is directed from the end node towards the begin node. Further distribution to Subarea 1 is simulated by the discharge at Weir / by-pass S-163 (Section 3142). During the period of external supply there is no discharge simulated at Weir S-63. This is according to the requirements formulated.

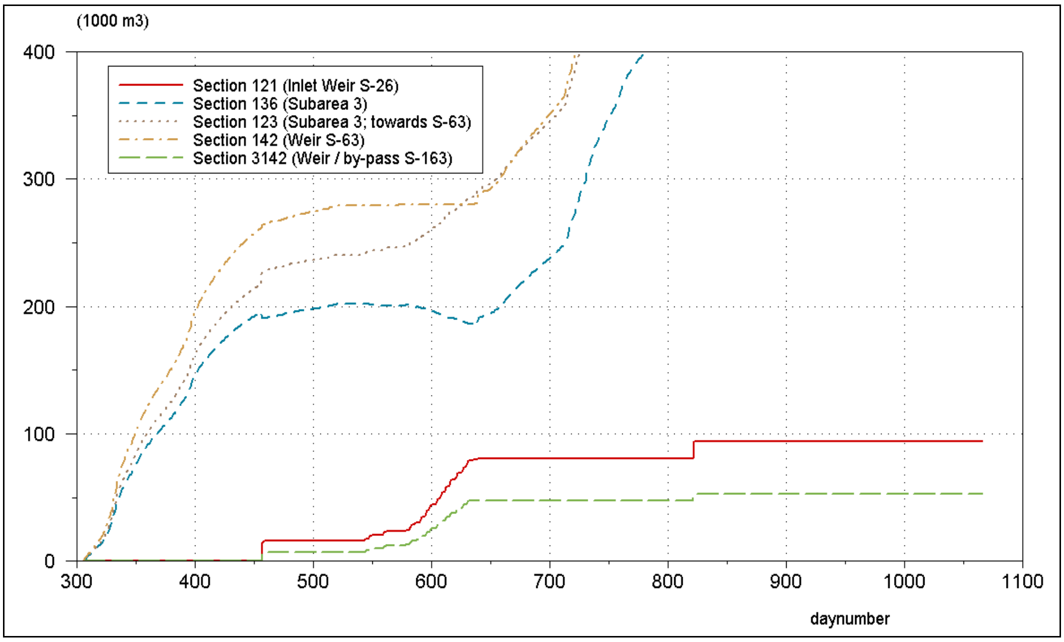

Figure 6.6: Cumulated discharge showing the external water supplied to Subarea 3, and further distributed to Subarea 1.

Figure 6.7 shows the water supplied (from Subarea 5) to Subarea 2 through the Inlet Weir S-45 (Section 145). During the period of supply there is no discharge simulated at the Drainage Pump G-18 (Section 133).

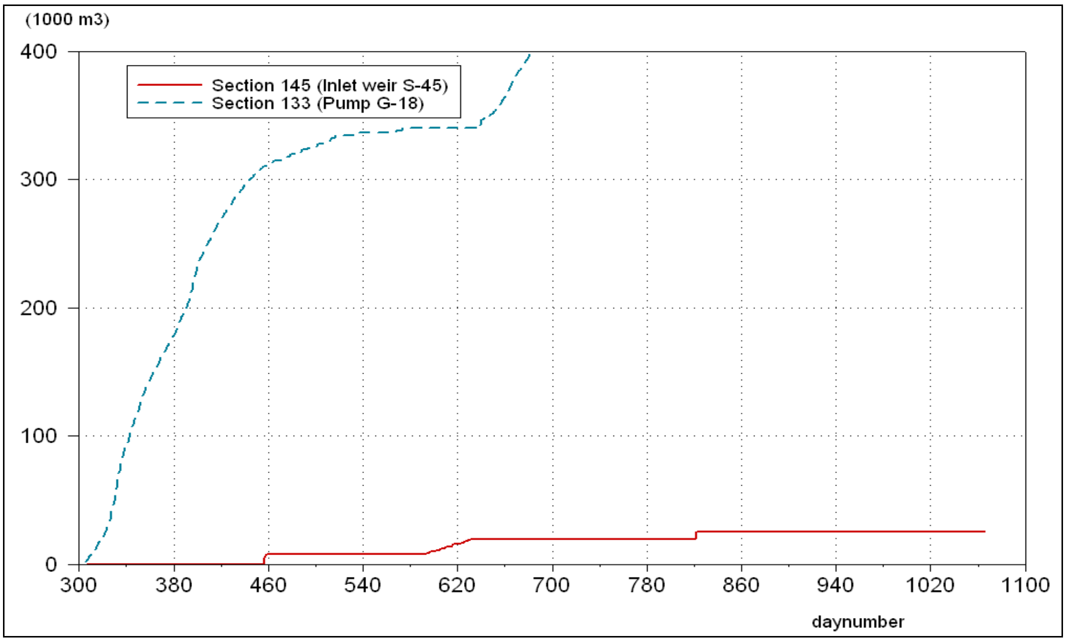

Figure 6.7: Cumulated discharge showing the water supplied to Subarea 2.

Conclusions
A special simulation with artificial meteorological data shows that the calibrated SWQN model can produce an acceptable simulation of surface water flow during a period of prolonged drought with external water supply.

Simulated water levels based on artificial meteorological input show a similar fluctuation of the water level above and below the target water levels, compared to those based on local meteorological data. This applies both to circumstances of prolonged drought and of excess rainfall.

According to the requirements formulated, there is no external supply of water simulated during periods of discharge at the outlet. Also, there is no discharge simulated at the outlet during periods of external water supply. The water supplied is further distributed within the area via the structures that were included in the surface water network for this purpose.

Based on the simulation results with artificial meteorological input it can be expected that the SWQN model parameterised for the study area can simulate surface water dynamics for a long-term series of meteorological years.