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Modelling climate change in a Dutch polder system using the FutureViewR modelling suite

W.W. Immerzeel [a,*], C.C. van Heerwaarden [b], P. Droogers [a]

[a] FutureWater, Costerweg 1G, 6702 AA Wageningen, The Netherlands
[b] Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands

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ABSTRACT

This paper describes the development of a hydrological modelling suite, FutureViewR, which enables spatial quantification of the complex interaction between climate change, land use and soil in the Quarles van Ufford (QvU) polder entangled in and under influence of the Dutch river delta. The soil–water–atmosphere–plant (SWAP) model is used in a grid-based mode. A river module was developed to take into account seepage and percolation in the polder as an effect of the interaction with the main rivers. A simple surface water model was linked to the grid-based SWAP models. The model suite is managed from a Visual Basic (VB) interface which links the different modules. The interface uses a mainstream database management system (MS SQLServer), structured query language (SQL) and open database connectivity (ODBC) to store, transfer, manipulate and analyse model inputs and outputs. The functionality of the FutureViewR modeling suite is demonstrated by modeling a climate change scenario for 2050. The preliminary analysis showed that it is likely that the dryer summers in combination with low water levels in the Rhine and Meuse will yield a decrease in agricultural production. The wetter winters do not necessarily result in an increase in discharge, since the initial soil moisture storage at the winter onset is lower due to the dryer summers. It is concluded that the effects of climate change on polder hydrology is more intense caused by the dependence on local climate conditions and water levels on the Rhine and Meuse rivers, which are mutually reinforcing.

1. Introduction

Data on spatial and temporal patterns of key hydrological variables are essential to assess the current conditions of water resources and to evaluate trends in the past. However, to explore options for the future, tools are required that enable the evaluation of the impact of future trends and how we can adapt to these in the most sustainable way (Droogers and Immerzeel, 2006). A simulation model, defined here as a computer-based mathematical representation of dynamic processes, is the appropriate tool to do these analyses. There are three major motivations to use hydrological models: (i) formalizing our knowledge in mathematical representations, (ii) understanding processes and (iii) scenarios analyses. The use of simulation models in the exploration of different scenarios is particularly important. These scenarios generally refer to aspects that cannot directly be influenced, such as land use changes, population growth and climate change. A huge number of hydrological models exists, applications are growing rapidly and an important issue to consider is the continuum between physical detail and spatial scale. In general, it can be stated that the larger the spatial scale the less physical detail is included (Immerzeel, 2008).

The recently published fourth assessment report of the International Panel on Climate Change (Solomon et al.,

* Corresponding author. Tel.: +31 317 460050.
E-mail address: w.immerzeel@futurewater.nl (W.W. Immerzeel).

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2007) concludes that warming of the global climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. At continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include widespread changes in precipitation amounts, wind patterns and aspects of extreme weather including droughts, heavy precipitation and heat waves. Based on a large number of simulations from a wide variety of atmosphere ocean general circulation models (AOGCM), the report also presents the analysis of possible futures for the period 2000–2100 following the scenarios defined in the IPCC special report on emission scenarios (SRES) (Nakicenovic and Swart, 2000). The analysis shows that irrespective of the scenario, the average global temperature is very likely to increase between 1.8 and 4 °C by the year 2100. Van den Hurk et al. (2006) have constructed specific climate change scenarios for the Netherlands based on these IPCC results, regional climate modelling and observations. The scenarios generally result in wetter winters and dryer summer, which will have considerable effects on the Dutch hydrology.

This paper describes the development of a hydrological modeling suite that enables spatial quantification of the complex interaction between climate change, land use and soil in the Quarles van Ufford (QvU) polder entangled in and under influence of the Dutch river delta.

The complexity of the system and the need to assess the effects of climate change poses a number of serious requirements that cannot be provided by existing simulations models. The model needs to be able to cope with a dual effect of climate change in the polder, because precipitation and evapotranspiration will change in QvU, and climate change will affect local water levels in the Rhine and Meuse resulting in changing percolation and seepage characteristics in QvU (Van Heerwaarden and Ketelaar, 2006). The model also needs to quantify the (spatial) interaction between precipitation, evapotranspiration, seepage, percolation, runoff and drainage. These requirements impose a high level of physical detail at an intermediate spatial scale and a semi-distributed model is needed that integrates the effects of water level fluctuation in the Rhine and Meuse, processes in the unsaturated zone and groundwater and the interaction with the surface water of the QvU polder. This paper describes the development, provides background on the technical implementation, and demonstrates the use of a new tool called FutureViewR. FutureViewR is a hydrological modelling suite that attains to these requirements and this paper reports on the different components and technical implementation of FutureViewR. The use of FutureViewR is illustrated with an assessment of climate change in the QvU polder.

2. Study area

The QvU polder (117 km^2) is located in the province of Gelderland in the central part of the Netherlands. Precipitation in QvU is relatively constant throughout the year and ranges from 46 in April to 72 mm in October with an average annual total of 791 mm (1995–2004). On average, there is a precipitation surplus (precipitation minus potential evapotranspiration (ET$_{pot}$)) of 168 mm y^{-1} and ET$_{pot}$ ranges from 5 mm in December to 107 mm in June. QvU is enclosed between the river Meuse in the south and the river Rhine in the north (Fig. 1). This has

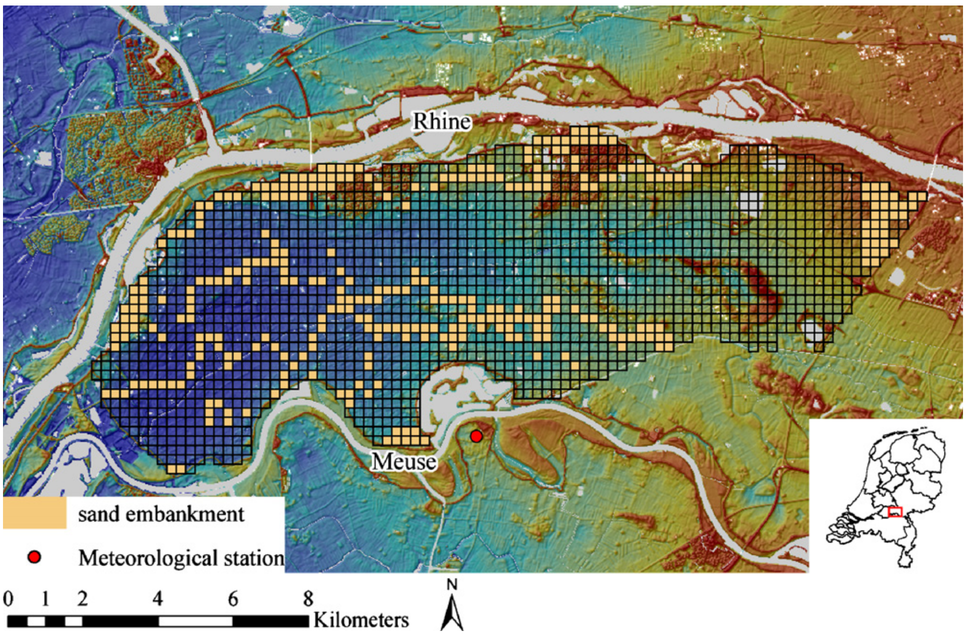

Fig. 1. Location of QvU polder, rivers Meuse and Rhine, Location of meteorological station and modelling grid. Sand embankments are shown in yellow and background image is a digital elevation model.

important hydrological consequences as the water levels in these rivers influence seepage and percolation in QvU. The water level in the river Meuse is controlled by a nearby weir and is relatively constant over time, whereas the Rhine discharges its water freely and water levels exhibit a more capricious pattern. The Rhine water levels, therefore, have a much larger influence on the variation in QvU seepage and percolation than the Meuse. The hydrogeology of QvU is characterized by a Holocene impermeable top layer of approximately 5 m of different textures (clay and loam), which is typical for the Dutch river delta geology (Dufour, 1998). The aquifer below this top layer has a Pleistocene origin and there is a large variation in depth between the levees and the planes. Within the polder, there are a number of highly permeable sand embankments, which dissect the Holocene top layer and have their origin in ancient meanders. These embankments play an important role in the transport of percolation and seepage water to and from the Meuse and Rhine (Fig. 1)

3. Methods

3.1. Soil–water–atmosphere–plant(SWAP)

FutureViewR is based on the one-dimensional (1D) unsaturated zone SWAP model. SWAP is used to simulate all the terms of the water and salt balances and to estimate relative yields (actual over potential yield). SWAP is an integrated physically based simulation model for water, solute and heat transport in the saturated–unsaturated zone in relation to crop growth. For this study, the water transport and crop-growth modules are used. SWAP development started in 1978 (Feddes et al., 1978) and from then on, the model has continuously been improved. The version used for this study is SWAP 3.0.3 and is described by Kroes and Van Dam (2004). The core part of the program is the vertical flow of water in the unsaturated–saturated zone, which can be described by the Richards' equation

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z}+1\right) - S(h)\right] \tag{1}$$

where θ denotes the soil–water content ($cm^3\,cm^{-3}$), t is time (d), h (cm) the soil matric head, z (cm) the vertical coordinate, taken positive upwards, K the hydraulic conductivity as a function of water content ($cm\,d^{-1}$). S (d^{-1}) represents the water uptake by plant roots (Feddes et al., 1978), defined in case of a uniform root distribution as

$$S(h) = \alpha(h)\frac{T_{pot}}{|z_r|} \tag{2}$$

where T_{pot} is potential transpiration ($cm\,d^{-1}$), z_r is rooting depth (cm), and α (h) is a reduction factor as function of h and accounts for water deficit and oxygen deficit. Total actual transpiration, T_{act}, was calculated as the depth integral of the water uptake function S.

Actual soil evaporation can be estimated by the Richards' equation using the potential evaporation as the upper boundary condition. However, this requires information about the soil hydraulic properties of the first few centimetres of the soil, which are hardly measurable and are highly variable in time as a consequence of rain, crust and crack formation, and cultivation (Van Dam et al., 1997). All these processes reduce the real actual evaporation in comparison with the values obtained by applying Richards' equation. Therefore, the additional soil reduction function option from SWAP was used, whereby the actual evaporation is a function of the potential evaporation, the soil moisture content of the top soil, an empirical soil-specific parameter, and the time since the last significant rainfall. Details of this procedure are given by Boesten and Stroosnijder (1986).

Crop yields can be computed using a simple crop-growth algorithm based on Doorenbos and Kassam (1979). Relative growth is proportional to quotient between actual evapotranspiration and potential transpiration according to

$$1 - \frac{Y_{act}}{Y_{pot}} = K_y\left(1 - \frac{ET_{act}}{ET_{pot}}\right) \tag{3}$$

where Y_{act} ($kg\,ha^{-1}$) is the actual yield, Y_{pot} ($kg\,ha^{-1}$) is the potential yield, K_y (−) is a sensitivity factor to account for a different response during the crops phenological stages, ET_{act} is the actual evapotranspiration (m) and ET_{pot} (m) is the potential evapotranspiration.

The drainage and infiltration fluxes from and into the SWAP columns are influenced by the surface water levels. It is assumed that the surface water levels are kept constant at their winter and summer target levels. This is a safe assumption, since in dry period water from outside the polder is let in to sustain the water levels.

The SWAP model has been applied and tested for many different conditions and locations and proven to produce reliable and accurate results (e.g. Feddes et al., 1988; Bastiaanssen et al., 1996; Droogers, 2000; Droogers et al., 2000; Droogers et al., 2001; Heinen, 2006; Varado et al., 2006; Bastiaanssen et al., 2007).

A more detailed description of the model and all its components is beyond the scope of this paper, but can be found in Kroes and Van Dam (2004).

A modelling grid with a cell size of 250 m was superimposed on the QvU polder, and a SWAP model was parameterized for each grid cell (Fig. 1). For a total of 1892 SWAP columns model parameters were assigned.

3.2. River module

For clarity, both percolation and seepage processes are referred to as seepage, e.g. percolation is negative seepage. To account for seepage from the rivers Meuse and Rhine, a specific module has been developed. The basis of this module is Darcy's law (Darcy, 1856)

$$q = -k\frac{dH}{dz} \tag{4}$$

where q is the flux density ($m\,d^{-1}$), k is the permeability of the soil ($m\,d^{-1}$), dH is the pressure head difference and dz is the length dH takes place over. It is assumed that transport of water between the river and the QvU polder only occurs through the aquifer. Following Dupuit's assumption (Dupuit, 1863) that water transport through an aquifer is horizontal, the system can then be described by a one-dimensional differential equation. The solution is given by Mazure (1936):

$$q(x) = \frac{H_0 - H_{polder}}{c} \cdot e^{-(x/\sqrt{kDc})} \tag{5}$$

where x (m) is the distance to the river dike, H_0 (m) is the total head in the aquifer directly beneath the axis of the river (= river water level), H_{polder}(m) is the total head in the aquifer beneath the polder, c is the resistance of the impermeable top layer (d), k is the hydraulic conductivity of the aquifer (m d^{-1}) and D is the thickness of the aquifer (m). This leads to the interesting conclusion that seepage at a certain location in the polder is only depending on the pressure head difference (Eq. (6)), as the other terms in Eq. (5) can be grouped to a constant factor (Eq. (7)), which is determined by the distance to the dike and aquifer characteristics.

$$q_{seepage}(x) = \text{factor}(x)(H_0 - H_{polder}) \tag{6}$$

$$\text{factor}(x) = \frac{1}{c} e^{(-x/\sqrt{kDc})} \tag{7}$$

The water levels in the rivers are available and SWAP calculates pressure heads for each model grid cell. Combining both enables calculation of daily seepage at each grid cell of QvU. If a grid cell is characterized as sand embankment (Fig. 1), the constant factor is multiplied by 10. The approach has been extensively validated by Van Heerwaarden et al. (2005). The river module was included in SWAP 3.0.3 and incorporated as a new optional bottom boundary condition for each SWAP column.

3.3. Surface water model

To evaluate effects of the unsaturated zone and river seepage on the surface water hydrology of QvU, the model has been further extended with a surface water module. The surface water in Dutch polder systems is typically controlled by a network of rectangular weirs. Discharge across such weirs is given by

$$Q_{out} = 1.7\mu b h^{3/2} \tag{8}$$

where Q_{out} the discharge (m^3 s^{-1} ha^{-1}), μ (–) is the weir constant, b is the width of the weir (m) and h (m) is the water level above the crest height. The weirs are designed for a standard discharge of 7.5×10^{-4} l s^{-1} ha^{-1}. Assuming a corresponding crest height of 0.2 m and $\mu = 1.1$, the width of the weir can be calculated using the total surface area that is drained by the weir.

The QvU polder is schematized in 190 homogeneous areas with equal surface water levels. For each area, one representative water course (RW) controlled by a representative weir is assumed. All SWAP model grids that fall within such a homogeneous area exchange water with the corresponding RW. On a daily basis, the net supply of water (Q_n (m^3 d^{-1})) to or from the RW summed over all grid cells is given by

$$Q_n = Q_u + P_w - E_w + S_w + D - I + R \tag{9}$$

where Q_u (m^3 d^{-1}) is the discharge from the upstream RW, P_w (m^3 d^{-1}) is the open water precipitation, E_w (m^3 d^{-1}) is the open water evaporation, S_w (m^3 d^{-1}) is the net open water seepage, D (m^3 d^{-1}) is drainage from the SWAP grid cells, I (m^3 d^{-1}) is infiltration to the SWAP grid cells and R (m^3 d^{-1}) is surface runoff from the SWAP grid cells.

Based on this net discharge and the open water surface (A_w (m^2)) a change in crest height on day t can be calculated according to

$$\Delta h(t) = \frac{Q_n(t)}{A_w} \tag{10}$$

By inserting the crest height in Eq. (8) the discharge to the next downstream RW can be determined. The new crest height at day t+1 is now given by

$$h(t+1) = h(t) + \Delta h(t) + \frac{Q_n(t+1) - Q_{out}(t)}{A_w} \tag{11}$$

The surface water calculation starts at the most upstream RW and is progressively routed through the polder. The general discharge direction is from east to west. The routing pattern is determined by the order of target water levels of each area draining into a RW. This is schematically shown in three dimensional (3D) in Fig. 2. The figure represents the QvU polder. The management units that have similar target levels are shown schematically.

3.4. Technical implementation

The SWAP model, originally developed in Fortran, has been modified to include the river module (SWAPRIV), and one modified SWAP column is parameterized for each grid cell. SWAP uses four types of ASCII input files; a main input file with general settings, daily meteorological data, drainage data and a crop-growth data file. The output of SWAP includes daily water balance and crop-growth data for a large number of variables, which is also stored as ASCII type files. (Kroes and Van Dam, 2004)

Managing input data of 1890 SWAP models and storing their output on a daily basis for a large number of variables for multiple year simulation periods yields specific data management consequences. Therefore, all input data and output data are centrally stored in a Microsoft SQLServer 2005 database. It is a comprehensive database software platform that supports relational databases and is capable of storing and manipulating large amounts of data. The software is highly compatible with the Visual Basic (VB) programming language. A FutureViewR engine was (FV engine) developed in VB that communicates between the database and SWAP. A template file for each SWAP ASCII input file was generated with specific tags for input parameters. For each SWAP grid cell, the FV engine reads the input parameters from the database, replaces the tags in the template input files, runs SWAP, reads the SWAP ASCII output files and stores the results in the central database.

The surface water module is also developed in VB and is run from the FV engine after all SWAP simulations have been finalised. The surface water module commences with the most upstream RW. The relationship

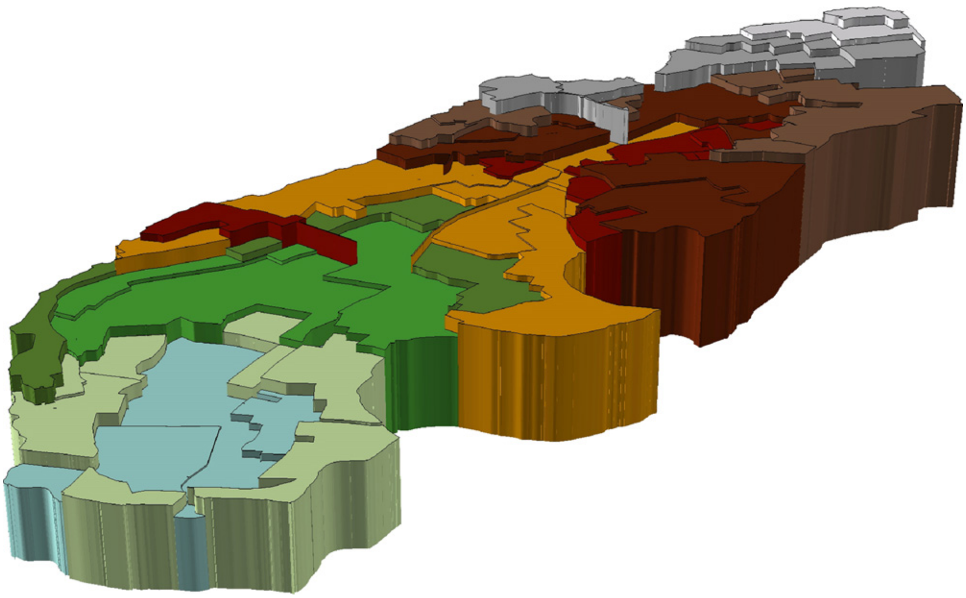

Fig. 2. Schematic representation of routing pattern for QvU polder.

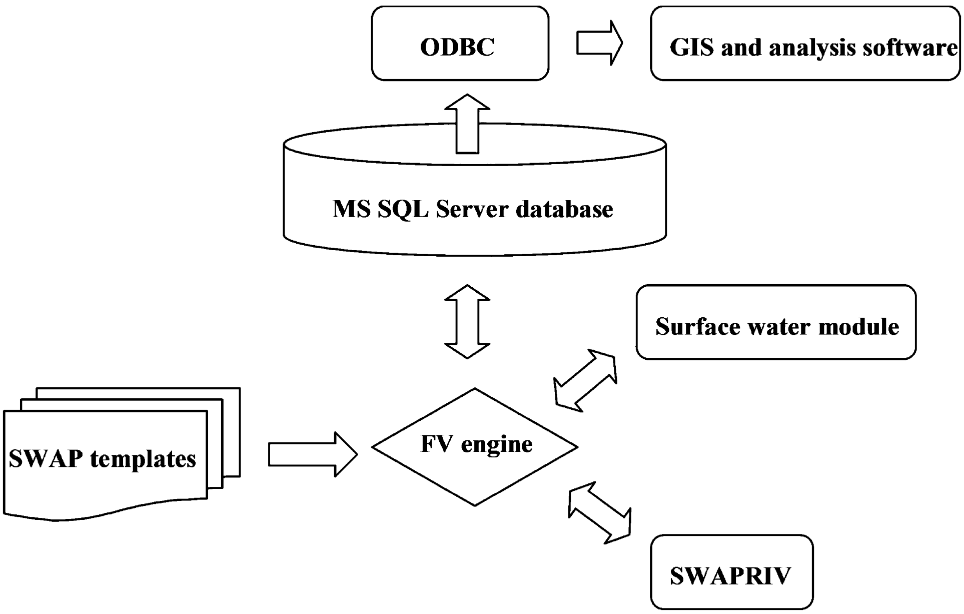

Fig. 3. System architecture of FutureViewR.

between the RW and the corresponding SWAP columns is stored in the database and the required SWAP output to calculate the net supply of water is aggregated per RW. After determining the outflow to the next downstream RW (Eqs. (9)–(11)), this process is repeated until the outlet of QvU is reached. The daily outflow and water level of each RW is stored in the database. The communication between the database, the swap templates, SWAPRIV and the surface water module goes via SQL. SQL is a standardized computer language designed for retrieval and management of data in relational databases. An extension to standard SQL is used, called transact SQL (T-SQL). T-SQL is Microsoft's proprietary extension to SQL and is included in Mircorsoft SQLServer 2005.

Using open database connectivity (ODBC) and T-SQL the model output is extracted from the database for further presentation and analysis in GIS and other data analysis software. ODBC is a standard software API for communicating with database management systems, independent of programming language, database system and operating system. The schematic representation of FutureViewR is shown in Fig. 3.

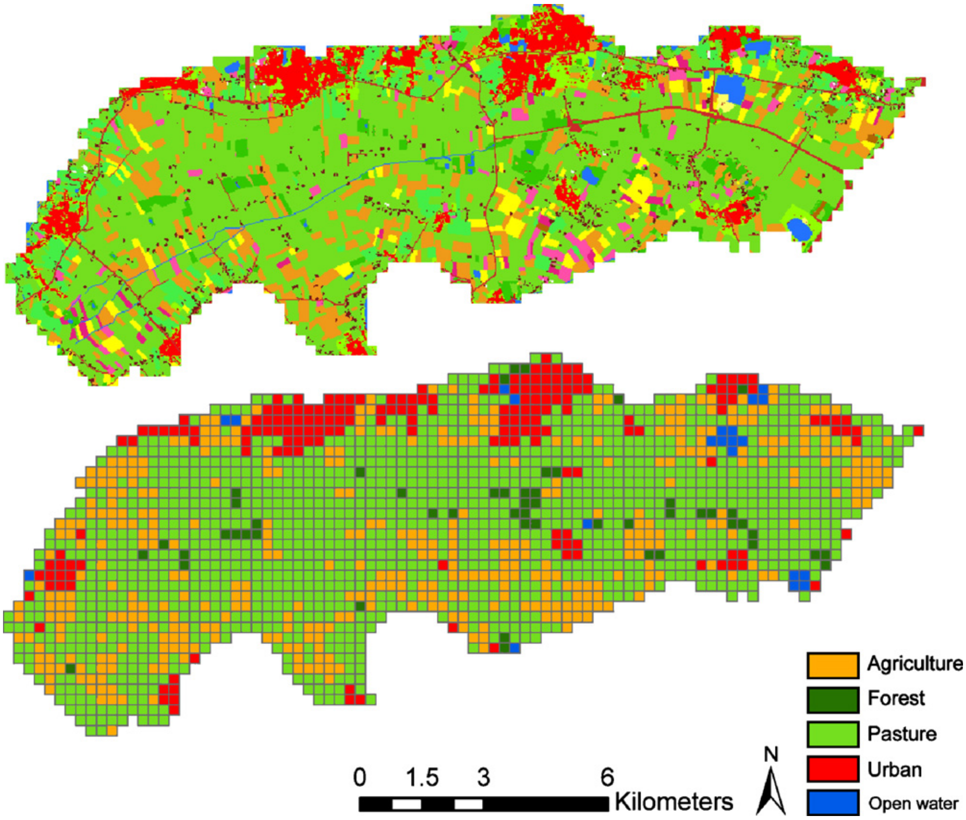

Fig. 4. Land use in QvU. Original (top figure) and generalised (bottom figure).

3.5. Data

3.5.1. Model parameters estimation

Target levels of water levels in the polder are provided by the water board and a detailed elevation model[1], with a horizontal resolution of 25 m, was used to specify relative water levels per model grid cell.

Soil physical characteristics are determined using a procedure described by Wösten et al. (2001) that uses pedo-transfer functions to convert soil texture data, derived from a 1:50,000 soil map, to specific water retention and permeability characteristics of each soil type. By GIS overlay these characteristics are attributed to the model grid cells.

Drainage properties are derived from the STONE database (Kroon et al., 2001). At 250 m resolution, this database provides drainage resistances for the primary (major water courses), secondary (small streams) and tertiary drainage system (ditches). These resistances are direct input to the SWAP model. Using GIS, the geometric average are determined and attributed to each model grid cell. The STONE database also provides information on the length of each drainage system within a grid cell. These lengths are used to determine the area of open water (A_w), which is required for the open water module (Eqs. (10) and (11))

One land use type is assigned to each model grid cell. Land use is derived from a national land use database with an original spatial resolution of 25 m (Thunnissen and de Wit, 2000). For each model grid cell, the most abundant land use is selected and assigned. Five different classes are distinguished; agriculture, forest, pasture, urban areas and water. The original and generalised land use per model grid cell is shown in Fig. 4. Land use is further parameterized using standard land use files for SWAP.

Daily water levels from 1995 to 2004 for the rivers Rhine and Meuse were used to parameterize the river module. Data were obtained from the institute for inland water management and waste water treatment (RIZA)

3.5.2. Climate change scenario

In the analyses, we distinguish between the reference situation (1995–2004) and a future climate around the year 2050. For the reference situation use was made of meteorological data from the station Megen (Fig. 1). The 1995–2004 time series from Megen (precipitation and ET_{pot}) was transformed to a time series around the year 2050 for the *W*+ scenario (Van den Hurk et al., 2006). The "*W*" is taken from "Warm" (+2 °C in 2050 relative to 1990) and "+" indicates a strong change in large-scale circulation patterns. The *W*+ scenario is the most extreme scenario amongst the four scenarios constructed with respect to dry situation. For wet situations, specifically in summer, the *W* scenario is more extreme. All scenarios are equally

[1] Actueel Hoogtebestand Nederland, 2005. www.ahn.nl.

likely to occur. The scenarios are constructed by combining outputs from global climate models and regional climate models for Europe in combination with Dutch historical measurement series. The transformation of precipitation is based on projected changes in the number of wet days, the average precipitation on a wet day and the change in extreme precipitation (Table 1). This transformation has been performed using software provided by the KNMI. The transformation of potential evapotranspiration is based on projected seasonal increases (Table 2). Both precipitation data as well as potential evapotranspiration were used as input to FutureViewR for the reference situation and the *W*+ scenario.

Climate change also impacts water levels in the Rhine and Meuse and we have used *W*+ scenario model output of basin scale hydrological models to address this change. The model is described by Van Deursen (2002). The results were used to transform the observed time series of water levels to a time series depicting the *W*+ scenario around 2050. The transformed time series was input to FutureViewR.

3.5.3. Validation

The model was calibrated for one specific grid cell within QvU based on measured groundwater levels. A validation with measures discharges at the outlet of the polder was also performed. The observed data was available for the year 2000.

4. Results

The application of the newly developed tool FutureViewR will be presented. First the validation results will be presented and then focus will be on the most salient features in temporal patterns of water balance constituents and discharge and spatial patterns in evapotranspiration and seepage, for both current and future climates.

Fig. 5 shows the results of the validation. The top figure shows that FutureViewR is capable of realistically simulating groundwater levels. Especially the seasonal dynamics between winter and summer are in good accordance. Measured data are collected at a 14-day interval and therefore the extreme peaks, which are clearly visible in the modelled series are averaged out in the case of the observed data. The discharge at the outlet of the QvU polder (bottom figure) is well mimicked in case of average to high discharges, however, FutureViewR consistently underestimates discharge in a low flow situation. This can be explained by the fact that, as part of the water board management strategy, there are considerable amounts of water from outside the polder, which artificially enters QvU. This is done intentionally to prevent water levels in dryer areas from dropping below target levels, and to ensure water quality standards are maintained. The locations, timing and quantity of the points where outside water enters QvU were not available and cause an underestimation of modelled discharge at the QvU outlet. The peak discharge during November 2002 is not captured by the model. There are two possible explanations. Firstly, it could be that there has been a local extreme precipitation event, which was missed by the meteorological station, which is located just outside the study area. Secondly, it could be that due to the inlet of water in the polder during the summer soils are saturated earlier than simulated resulting in a higher peak discharge.

Fig. 6 illustrates the effects of the river module on seepage (blue) and percolation (red). The top figure shows the total seepage aggregated over the winter months in the wet year 1995 (December, January and February). The bottom figure shows the total seepage for the summer (June, July and August). The patterns are highly variable in space and time, and the influence of the river water levels is evident from the high variation, close to the river bed. In a wet year (1995), seepage for a large number model grid cells close to the Meuse and Rhine exceeds 100 mm. The average winter precipitation from 1995 to 2004 in QvU is 207 mm, so these are considerable amounts and will have significant effects on the hydrology in the polder. The situation in the summer of 2003 is completely different, and low water levels in the river Rhine result in percolation to the groundwater that amounts to over 100 mm close to the river dike. Along the river Meuse, the situation is different, and seepage is still observed. The main reason is that just downstream there is a large weir in the river Meuse, and, therefore, river levels in dry periods are kept constant and artificially high, and thus have less effect on seepage and percolation dynamics in QvU.

Fig. 7 shows average monthly model outputs for the entire QvU based on a 10-year simulation for the reference situation (1995–2004) and the *W*+ scenario (around 2050). The figure reveals that there will be significant changes in the temporal precipitation distribution. The

Table 1
Monthly change (%) in number of wet days (f_{wet}), the average precipitation on a wet day (m_{wet}), and 99% percentile(Q_{99}) for 2050.

	f_{wet}	m_{wet}	Q_{99}
January	3	13	11
February	1	12	11
March	−2	10	11
April	−9	6	12
May	−15	3	12
June	−19	1	12
July	−20	0	12
August	−19	1	12
September	−15	3	12
October	−8	7	12
November	−1	10	11
December	1	12	11

Table 2
Seasonal change (%) in potential evapotranspiration for 2050.

DJF	3.0
MAM	7.2
JJA	15.2
SON	10.4

DJF = December, January, February; MAM = March, April, May; JJA = June, July, August; SON = September, October, November.

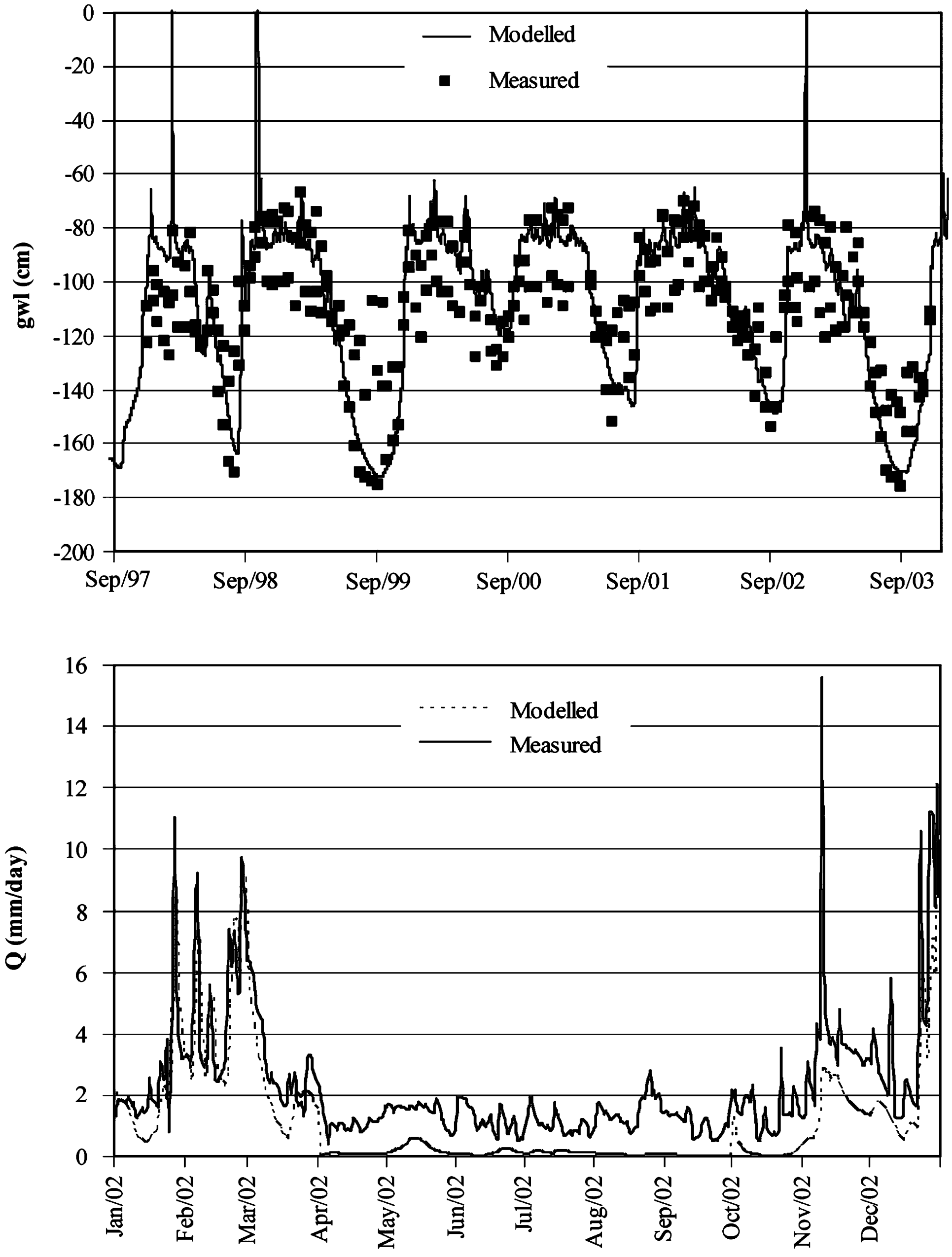

Fig. 5. Measured and modelled groundwater levels (gwl, top figure), and measured and modelled discharge at QvU outlet (Q, bottom figure).

total annual precipitation is projected to decrease minimally from 791 to 777 mm, however, the winter months will be wetter (15%), and the summer months will be drier (19%). The potential evapotranspiration shows a significant increase in the summer months (15%), yielding a higher water demand and higher potential crop yields. Although water demand is higher in summer, it cannot be met, because soil moisture is limiting actual water uptake by crops. Therefore, the temporal actual evapotranspiration pattern does not exhibit a large difference between the reference situation and the *W+* scenario. The seepage plots shows an increase in seepage from January to March relative to the reference situation (30%), while in the other months seepage remains relatively similar. This is the effect of the increased water levels in the rivers Meuse and Rhine in these months. The increase in drainage from January to April is the combined result from the increase in precipitation and seepage, the decrease in the remaining months is the results of soil moisture depletion. The soil moisture storage changes are the net result of all hydrological processes. It is interesting to note that the temporal variation has increased significantly under the

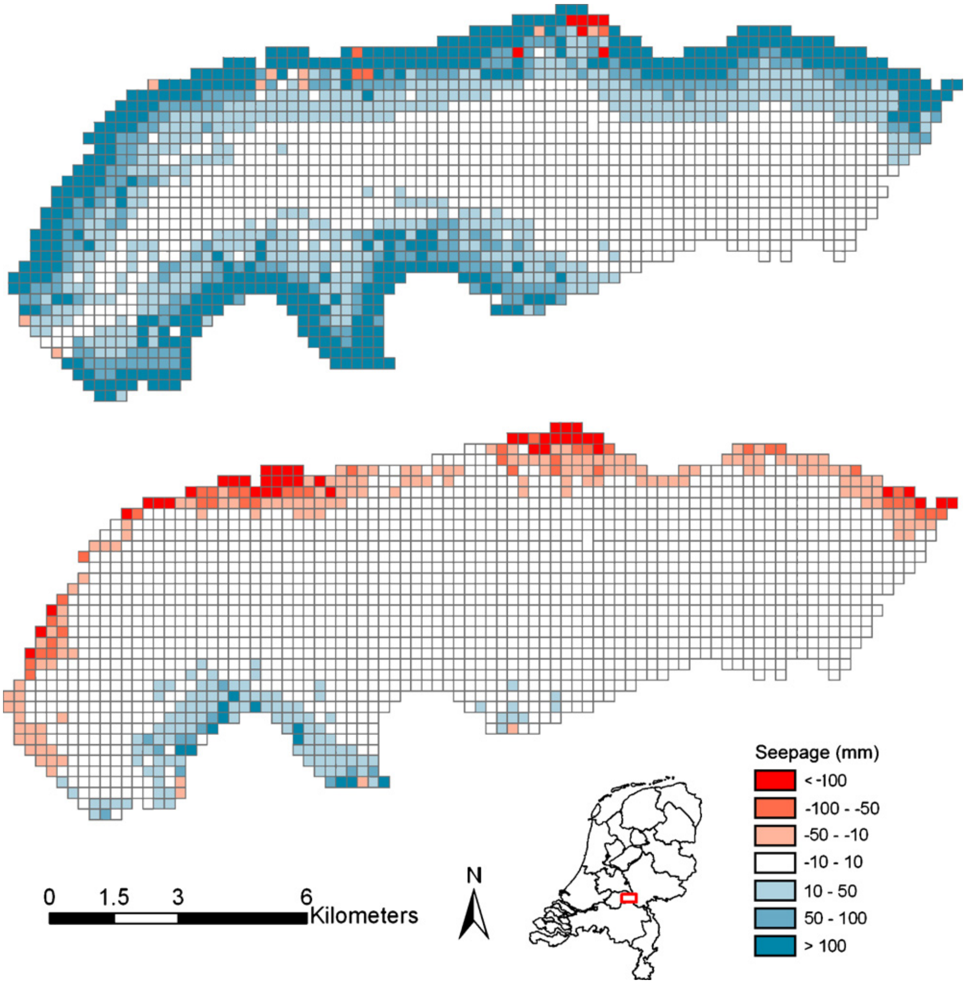

Fig. 6. Spatial patterns in seepage and percolation for winter 1995 (top figure) and summer 2003 (bottom figure).

W+ scenario. There is increased depletion in spring and increased replenishment at the end of the autumn. Aggregated over the entire polder, the soil has a strong buffering capacity and the increases in precipitation in winter and autumn are stored in the soil and are depleted by evapotranspiration in spring and summer, when precipitation is lower than the reference situation.

The spatial component of FutureViewR also reveals interesting changes in the spatial distribution of water balance constituents. Fig. 8 shows the average 10-year actual evapotranspiration for the reference situation and the difference with the *W*+ scenario. There is a large variation in ET_{act} in the polder. The ET_{act} in urban areas is the lowest, as there is no plant transpiration and soil evaporation is limited since most precipitation is directly lost through runoff. The central part of the polder also reveals a significantly lower ET_{act} relative to the non-urban belts along the rivers. This is explained by the soil type. In the central part, heavy clay soils are abundant, and the heavy clays retain the water so strongly that it is not available to the plants for transpiration. For the *W*+ simulation, these general patterns are preserved, however the spatial variation has further increased both in the central part of the polder as in the river belts. In the central part a slightly decreasing trend can be observed, while an increase in ET_{act} along the rivers is found.

Fig. 9 further illustrates the spatial diversity. The relative yields are proportional to ET_{act}/ET_{pot} and we concluded earlier that ET_{pot}, likewise the potential yield, is increasing due to climate change. The decrease in ET_{act} in the central part and increase in the belts along the river amplifies the variation in relative yields in QvU. Actual yields are directly proportional to ET_{act} and efforts to sustain agricultural yields should focus on maintaining water in the soil profile by, for example, maintaining higher water levels in the surface water system.

Fig. 10 presents the outputs of the surface water module at the outlet of the QvU polder. The discharges are presented at three different time scales; annual averages from 1995 to 2004 (left), 10-year monthly averages (middle), and daily discharges for the year 1998. The *W*+ data are related to the transformed time series for 1995–2004, and represent a 10-year period around 2050. There is a large variation between different

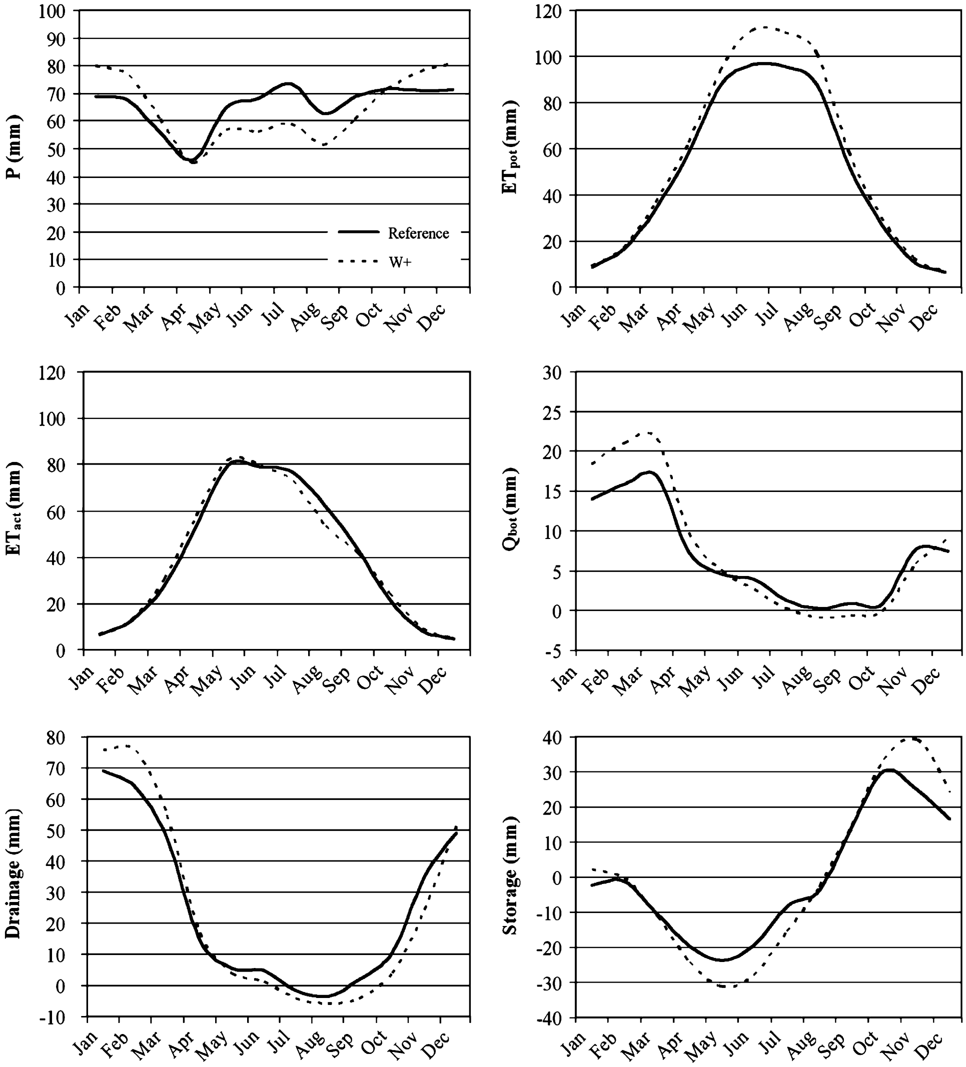

Fig. 7. Results of FutureViewR model simulations for reference situation and *W+* scenario for entire QvU. Results are monthly averages for the 1995–2004 period (reference) and transformed 1995–2004 time series (*W+*). P = precipitation; ET_{pot} = potential evapotranspiration; ET_{act} = actual evapotranspiration; Q_{bot} = seepage (+) or percolation (−); drainage (+) or infiltration (−); storage = change in soil water storage.

years and the average daily discharge ranges from 0.3 to 1.4 mm day^{-1} and 0.2 to 0.7 mm day^{-1} for the reference and *W+* scenario, respectively. It is interesting to note that the *W+* discharge is significantly lower than the reference situation.

The dry summers deplete the soil water, which is partly compensated for during winter, but eventually results in lower discharge at the polder's outlet. The intra-annual variation is also large, with the highest peaks in the winter months, when evaporative demands are low, and the lowest peaks in summer. The daily data for 1998 show that even for the annual extremes, the *W+* simulation results in lower peaks. This is remarkable, as it is anticipated that under climate change extremes will be more extreme, and an increased soil storage capacity will not dampen truly extreme events. A possible explanation could be the fact that these data represent discharges at the polders outlet, which is an accumulation of all RWs. Locally the *W+* scenario may yield more extreme discharges. Another possible explanation could be the relatively short length of the precipitation data set (~10 years). It could well be that the time series does not include an event that is extreme enough to generate an extreme discharge that is higher than the reference situation.

5. Discussion and conclusions

In this study a new tool, FutureViewR, has been developed and applied in a polder area in The Netherlands. The FutureViewR model suite provides a unique toolkit to model the complex interaction between meteorology,

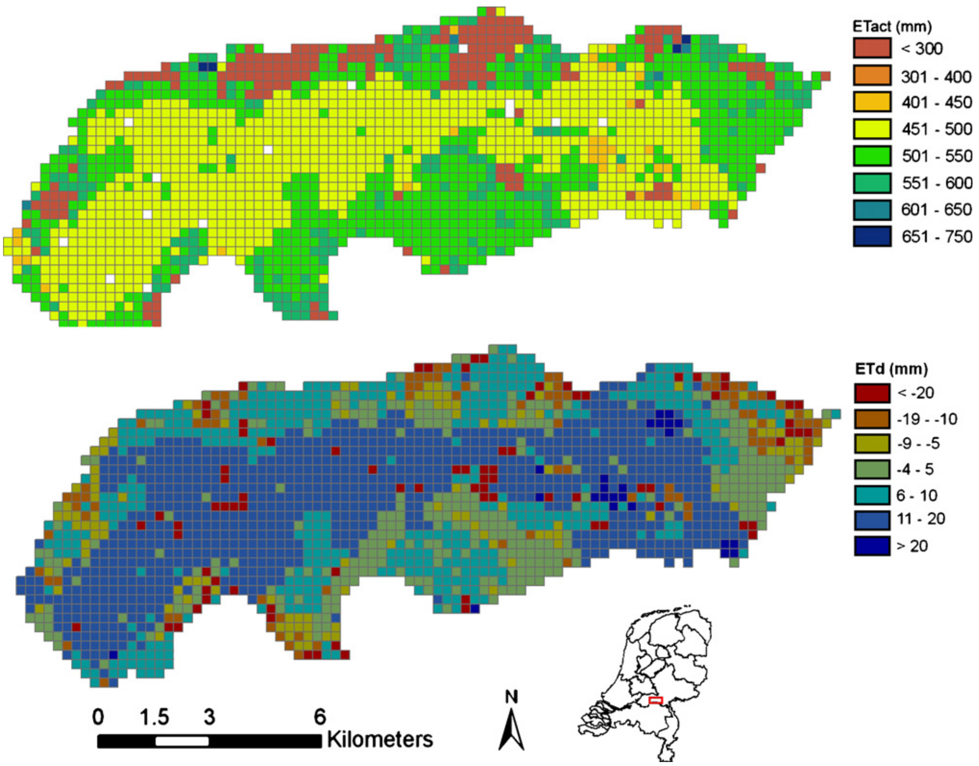

Fig. 8. Spatial patterns in 10-year average annual actual evapotranspiration for reference situation (ET_a, top figure) and difference between reference and the *W+* scenario (ET_d, bottom figure).

spatial hydrology and the surface water and the following core functionalities can be distinguished:

- FutureViewR combines high physical detail with high spatial detail. This is enabled by using the SWAP model in a grid-based mode. The use of MS SQLServer facilitates the management of the large amounts of data, which would otherwise be impossible to handle.
- Normally focus in these kinds of studies is on the surface water system, and simple rainfall–runoff modules provide input for the surface water models. FutureViewR enables linking the complex interaction between atmosphere, vegetation, soil and drainage to the surface water system. Possible adaptation strategies such as land use change and water management can directly be modelled and its effect on the polder discharge can be quantified.
- The river module is a useful extension and has provided insight in the interaction between the water levels in the entangling rivers and the polder hydrology.
- All data are based on public domain datasets and the entire system is flexible and generic and can be easily applied in other areas.

Regarding the demonstration of the application of FutureViewR and the analysis of climate change, the following conclusions can be drawn:

- In the *W+* scenario, the summers get dryer and the winters get wetter, as a result the soil water is depleted in summer, which provides a buffer capacity for the increased winter precipitation. Therefore, although the extremes in precipitation in winter increase, there is no evidence that this will also yield an increase in discharge out of the polder mainly, because the initial situation is dryer than in the reference situation.
- The longer and more prolonged droughts in the summer will have adverse effects on agricultural production, and there will be a larger demand for external water. In case of low water levels in the Rhine and the Meuse, it could well be that this demand cannot be met and agricultural yields will decline.
- Polders like QvU are particularly vulnerable to climate change, because of the river influence on the polder hydrology. This is particularly true during prolonged dry periods. In that case, it is anticipated that water levels in the rivers drop faster than the groundwater levels, and, therefore, the pressure difference between river and polder will decrease resulting in less seepage. In combination with less precipitation and an increased potential evapotranspiration, a decline of agricultural yields can be expected.

This study was intended to showcase the potential of FutureViewR to analyse the influence of climate change on polder systems in river deltas. Future analysis will focus on the inclusion of a more comprehensive set of climate

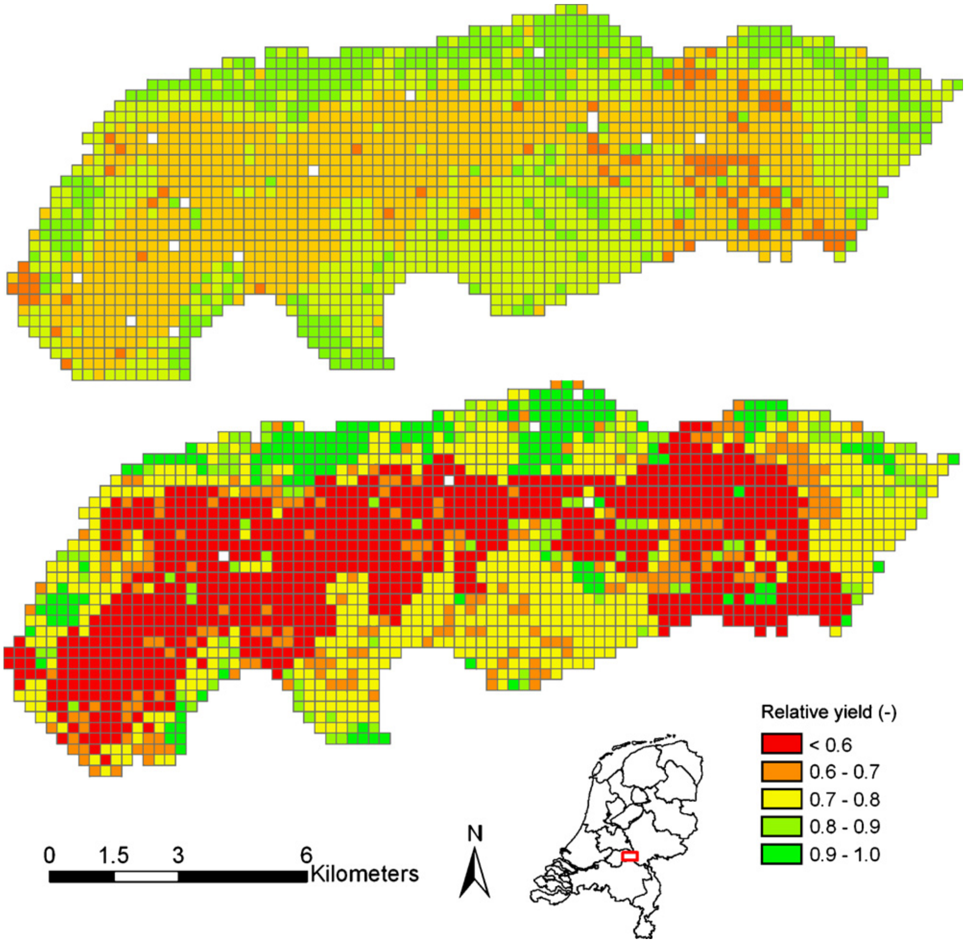

Fig. 9. Spatial patterns in 10-year average annual relative yields for reference situation (top figure) and *W+* scenario (bottom figure).

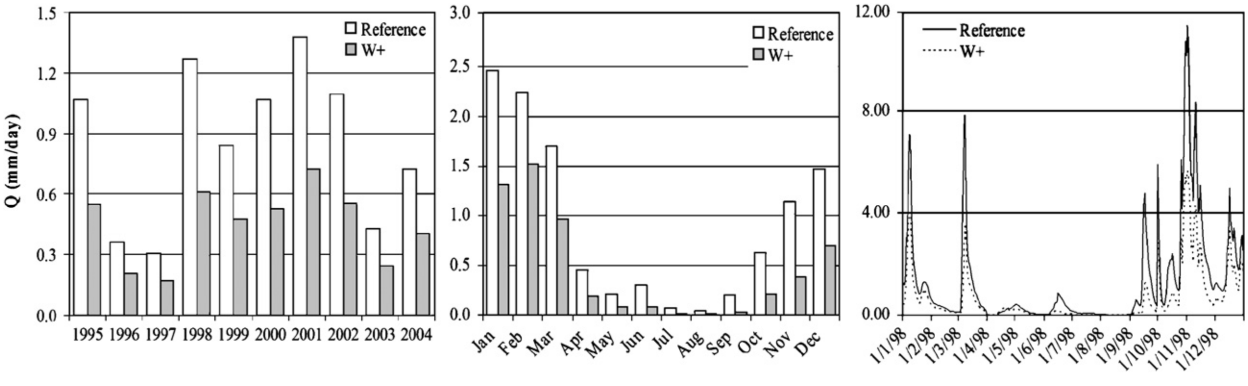

Fig. 10. Annual average discharge from 1995 to 2004 (left figure), 10-year monthly average discharges (middle figure), daily discharges in 1998 (right figure) at an outlet of QvU for reference situation and *W+* scenario.

change scenarios, the evaluation of different adaptation strategies, and the extension to other areas. As far as model developments are concerned, the user interface will be further improved and an automated sensitivity analysis package will be developed.

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