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Influence of feedbacks from simulated crop growth on integrated regional hydrologic simulations under climate scenarios

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Abstract

Climate change impact modelling of hydrologic responses is hampered by climate-dependent model parameterizations. Reducing this dependency was one of the goals of extending the regional hydrologic modelling system SIMGRO with a two-way coupling to the crop growth simulation model WOFOST. The coupling includes feedbacks to the hydrologic model in terms of the root zone depth, soil cover, leaf area index, interception storage capacity, crop height and crop factor. For investigating whether such feedbacks lead to significantly different simulation results, two versions of the model coupling were set up for a test region: one with exogenous vegetation parameters, the "static" model, and one with endogenous simulation of the crop growth, the "dynamic" model WOFOST. The used parameterization methods of the static/dynamic vegetation models ensure that for the current climate the simulated long-term average of the actual evapotranspiration is the same for both models. Simulations were made for two climate scenarios. Owing to the higher temperatures in combination with a higher CO_2-concentration of the atmosphere, a forward time shift of the crop development is simulated in the dynamic model; the used arable land crop, potatoes, also shows a shortening of the growing season. For this crop, a significant reduction of the potential transpiration is simulated compared to the static model, in the example by 15 % in a warm, dry year. In consequence, the simulated crop water stress (the unit minus the relative transpiration) is lower when the dynamic model is used; also the simulated increase of crop water stress due to climate change is lower; in the example, the simulated increase is 15 percentage points less (of 55) than when a static model is used. The static/dynamic models also simulate different absolute values of the transpiration. The difference is most pronounced for potatoes at locations with ample moisture supply; this supply can either come from storage release of a good soil or from capillary rise. With good supply of moisture, the dynamic model simulates up to 10 % less actual evapotranspiration than the static one in the example. This can lead to cases where the dynamic model predicts a slight increase of the recharge in a climate

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scenario, where the static model predicts a decrease. The use of a dynamic model also affects the simulated demand for surface water from external sources; especially the timing is affected. The proposed modelling approach uses postulated relationships that require validation with controlled field trials. In the Netherlands there is a lack of experimental facilities for performing such validations.

1 Introduction

In hydrologic models, vegetation characteristics are usually defined by "exogenous" parameters that are based on averages of historic data; a fixed dependency on the days of a year is assumed. It means that feedbacks from the vegetation to the hydrologic system are then neglected. The resulting limitations of this approach have become more poignant with the advent of climate change impact modelling using scenarios. These scenarios usually differ widely from the current climate. That increases the necessity for *endogenously* simulating the weather- and climate-dependent feedback from the vegetation to the hydrologic system. Here the focus is on models that involve the simulation of crop growth.

Diverse models exist that simulate the interactions between a soil column and agricultural crop development. Examples are the SWAP model (Van Dam et al., 2008) coupled to the WOFOST model (Van Ittersum et al., 2003; Supit et al., 1994), and the Theseus model (Wegehenkel, 2009) that has been coupled to WOFOST too. However, in both model combinations, not all of the feedbacks from the vegetation have been included, and neither has the feedback loop via the regional groundwater system.

SWAT (Arnold and Fohrer, 2005; Neitsch et al., 2011) is an example of a regional hydrologic model that includes a dynamic simulation of crop growth and also the feedback to the vegetation-related parameters. However, the used soil water submodel is of a very simple two-layer type which cannot simulate capillary rise. That severely limits its applicability for simulations that require a feedback loop via groundwater. Another example of a regional integrated model is provided by PROMET (Mauser and Bach, 2009). Also this approach suffers from lack of sophistication in the soil water modelling, involving the repeated use of an analytical model for four sublayers. Compared to SWAT, the improvement is that capillary rise can be modelled. But the coupling to the groundwater model is of the simple "recharge module" type. This neglects the influence of the soil water state on the storage coefficient of the groundwater, leading to diminished dynamics of the simulated phreatic level.

The regional hydrologic modelling system SIMGRO (Van Walsum and Veldhuizen, 2011; Van Walsum et al., 2011), includes a soil water "meta"-model, MetaSWAP (Van Walsum and Groenendijk, 2008). MetaSWAP is based on a quasi-steady state schematization of the flow processes in combination with water balances for control volumes at aggregate scale. It is suitable for regions with modest slopes, for both shallow and deep groundwater levels. It has been calibrated and successfully validated using results of the Richards-type SWAP model. A robust two-way coupling to the groundwater model MODFLOW (McDonald and Harbaugh, 1988) has been implemented within the SIMGRO framework, involving a dynamically updated storage coefficient. Recently, the crop growth simulation model WOFOST has been coupled to MetaSWAP, including the option for two-way feedback.

In the paper, an outline is first given of SIMGRO components that are relevant for the results reported here. Special attention is given to the coupling between MetaSWAP and WOFOST. Next, a brief description is given of the used test region, the area around the *Kromme Rijn*, which is a fork of the Rhine. Then follow the simulated effects of climate scenarios on the soil water and groundwater regime. Results are compared to those obtained with exogenous vegetation parameters. The latter will be referred as results for the "static" vegetation model, in contrast to those for the "dynamic" vegetation model.

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2 Methods and materials

2.1 Model

An overview of the used modelling framework is given in Fig. 1, involving four main components:

- MODFLOW (McDonald and Harbaugh, 1988) for the flows in the saturated zone;
- MetaSWAP (Van Walsum and Groenendijk, 2008) for the water flows in a SVAT column (*S*oil *V*egetation *A*tmosphere *T*ransfer);
- WOFOST (Supit et al., 1994) for the crop growth;
- a surface water model.

The linking of submodels is done with SIMGRO (Van Walsum and Veldhuizen, 2011). Its communication with WOFOST takes place for each day of the simulation. SIMGRO supplies WOFOST with the following data:

- altitude, minimum day temperature, maximum day temperature, average day temperature, short wave radiation;
- potential transpiration, actual transpiration and interception evaporation;
- maximum rooting depth of the soil (if applicable).

WOFOST returns the following data: root zone depth, soil cover, leaf area index, interception storage capacity, crop height and crop factor. In the following, a short description is given of model features that directly involve a vegetation component.

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2.1.1 Calculation method for evapotranspiration terms

For modelling the interception cycle, this study uses a simplified version of the approach presented by Valente et al. (1997) for tree vegetation, which in turn is an adaptation of Rutter et al. (1971). The latter is for a 100 % vegetation cover, whereas the Valente-method can be used for situations with a less than complete soil cover that can also vary in time. The approach involves making a closed water balance for water stored in the canopy storage elements. This distinguishes the method from e.g. Von Hoyningen-Hüne (1983) and Gash et al. (1995), who assume that after a precipitation event all of the intercepted water gets evaporated *during the same day*, whatever the atmospheric conditions. Such an approach is only applicable for isolated storms with precipitation of the "convective" type, and not for locations where much of the precipitation is of the "advective" type, like in the Netherlands (Savenije, 2004).

In the Valente-method, the actual evaporation rate is set equal to the canopy saturation fraction multiplied by the potential rate. But this means that the canopy can never completely dry out, which is conceptually questionable. An alternative method is to simply assume that the evaporation rate is equal to the potential value as long as there is water in the canopy reservoir, and then abruptly drops to zero. The resulting differential equation for the storage dynamics is "discrete". But it can readily be solved analytically, thus avoiding a dependency of the simulated evaporation total on the used time step of the numerical scheme. Details are given in Van Walsum et al. (2011).

During the time fraction that interception evaporation is active, all the other evaporative processes are assumed to be inactive. In the case of a sparse vegetation (with a soil cover less than the unit), strong lateral energy exchange is assumed between the non-vegetated and vegetated part to sustain the interception evaporation. For taking this effect into account, the following ratio is used:

$$W_{\mathrm{frac}} = \frac{E_{\mathrm{ic}}^{\mathrm{ave}}}{\mathrm{ET}_{\mathrm{w0}}^{\mathrm{ave}}}, \quad (1)$$

where W_{frac} is the time fraction that interception evaporation is active (–), E_{ic}^{ave} is the actual interception evaporation, per unit of the whole SVAT area, time averaged ($m\,d^{-1}$), and ET_{w0}^{ave} is the evapotranspiration rate from a wet canopy, time averaged ($m^3\,m^{-2}\,d^{-1}$). The difference in the used notations for the units of E_{ic}^{ave} and ET_{w0}^{ave} is to convey that the former is computed as the product of the soil cover and the interception evaporation per unit of (covered) soil area. This distinction between length units is also used in the subsequent notations.

The computational method for the potential soil evaporation includes a reduction factor for the shielding of the radiation by the canopy. It is assumed that the nett radiation inside the canopy decreases according to an exponential function involving the Leaf Area Index (LAI) and that the soil heat flux can be neglected (Goudriaan, 1977; Belmans et al., 1983). In combination with the interception reduction, this gives:

$$E_p = E_{p0}e^{-\kappa_{gr}\mathrm{LAI}}(1-W_{frac}), \tag{2}$$

where E_p is the potential soil evaporation receiving reduced radiation ($m\,d^{-1}$), E_{p0} is the potential evaporation of a wet, bare soil receiving full radiation ($m^3\,m^{-2}\,d^{-1}$), LAI is the Leaf Area Index ($m^2\,m^{-2}$), and κ_{gr} is the extinction coefficient for solar radiation (–); Ritchie (1972) and Feddes et al. (1978) used $\kappa_{gr} = 0.39$ for common crops. The reduction from potential to actual soil evaporation is calculated with the method of Boesten and Stroosnijder (1986).

The radiation energy that reaches the soil surface is assumed to be not available for transpiration, even though the soil evaporation can be sub-potential. This is to avoid over-estimation of the transpiration, as experiences with the SWAP-model have shown (Van Dam et al., 2008). The computation of the potential transpiration is therefore done with:

$$T_p = ET_{p0}(1-W_{frac}) - E_p, \quad T_p = \max(T_p, 0.) \tag{3}$$

where T_p is the potential transpiration ($m\,d^{-1}$), ET_{p0} is the potential evapotranspiration of a dry canopy receiving full radiation ($m^3\,m^{-2}\,d^{-1}$). The potential value is distributed

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over the root zone depth in a uniform manner. The reduction from potential to actual value of the root uptake is based on the reduction function given by Feddes et al. (1978).

The method used here for simulating the potential evapotranspiration terms (interception evaporation from a wet canopy, evaporation from a wet bare soil, transpiration) uses the Makkink reference crop evapotranspiration and not the Penman-Monteith one, for reasons given by De Bruin (1987). The potential values of evapotranspiration terms are calculated by applying a factor, which is commonly known as the "crop factor" method.

2.1.2 Calculation method for crop water stress in WOFOST

Crop water stress causes the leaf pores to close partly or completely, to minimize further loss of moisture. This also increases the pore resistance for entrance of CO_2, thus reducing CO_2 assimilation. For modelling this reduction, WOFOST requires the "relative transpiration" as an input variable, which is equal to the unit in situations when the actual transpiration equals the potential one. Here this definition has been refined, to take into account that the used evapotranspiration model includes the interception evaporation. For situations with a wet canopy, the assumption has been made that there is no need for the pores to close, even if the soil is dry: the wetness of the canopy causes a (nearly) saturated vapour pressure in the direct vicinity of the leaves, thus impeding the vapour flux through the pores. For this reason, the relative transpiration is computed in the following modified manner:

$$T_{\mathrm{rel}} = (T_{\mathrm{a}} + E_{\mathrm{ic}})/(T_{\mathrm{p}} + E_{\mathrm{ic}}), \tag{4}$$

where T_{a} is the actual transpiration (m d^{-1}), E_{ic} is the interception evaporation (m d^{-1}), and T_{p} is the potential transpiration (m d^{-1}). Obviously, the lower T_{rel}, the higher the crop water stress. So the latter is taken as $(1-T_{\mathrm{rel}})$ for comparing results of different modelling approaches.

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2.1.3 Vegetation-related parameters

The described parameterization of the vegetation is here limited to agricultural land use types. For grassland, the WOFOST parameters have been taken from Kroes and Supit (2011), using the "hay" management option. All arable land crops have here been modelled with "potatoes"; the WOFOST parameters have been obtained from Wolf et al. (2010). In the standard version of WOFOST (Supit et al., 1984), the time from sowing to germination is only dependent on temperature. There is, however, also a dependency on the soil moisture conditions. Germination is retarded when the conditions are either too dry or too wet, which is here described with the method of Van Wijk et al. (1988). The climate dependency of the sowing date itself has not been taken into account; the day 111 has been used in all model runs.

The evapotranspiration model involves the following vegetation-related parameters:

- interception storage capacity of the vegetation canopy;
- soil cover;
- "crop factors" of interception evaporation, transpiration, bare soil evaporation;
- transpiration reduction function for suboptimal conditions in the soil.

The first three of the listed parameters are dependent on the time of year, and possibly also the last one. In the "static" crop model, the time-dependent parameters are specified by tables of values for the days of the year. If WOFOST is used, the parameters are endogenously determined by the simulated crop development.

It is a general problem of evapotranspiration models that the number of parameters is usually not matched by sufficient information to determine them from. This "over"-parameterization problem can be partly solved by making use of information obtained from the crop growth model. For this the Leaf Area Index (LAI) is very suitable; it has been used in the following ways:

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- the interception storage capacity of a vegetation canopy $S_{c,cap}$ has been made linearly dependent on LAI, $S_{c,cap} = s_{c,cap} \cdot \mathrm{LAI}$, where $s_{c,ap}$ is the capacity per unit of LAI (mm LAI^{-1});
- the soil cover C_s has been set equal to the complement of the exponential function representing the bare-soil area fraction in Eq. (2): $C_s = [1 - \exp(\kappa_{gr} \cdot \mathrm{LAI})]$
- the crop factor Kc_{MAK} of transpiration has been made a piece-wise linear function of LAI.

The information on crop factors for transpiration was obtained from Feddes (1987). For potatoes the factor reaches a maximum value of 1.2 (Makkink reference crop evapotranspiration). For the feedback from WOFOST to the crop factor, a piece-wise linear function of the LAI was postulated (Fig. 2). The unknowns of the relationship are the breakpoints between the segments and the slopes of the segments. To determine these unknowns, first a 30-yr run was made with a stand-alone MetaSWAP-model coupled to WOFOST, but *without* the feedback from WOFOST enabled. The simulated LAI-values were then used as input data of a calibration tool that makes use of Linear Programming. The tool determines the unknown break points and slopes in such a manner that the 30-yr averages of the crop factors correspond as closely as possible (Fig. 3) to the 10-day values given by Feddes (1987).

For the crop factor of interception evaporation of arable land crops (potatoes) the value 1.25 of open water is used (Makkink reference crop evapotranspiration). For the interception capacity of arable land crops, Von Hoyningen-Hüne (1983) give $s_{c,cap}$ a value of 0.25 mm LAI^{-1}, for simulations using day-averaged precipitation. This value was used in the WOFOST model for providing information about the interception capacity for each day of the simulation. With the above crop parameterization, a 30-yr run was made using day-averaged precipitation, yielding the following averages: bare soil evaporation of 157 mm a^{-1} (36 %), a transpiration of 209 mm a^{-1} (47 %), and interception evaporation of 73 mm a^{-1} (17 %), totalling 438 mm a^{-1}.

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The 30-yr run was also used for deriving time-dependent parameters of the static crop model. The parameters were derived by computing averages for the days of a year, for the leaf area index, the interception storage capacity, the soil cover, and the rooting depth. These values were used for making runs without the dynamically simulated feedback from the vegetation, as a baseline for comparing model results.

Interception evaporation of grassland was reported to be about 15 % of rainfall for sites in upland areas of Great Britain (Calder, 1990), as compared to 30 % for forests. Such figures should be treated with great care when using them for other locations. Roughly the same figure for forests is reported for the Netherlands (Dolman et al., 2000), providing some degree of confidence that the grassland figure can be used for this study. Applied to the annual mean rainfall of 800 mm that yields an estimate of 120 mm a^{-1} for the interception evaporation of grassland, which is about 25 % of the total evapotranspiration.

The long-term average of the interception evaporation is not enough information to uniquely determine the storage capacity of the canopy in combination with the (unknown) "crop factor". The latter was therefore simply estimated at 1.15, a value that is in between the "mean" crop factor 1.0 of grassland itself (Feddes, 1987), and 1.25 of open water (De Bruin, 1987). For the crop factor of the grassland transpiration, Feddes (1987) indicates that outside the summer season the factor is 0.9 instead of 1.0. Going on this scarce information, a function was constructed as given in Fig. 2 for grassland.

With this relationship, a number of 30 yr runs were made with the MetaSWAP-WOFOST combination, for various values of the interception capacity $s_{c,cap}$ per unit of LAI. For day-averaged precipitation data a value of 0.065 mm LAI^{-1} was found. This value is lower than that for potatoes (0.25 mm LAI^{-1}), due to the more vertical orientation of the grass leaves, thus reducing the retention capacity per unit of leaf area. Like was done for potatoes, the results of the 30-yr run were used for computing averages of the vegetation parameters on the days of a year, to be used in the static crop model for grassland.

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2.1.4 Influence of climate scenarios on vegetation-related processes

The effect of a rising CO_2-concentration of the atmosphere on transpiration has been reviewed and estimated by Kruijt et al. (2008), giving a practical approach for the Netherlands. For 2050 they assume a concentration of 520 ppm. The nett effect on the crop factors is for grassland a reduction of 2.5 %, and for arable land C3-crops 5 %. The effect of rising CO_2-concentration on crop production is included in WOFOST via parameter changes of "EFF" (initial angle of light response curve) by +5 % and of "AMAX" (maximum CO_2-assimilation) by 25 % (changes for C3-crops; Wolf, et al., 2010).

Temperature sensitive processes are:

- evapotranspiration of reference crop, as part of a climate scenario (Sect. 2.3);
- root water uptake;
- germination;
- growth rate of leaves, roots, and storage organs.

With the exception of the root water uptake, the temperature sensitivity of these processes has been modelled in the current study. The influence of temperature on the growth rates is mainly simulated via the temperature sum, which is a summation of daily temperatures above a certain threshold value. It plays a determining role in the germination process, but also in determining the "phenological" crop stage; this stage goes from the initial "vegetative" phase – with development of roots, stems and leaves – to the "generative" phase in which the storage organs (e.g. potatoes) are formed. Processes like CO_2-assimulation are influenced by the development stage. Apart from this indirect effect via a temperature accumulation variable, there is also the simulated direct effect of a suboptimal day temperature.

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2.2 Study region

The *Kromme Rijn* is a fork of one of the main Rhine branches, the *Lek* (Fig. 4). The region surrounding it (33 610 ha) is part of the waterboard *De Stichtse Rijnlanden* (www.hdsr.nl). Along the northeastern side, the region is bordered by what is left over of an end-moraine, the *Utrechtse Heuvelrug*, rising to an elevation of 65 m above sea level. The southeastern border of the region is formed by the Amsterdam-Rhine Canal, with a water level of 0.40 m below sea level, which is several meters below the soil surface, thus causing a substantial regional drainage. This drainage is mainly balanced by infiltration from the *Lek* and the *Kromme Rijn*. There is also some seepage coming from the *Utrechtse Heuvelrug*, but that is much reduced in comparison to the past. The reduction is caused by heavy groundwater pumping for drinking water supply. An overview of the land use in the region is given in Table 1.

SIMGRO has been implemented using MetaSWAP, WOFOST and MODFLOW for the waterboard as a whole (and beyond). The models have a grid of 100 × 100 m. There can be several SVAT columns coupled to a single grid cell, for representing the areal fractions of vegetated soil, surface water, and impermeable surface ("tiles"). The groundwater model has a schematization of 8 aquifers.

Calibration of the model on time series of phreatic levels is not yet possible, due to the scarcity of usable data. Most of the available phreatic measuring points are on the boundaries of fields and/or near to water courses, thus making them non-representative. The comparison between measured and simulated values for one of the points is given in Fig. 5. This comparison is of course no more than a cursory "plausibility check". However, for the purposes of the current study it is seen as sufficient: the focus is here on the influence of the feedbacks from the vegetation simulation. In such a conceptual exploration, it is the sensitivity of the model results that is of interest, and not so much the absolute predictions for the investigated scenarios and variants.

The available data deck of the model covers the 17-yr period 1989–2005. Dynamic simulation of vegetation can be expected to differ most from the static simulation in

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relatively warm and dry years. An example of such a year is 2003; for this year the maximum and minimum groundwater level transects are shown in Fig. 6, for the cross-section AB that is indicated in Fig. 4. The nett saturated flux (as simulated with the "BCF"-package of MODFLOW) is shown in Fig. 7, as a time-average for the year 2003. Locations with positive values correspond to locations with active drainage media.

2.3 Scenarios and investigated variants

Climate scenarios for the Netherlands (Table 2) have been taken from Van den Hurk et al. (2006). The per cent changes given in Table 2 relate to climatic means, involving a 30-yr period. For individual years in such a series, the changes can vary.

The four scenarios form a 2 × 2 matrix, with respectively two possible developments for the global temperature increase and two possible developments for the atmospheric circulation. This study uses the scenarios with the +2 °C increase in 2050, because they have the biggest impact on the vegetation development and on any feedbacks affecting the hydrologic system.

As can be seen from Table 2, substantial changes of the potential evapotranspiration are expected in the scenarios. These changes are based on the temperature change and the wind change. Little is known about the possible changes of the radiation due to changes of cloud cover patterns in the climate scenarios; for this reason the radiation has been assumed unchanged.

In the current land-use situation, the agricultural land use includes both grassland and arable land. Grassland and arable land can be expected to have a different sensitivity to climate change. Therefore, separate runs have been made for two land-use scenarios, one with all of the agricultural land as grassland and the other with all of it as arable land. The investigated variants of climate and land use scenarios without/with endogenously simulated crop growth are listed in Table 3.

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3 Results

3.1 Introduction

The parameterization of vegetation-related parameters has been conceived in such a manner that the long-term averages of evapotranspiration terms for static/dynamic vegetation simulations are the same. For this procedure a 30-yr period was used (Sect. 2.1.3). As a verification of this parameterization, the simulated mean evapotranspiration terms of static and dynamic models were compared for the 17-yr simulation period used here (Table 4). For both grassland and arable land the mean total evapotranspiration of static and dynamic models are within 0.5 % of each other; separate terms are within 2 % of each other, which is not considered to be a significant difference.

The conceptual differences between the static and dynamic crop models can be expected to have larger impacts on the simulation results in the more extreme meteorological years of a series. For analysing the effects under warm and dry conditions, the simulation year of 2003 has been used; in the climate scenarios for "2050", the year 2003 has its pendant in 2063.

3.2 Grassland

The role of the crop growth model for grassland is illustrated by the LAI simulations given in Fig. 8. The drops in the simulated LAI's of the dynamic model are due to hay making. As can be seen from the plot for the static model, the LAI never reaches the peak values of the dynamic simulation. That is because the "static" LAI development has been derived as a long term average for a certain day of the year. In these simulations the peaks in the different years do not coincide, which gives a more smoothed time dependence than that of the dynamic model. (The graph has also been further smoothed for presentation purposes.)

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For grassland in 2003/2063 in the W^+ climate scenario, Fig. 8 shows that the LAI development in the dynamic vegetation model starts earlier than the averaged LAI development of the static vegetation model. This has an increasing effect on the simulated transpiration of the dynamic model. In the second half of the summer, the dynamic simulation shows a faltering LAI development due to drought, which has a decreasing effect on the transpiration during that period. In the balance, the *change* of the year-total of grassland evapotranspiration with respect to the current *climate* (Table 5, column ΔR^{Cl}) predicted by the dynamic vegetation simulation does not significantly differ from the static one.

3.3 Arable land

Like with grassland, the dynamic simulation of potatoes shows a quicker start than the static one, especially in the W^+ climate scenario for 2003/2063 (Fig. 9). The quicker start is due to the shorter germination time of the dynamic model, compared to the long-term average for the current climate that the static model uses. But the strongest effects of using a dynamic vegetation model concern the growth cycle itself. In the first place, the cycle is influenced by the shorter time span needed by the dynamic model for reaching the peak of the leaf area index. The peak is also higher in the climate scenarios, mainly due to the increased CO_2-concentration of the atmosphere. The peak marks the end of the so-called vegetative phase. Then follows the generative phase, in which the tubers are formed. The dynamic simulation of this last phase is apparently even more sensitive to the relative warmth of the climate scenario, as can be seen from the quickened reduction of the LAI due to senescence of the leaves.

The quicker start of the LAI development leads to higher values of the potential transpiration in the vegetative phase. Contrasting this, in the generative phase the LAI of the dynamic simulation very soon drops below that of the static model, which is accompanied by a lowering of the potential transpiration to below that of the static

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model. This happens to such a degree in the W^+ scenario, that the year total potential transpiration of the dynamic model is 15 % less than that of the static model (Table 5).

In terms of the relative transpiration T_{rel}, the dynamic model simulates for the year 2003 in the current climate a slightly higher value than the static model, and thus a lower crop water stress $(1-T_{rel})$. That is because the lower potential transpiration of the dynamic model can be fulfilled to a larger degree. The difference becomes more pronounced in the results for the W and W^+ scenarios. The static model predicts an increase of the crop water stress by a factor $(1-0.72)/(1-0.82)=1.55$ for the W^+ scenario (Table 5, arable land). The dynamic model predicts an increase by a factor $(1-0.79)/(1-0.85)=1.40$, which is an increase that is 15 percentage points less (of 55) than with the static model.

In terms of the recharge $(P-ET_a)$ for the year 2003/2063, the dynamic simulation of arable land vegetation yields a slightly higher increase due to climate change than the static simulation (ΔR^{Cl}), for both the W and W^+ scenarios. That is due to the fact that the actual transpiration is slightly more sensitive to the drier conditions if the feedback from the vegetation is included.

As can be seen from Fig. 10, the recharge from arable land vegetation strongly varies along the cross-section AB indicated in Fig. 4. To a large part that is due to variations of the soil type, like the peak at $x_{AB}=4200$ m, which has a podzolic coarse-textured sandy soil with a poor water retention capacity, leading to a low actual evapotranspiration and high recharge. This high recharge is not sensitive for the dynamic/static simulation, because the soil moisture supply is in this case the limiting factor for the actual evapotranspiration.

To investigate the influence of the depth to the groundwater level on the sensitivity of the recharge for static/dynamic vegetation simulation (ΔR^{veg}), a selection was made of locations with the same soil, a podzolic medium-textured sandy soil. For this selection, the recharge was plotted against the mean of the groundwater level on day 4 and day 264 of 2003 (Fig. 11). The apparent strong correlation is explained by the difference between the potential and actual transpiration of static/dynamic models, with the static

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model simulating a 15 % higher potential value (Table 5). The higher potential transpiration can be better approached by the actual value at locations with a shallower groundwater level, which have an increased potential for moisture supply via capillary rise. The increased actual transpiration has a lowering effect on the recharge of the static model. Thus the gap between recharge simulated by dynamic and static models widens for conditions with shallower groundwater levels that are supported by seepage from deeper layers.

The effect of using a dynamic vegetation model versus a static one in the W^+ scenario on the recharge can become as much as 10 % of the simulated evapotranspiration in the used model cross section. The influence of this effect on the recharge sensitivity for climate change (ΔR^{Cl}) in this case leads to an effect with an opposite sign when using the static model ($-20\,\mathrm{mm\,a^{-1}}$) and dynamic model ($+10\,\mathrm{mm\,a^{-1}}$). In terms of effects on the groundwater level itself (cf. Fig. 6) or on the saturated flux (Fig. 7), however, the difference between the static and dynamic model is too small to be shown in a figure; this is partly due to the fact that agriculture is not the only land use.

Surface water supply to the *Kromme Rijn* region takes place in two ways: via supply of sprinkling water and via supply of water for subinfiltration. The simulated sprinkling demand is significantly affected by the choice between of static/dynamic vegetation models, as can be seen from Fig. 12: the peak demand in the dynamic simulation has forward a time shift of 20 days compared to the static one. A forward time shift is also evident in the time plot of the total subinfiltration (Fig. 13).

4 Discussion

4.1 Is the model parameterization climate-independent?

As is common knowledge in modelling practice, deficiencies of model conceptualizations are often compensated for by deriving "effective" parameters. There does not

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have to be any harm in that, as long as the model is used within the ranges of conditions that these parameters were derived for. In the presently used model, several relationships have been postulated, but not validated. Due to lack of experimental data such a validation is largely an impossible task: in the Netherlands, for instance, there is not a single lysimeter operational.

Relationships that are "suspect" in terms of implicit climate-dependency are the water uptake function and the crop factor relationship to the LAI: the water uptake process by plants is known to be influenced by temperature (e.g. Yoshida and Eguchi, 1989). The pressure-head dependent reduction function of Feddes et al. (1978) that is used here lacks the temperature dependency. Such a dependency is included in the process-based simulation method that has been proposed by Bartholomeus et al. (2008). That has, however, not yet found its way to modelling practice, mainly due to lack of soil-specific data and of experimenting facilities for validating the approach.

4.2 Comparison to other studies

In the approach followed here, the static vegetation model has been derived from averaging of crop variables of the dynamic model that was run for a 30-yr period; the averaging has been done for each day of the year. This approach has the advantage that the simulated long-term averages of water balance terms for the current climate are nearly the same for the static/dynamic crop models. That enables a more clear analysis of the role of the dynamic crop model in simulating effects of climate scenarios than when the baseline simulations differ widely.

In the approach of Wegehenkel (2009, Fig. 6), the components of the total evapotranspiration differ very strongly between the used static/dynamic approaches, even though the total evapotranspiration is nearly the same. This means that the hydrological feedbacks function very differently for the two models when a different climate is simulated, thus hindering the analysis of the outcomes. The approach of Wegehenkel also lacks two essential feedback elements: the influence of the simulated leaf area index on the crop factor (the function $F(t)$ is read from file), and the influence of the simulated leaf

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area index on the interception storage capacity. Furthermore, the approach lacks the feedback from the coupling to an integrated regional model: the simulations are for a "region", but in essence they have been done as stand-alone simulations of uncoupled column models. In the present study it has been shown that the differences between static/dynamic models are sensitive for the interactions with the hydrological context (groundwater, surface water).

The results of Wegehenkel (2009) for the transpiration indicate an increased sensitivity of the transpiration for climate change if a dynamic vegetation model is used; that is also found here. Results given by Wegehenkel in terms of differences in *per cent* change of recharge are considered unjustified if they are based on small changes of the total evapotranspiration (top half of Fig. 3, Wegehenkel, 2009). The per cent change of the recharge then gets "enlarged" in a manner that also applies to the errors that are made due to the inevitable conceptual deficiencies of the models. Wegehenkel also presents results in terms of the "crop stress": "‥, the dynamic vegetation model simulated a higher increase of crop water stress with an amount of 20 %". But it is found here that the *dynamic* simulation produces an increase that is 15 percentage points *less* (of 55).

The difference between the claims is partly caused by the different definitions of "crop stress": Wegehenkel (2009) defines it as the total daily evapotranspiration divided by the "potential" evapotranspiration. But in fact the *reference* evapotranspiration is used instead of the potential one (see ET_r/ET_p in Fig. 4, Wegehenkel, 2009, where ET_r is the actual transpiration, and ET_p is the Penman-Monteith evapotranspiration for a reference crop). In WOFOST (Supit et al., 1994), the crop stress is defined in terms of the actual transpiration divided by the potential transpiration. Here a slightly modified approach has been followed, taking the role of interception evaporation into account, as explained in Sect. 2.1.2. The real difference with the analysis of Wegehenkel, however, is that here not only the effect of the dynamic simulation on the actual transpiration is taken into account, but also the effect on the *potential* transpiration.

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That the potential transpiration is impacted to such a degree in the approach followed here, is because it is influenced via the LAI in two manners: via the soil cover (Eq. 2 and assumption given in Sect. 2.1.2) *and* via the crop factor (Fig. 2). The latter effect is not modelled by Wegehenkel (2009), and the difference with the present approach is therefore not just a question of presentation. In the approach presented here, the calculated potential transpiration for arable land is reduced by the shortening of the growing season in a warmer climate with increased CO_2-concentration.

5 Conclusions

The SIMGRO modelling system has been extended by a coupling to the crop growth model WOFOST with the intention of making the models and their parameterization less dependent on the climate. One of the limitations in achieving that goal is due to not taking the physiological temperature dependency of water uptake into account. A pervasive limiting factor of the approach is the lack of data and facilities to experimentally validate the postulated relationships.

For the hydrological response of grassland to climate change, dynamic simulation of the vegetation shows a higher potential transpiration than the static one, due to the earlier start of grass growth. But the effect on the water balance terms is minor. That is because grassland always has a soil cover of >50 %, with or without a dynamic simulation model, thus reducing the impact of any changes in the simulated growth. The main effect is the speeding up of the growth/hay-cutting cycle, with an effect that averages out over time.

The differences between static/dynamic simulations of arable land crops have been investigated for potatoes as an example. The dynamic simulation of arable land crops shows a forward time shift and shortening of the crop growth cycle. That causes a lowering of the potential transpiration by 15 % in the example year, which in turn leads to an increase of the relative transpiration and a decrease of the crop water stress. The dynamic model also has a lowering effect on the predicted change of the latter in the

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climate scenarios: the simulated increase of crop water stress due to climate change is 15 percentage points less (of 55) than with the static model.

If there is ample supply of moisture, then the higher potential transpiration of the static model translates directly to a higher transpiration. That is the case for locations having soils with a high moisture retention capacity and/or with capillary rise from a shallow groundwater level. The strong dependency on the local conditions means that the climate change effect on the recharge can either be higher or lower when using a dynamic versus a static vegetation model.

On a regional scale, the main effect of the dynamic vegetation simulation is on the timing of the water demand. In the case of the *Kromme Rijn* region this demand is for sprinkling and for the infiltration from the main water courses in the region. The dynamic vegetation simulation leads to a significant forward time shift of the demand, which is of relevance when the model is being used for water allocation.

Acknowledgements. The reported research was made possible by the Strategic Research Fund (KB2) of the Wageningen University and Research Centre and by the GENESIS project of the EU 7th Framework Programme (Project No. 226536; FP7-ENV-2008-1).

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Table 1. Land use in the "Kromme Rijn" region.

Land use	Area (%)
Built-up area and roads	17
Grassland	48
Arable land	5
Forest and orchards	28
Fresh water	2

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Table 2. Climate scenarios for The Netherlands, for two possible developments of the global temperature change for 2050 (ΔT_{2050}) and two possible developments of the atmospheric circulation (ΔA). The given changes are for the (climatic) mean precipitation (ΔP) and the mean potential evapotranspiration (ΔET_p). For this study the scenarios W and W^+ have been used.

Climate scenario	ΔT_{2050}	ΔA	ΔP (%) winter	ΔP (%) summer	ΔET_p (%)
G	+1 °C	Weak	4	3	3
G^+	+1 °C	Strong	7	−10	6
W	+2 °C	Weak	7	6	6
W^+	+2 °C	Strong	14	−19	11

Source: Van den Hurk et al. (2006)

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Table 3. Investigated variants of climate and land-use scenarios without/with dynamically simulated crop growth.

Variant	Climate scenario	Agricultural land use	Crop simulation
ClC_LuGr_Stat	Current	grassland	Static
ClC_LuGr_Dyn	Current	grassland	Dynamic
ClW_LuGr_Stat	W	grassland	Static
ClW_LuGr_Dyn	W	grassland	Dynamic
ClW$^+$_LuGr_Stat	W$^+$	grassland	Static
ClW$^+$_LuGr_Dyn	W$^+$	grassland	Dynamic
ClC_LuAr_Stat	Current	arable land	Static
ClC_LuAr_Dyn	Current	arable land	Dynamic
ClW_LuAr_Stat	W	arable land	Static
ClW_LuAr_Dyn	W	arable land	dynamic
ClW$^+$_LuAr_Stat	W$^+$	arable land	Static
ClW$^+$_LuAr_Dyn	W$^+$	arable land	Dynamic

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Table 4. Evapotranspiration terms (17-yr averages in $\mathrm{mm\,a^{-1}}$) of evaluation point EP1 in Fig. 4, simulated for the current climate, with static/dynamic simulation of the vegetation. The listed terms are: E_{ic} – interception evaporation; E_{bs} – bare soil evaporation; E_{pd} – ponding evaporation; ET_a – total actual evapotranspiration.

Variant	E_{ic}	E_{bs}	E_{pd}	T_a	ET_a
CIC_LuGr_Stat	132	76	1	321	530
CIC_LuGr_Dyn	134	78	1	319	532
CIC_LuAr_Stat	76	176	3	212	467
CIC_LuAr_Dyn	75	177	3	214	469

Table 5. Water balance terms (mm a^{-1}) of evaluation point EP1 in Fig. 4 (+/− = in/out) for the simulation year of 2003/2063. The listed terms are: P – precipitation; ET_{ref} – Makkink reference crop evapotranspiration; T_p – potential transpiration; T_a – actual transpiration; E_{ic} – interception evaporation; E_{bs} – bare soil evaporation; E_{pd} – ponding evaporation; T_{rel} – relative transpiration $(T_a + E_{ic})/(T_p + E_{ic})$; ET_a – total evapotranspiration; R – recharge $(P - ET_a)$; ΔR^{veg} – change of simulated recharge of dynamic versus static vegetation model; ΔR^{Cl} – change of simulated recharge with respect to current climate.

Variant	P	ET_{ref}	T_p	T_a	E_{ic}	E_{bs}	E_{pd}	T_{rel}	ET_a	R	ΔR^{veg}	ΔR^{Cl}
ClC_LuGr_Stat	648	635	398	352	105	78	1	0.91	536	112		
ClC_LuGr_Dyn	648	635	397	357	99	86	1	0.92	543	105	−7.0	
ClW_LuGr_Stat	675	670	413	361	100	80	1	0.90	542	133		21.6
ClW_LuGr_Dyn	675	670	414	372	94	85	1	0.92	552	123	−10.1	18.5
ClW$^+$_LuGr_Stat	644	708	443	353	95	73	1	0.83	522	122		10.1
ClW$^+$_LuGr_Dyn	644	708	461	359	94	75	1	0.82	528	115	−6.5	10.6
ClC_LuAr_Stat	648	635	291	231	39	187	3	0.82	459	188		
ClC_LuAr_Dyn	648	635	271	224	36	188	3	0.85	451	196	8.2	
ClW_LuAr_Stat	675	670	296	232	36	189	4	0.81	460	215		26.6
ClW_LuAr_Dyn	675	670	263	222	39	184	3	0.86	448	227	11.9	30.2
ClW$^+$_LuAr_Stat	644	708	326	225	29	184	3	0.72	441	202		14.2
ClW$^+$_LuAr_Dyn	644	708	276	213	28	183	3	0.79	427	216	14.1	20.0

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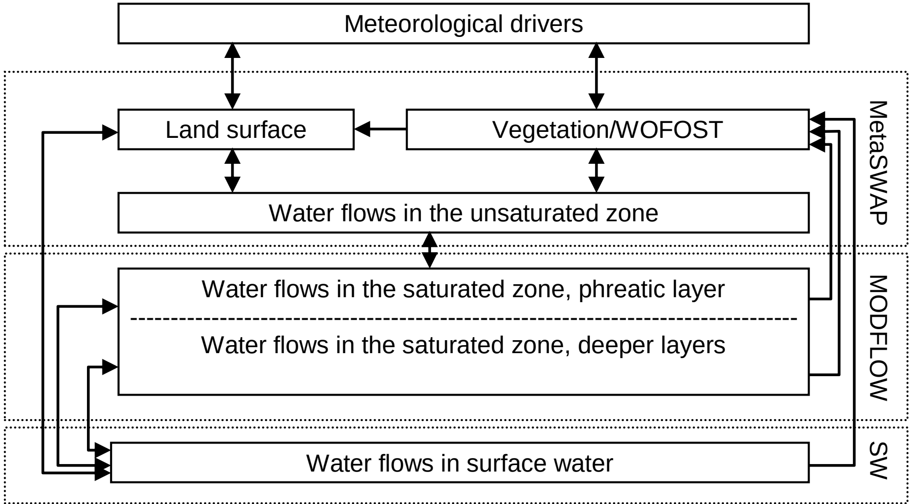

Fig. 1. Overview of SIMGRO modelling system.

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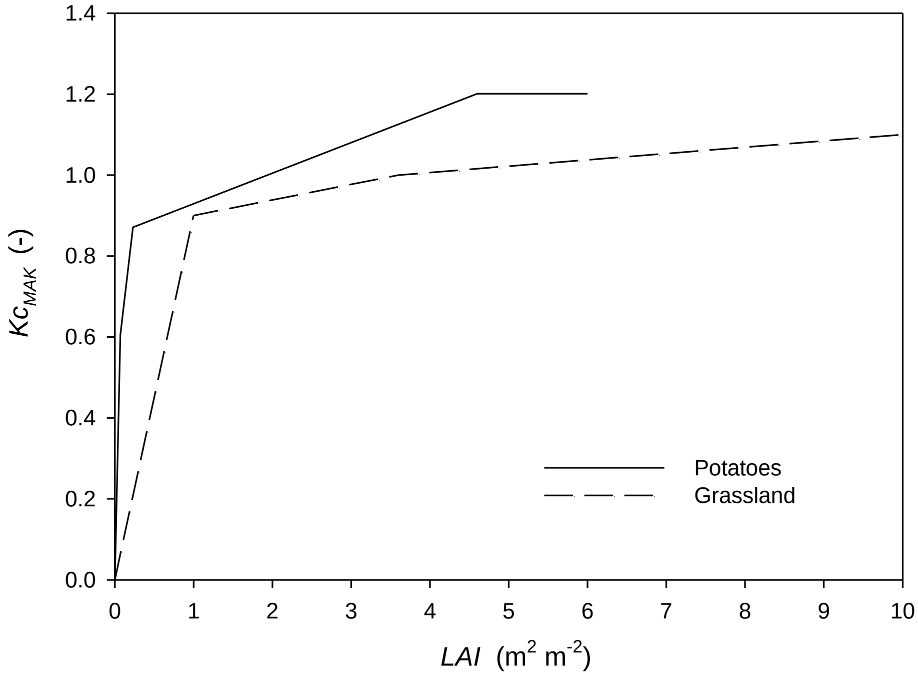

Fig. 2. Fitted relationships between the Leaf Area Index (LAI) and the crop factor Kc_{MAK} (of Makkink reference crop evapotranspiration), for potatoes and grassland.

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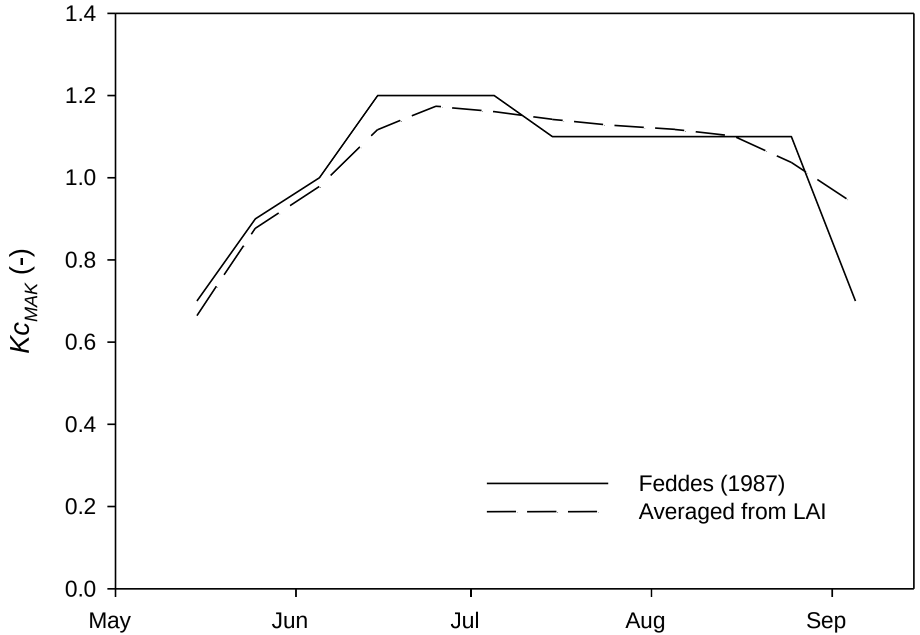

Fig. 3. Comparison between 10-day values of crop factor for potatoes given by Feddes (1987) and the averages (averaging for the days of a year, over 30-yr period) determined from the fitted Kc_{MAK}(LAI) relationship (Fig. 2).

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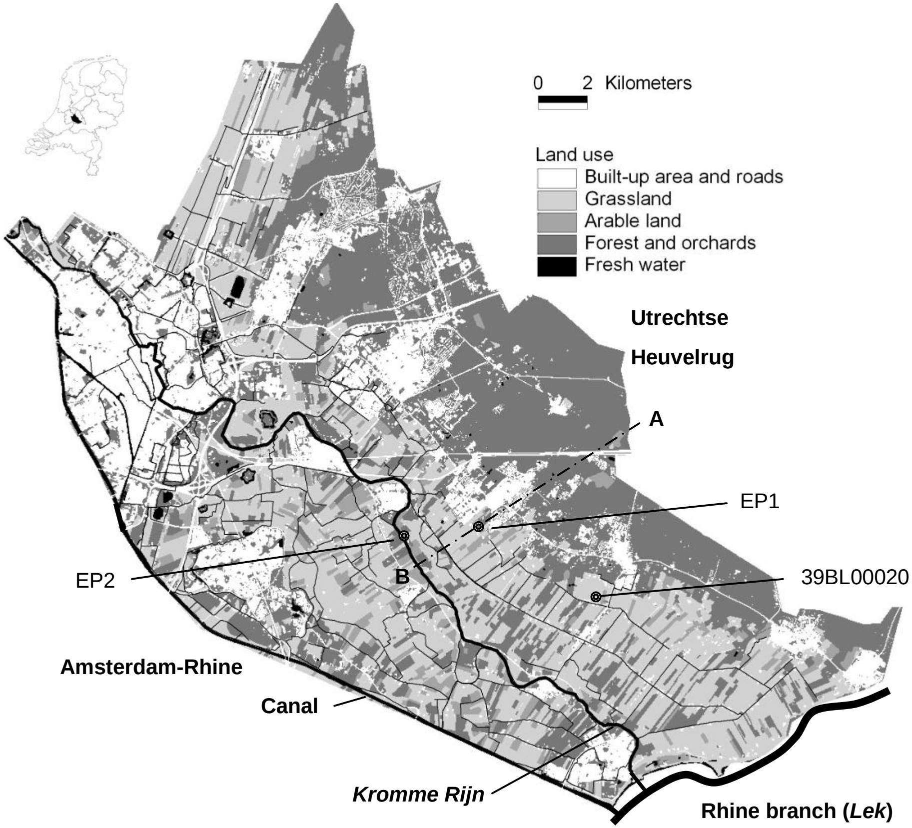

Fig. 4. "Kromme Rijn" region.

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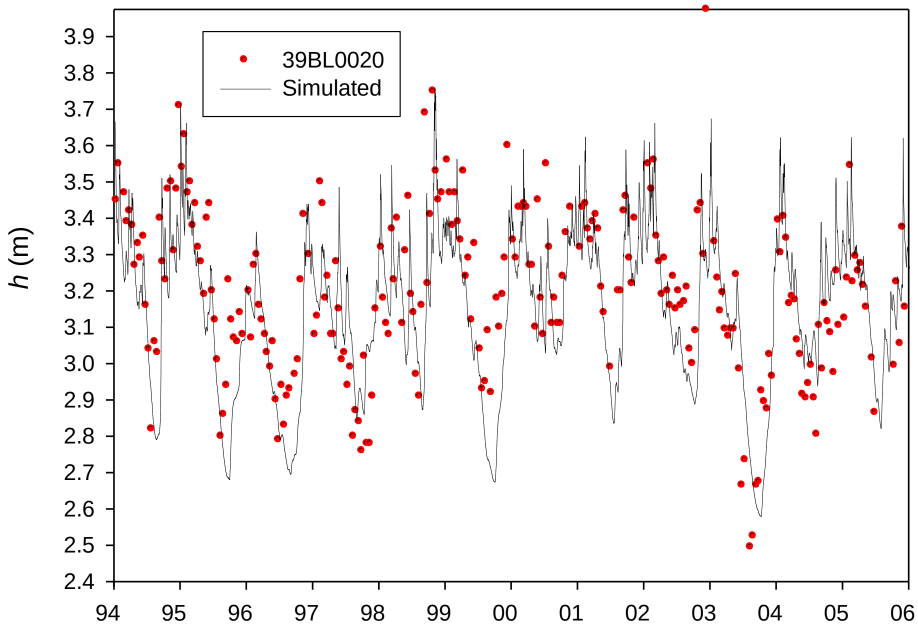

Fig. 5. Measured and simulated phreatic levels for the monitoring point 39BL0020 indicated in Fig. 4.

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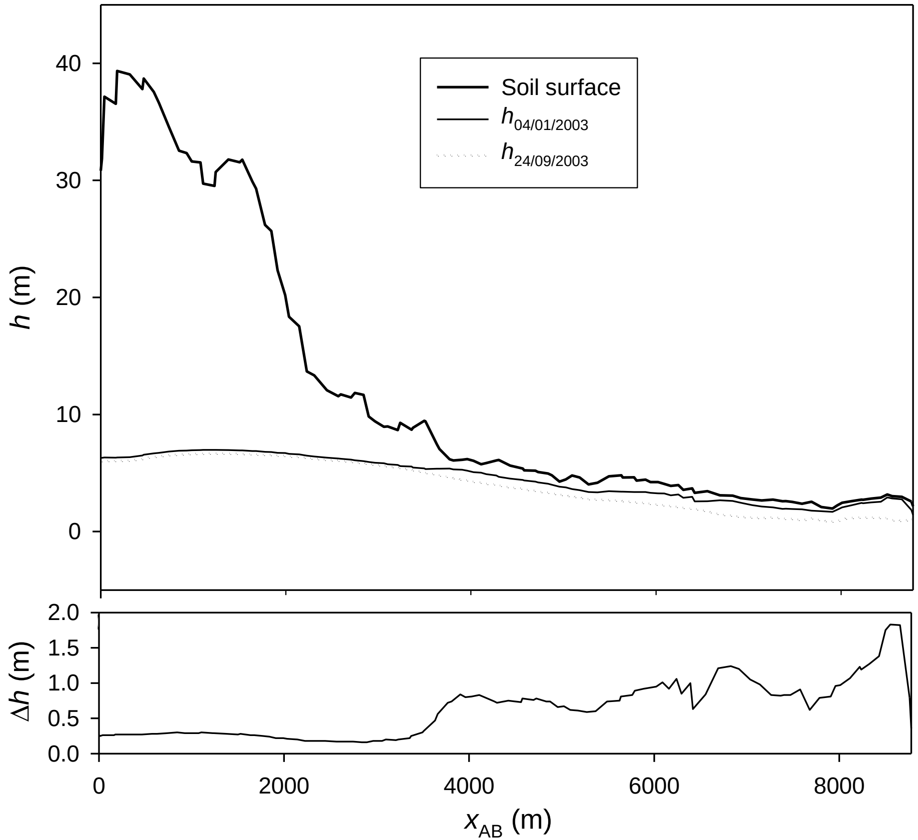

Fig. 6. Simulated groundwater level for 2003 (highest and lowest levels), for the cross-section AB in Fig. 4, and the groundwater level fluctuation $\Delta h = h_{04/01/2003} - h_{24/09/2003}$.

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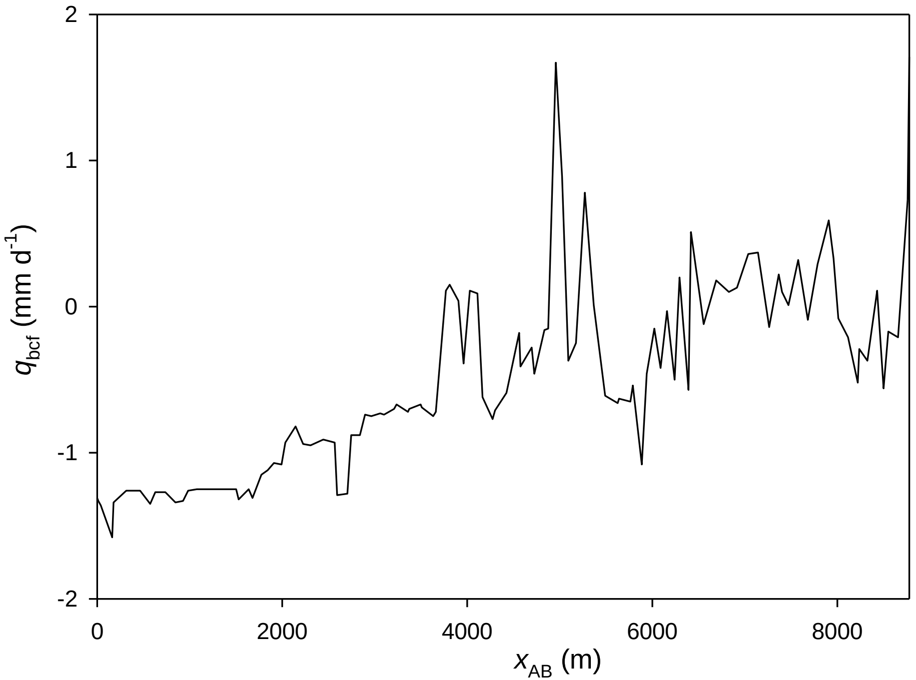

Fig. 7. Simulated nett groundwater flux (Darcy flow, "BCF" in MODFLOW) for 2003 (time average), for the cross-section AB in Fig. 4.

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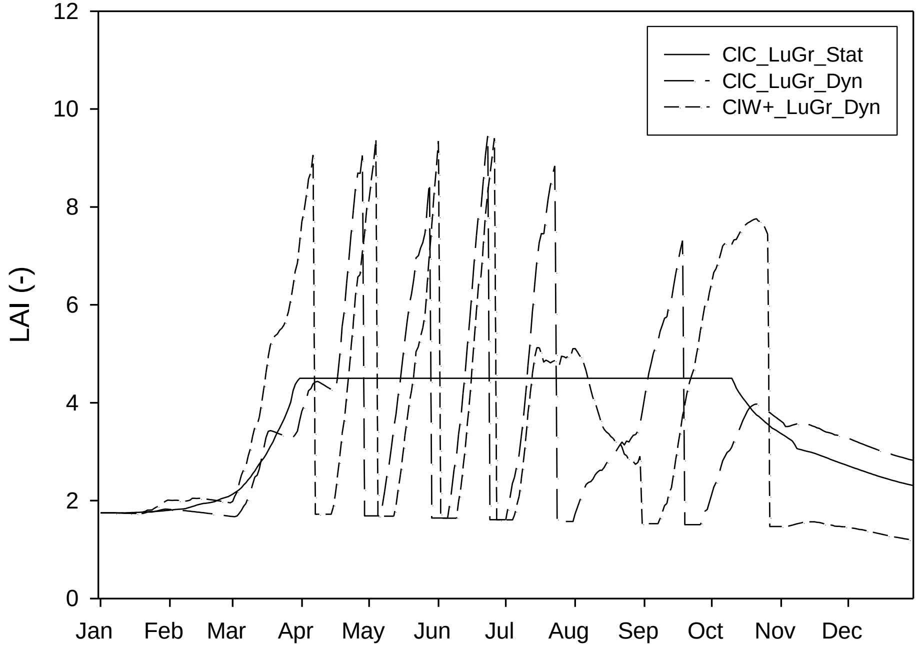

Fig. 8. Simulated Leaf Area Index of grassland in evaluation point EP1 (Fig. 4), for three of the variants (Table 3):
ClC_LuGr_Stat – static vegetation model current climate,
ClC_LuGr_Dyn – simulation with dynamic vegetation model, current climate,
ClW^+_LuGr_Stat – simulation with dynamic vegetation model, W^+-scenario.
The simulations are for the year 2003 (warm year, current climate) and 2063 (W^+-scenario).

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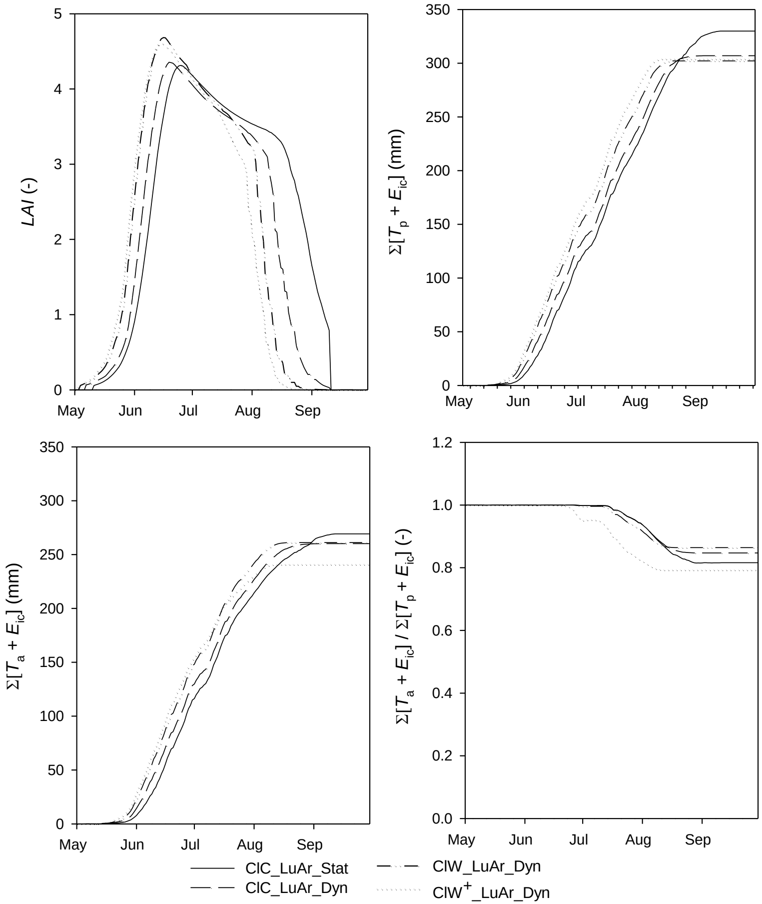

Fig. 9. Simulation results for arable land (potatoes) in evaluation point EP1 (Fig. 4), for four of the variants (Table 3): ClC - current climate, ClW/W$^+$ – scenarios, Stat/Dyn - static/dynamic vegetation model. The simulations are for the year 2003 (warm year, current climate) and 2063 (W/W$^+$-scenario).

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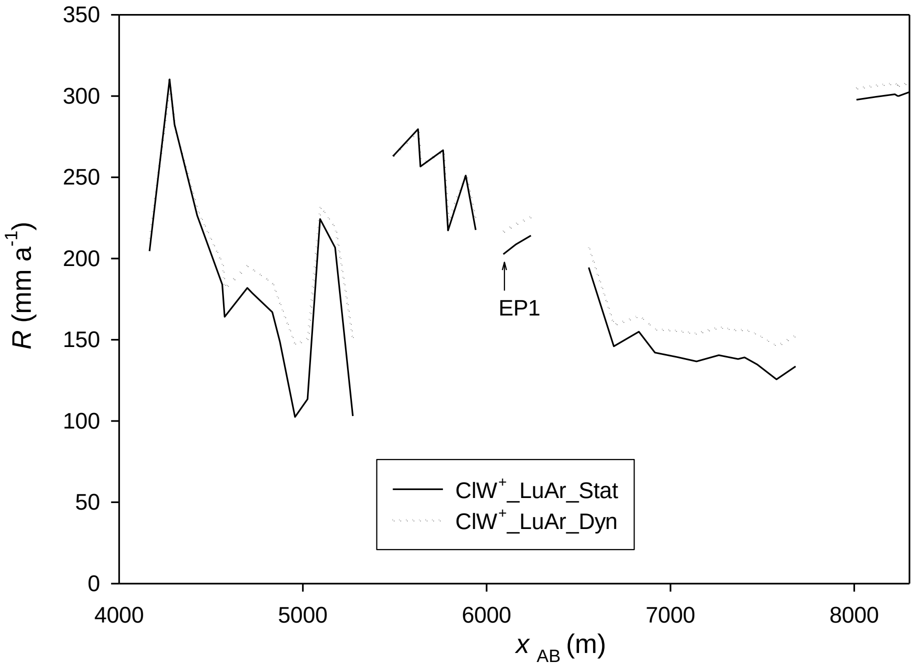

Fig. 10. Simulated recharge ($P - ET_a$) along the cross-section AB (Fig. 4), for the part that is in use by agriculture. The plot is for the arable land scenarios ("LuAr"), for the static/dynamic arable land simulations, for the W^+ climate scenario.

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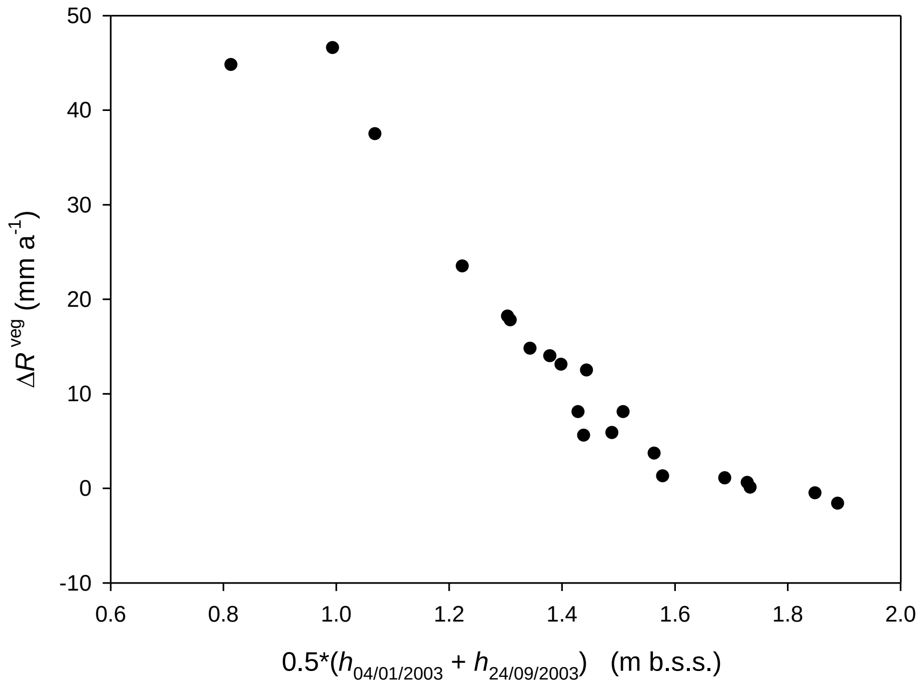

Fig. 11. Relationship between the mean groundwater level on day 4 January 2003 (day 4) and 24 September 2003 (day 264) and the difference between the recharge that is simulated for the W^+ scenario with dynamic and static vegetation models, with $\Delta R^{veg} = R_{dyn} - R_{stat}$ (mm a^{-1}).

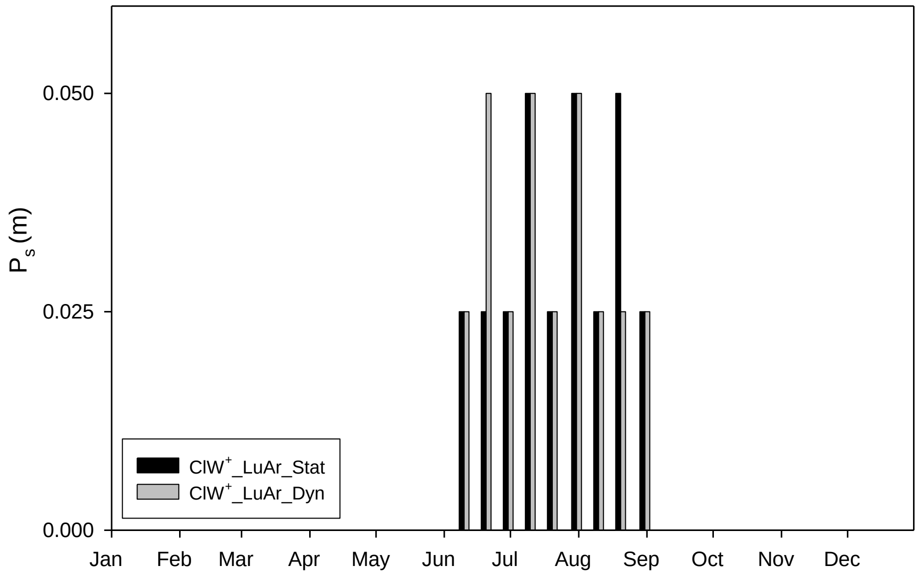

Fig. 12. Simulated sprinkling demand simulated for evaluation point EP2 in Fig. 4, with static and dynamic vegetation models, for the W^+ scenario.

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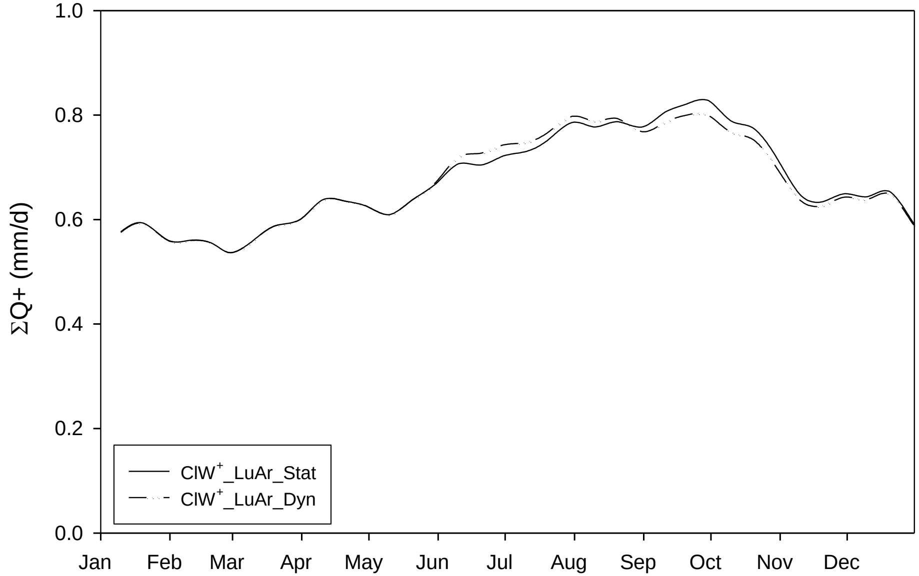

Fig. 13. Simulated total water demand, with static and dynamic vegetation models, for the W^+ scenario. The simulations are for the year 2063.

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