KWR 2015.062 | June 2015

Anticipating on amplifying water stress: Optimal crop production supported by climate-adaptive water management

TKI Groundwater for Crops

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KWR Watercycle Research Institute

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Project number
400527

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Year of publishing
2015

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Preface

Water has been designated as one of the country's top economic sectors (Top Sectors) by the Dutch Ministry of Economic Affairs. In late 2012, the Top consortia Knowledge and Innovation (TKI) scheme came into force with the objective of stimulating innovation and creating economic value from the knowledge developed. Private businesses along with research organizations play a fundamental role in the collaborative projects. One of the objectives of TKI Water Technology is to stimulate collaboration among water cycle players to make more efficient use of invested resources. The general thrust is to promote private-public collaboration within the "golden triangle" of business, science and government (www.kwrwater.nl/tki-watertechnologie).

Within the framework of TKI-Watertechnology, funding for the project 'Groundwater for Crops' was generated. This was only possible through investments by FutureWater. Within the project, FutureWater, KnowH_2O and KWR worked together on the development and testing of a management algorithm for the Climate Adaptive Drainage system (www.futurewater.nl/uk/projects/climate-adaptive-drainage/), which should enhance the application of Climate Adaptive Drainage (CAD).

We would like to thank farmer Asbreuk, Water Authority Vechtstromen, Topsector Water and DACOM for their support during the project.

Summary

Since climate change induces more extreme dry and wet conditions that have impact on crop growth and agricultural crop yield, it is important to anticipate on these amplifying soil moisture conditions. Technically advanced controlled drainage systems like the Climate Adaptive Drainage (CAD) system allow for such anticipative water management.

This 'TKI Groundwater for Crops' project aims at the development and actual field test of a controlled drainage management algorithm for CAD at the plot and farm scale. This algorithm should provide dynamic drainage crest settings for controlled drainage systems in order to optimize crop production and agricultural yield. By reducing both oxygen and water stress for crops, yields will increase, followed by an increase of the farmer's income. Crop yield depends on the actual transpiration of the crop, facilitated by soil moisture conditions in the root zone. As long as these soil moisture conditions in the root zone are good, transpiration will be at an optimal (maximum) level, given the meteorological boundary conditions.

We developed a climate adaptive drainage management algorithm (CAD-MA) which we theoretically tested on measurement data of soil moisture and groundwater levels at the Haaksbergen experimental CAD-field in the Netherlands. Simulations showed that dynamic drainage crest level control can lead to up to 10% increase of crop yield under wet conditions, and gives a less pronounced increase of crop yield during dry periods. SWAP model results at the plot-scale were successfully coupled with the SPHY spatial hydrological model at a 25m spatial resolution. This enables farm-scale analysis and automated drainage control, which can be expanded to irrigation control and a regional-scale optimization procedure.

Contents

1 Introduction

Agricultural crop yield depends largely on the moisture conditions in the root zone; drought but especially an excess of water in the root zone, and herewith limited availability of soil oxygen, reduces crop yield. With recent climate change, more prolonged dry periods alternate with more intensive rainfall events, which changes soil moisture dynamics (Bartholomeus et al., 2011; Porporato et al., 2004). With unaltered water management practices, reduced yield due to both drought and waterlogging are expected to increase (Knapp et al., 2008). Therefore, farmers and water managers need to be provided with possibilities to reduce risks of low yields. In the Netherlands, agricultural production of crops represents a market exceeding 2 billion euro’s annually. Given the increased variability in meteorological conditions and the resulting larger amplitudes in soil moisture contents, it is of economic importance to provide farmers and water boards with tools to reduce risks of reduced crop yield by anticipatory water management at field and at regional scale.

In order to reduce the risk of waterlogging, farmers have drained their land to get rid of excessive soil moisture quickly (Ritzema et al., 2006). While limiting waterlogging, conventional drainage may also induce drought stress as less soil water is available in dry periods (Tan et al., 2002). In order to limit excessive drainage, controlled drainage systems have been developed, which allow to retain water within agricultural parcels. Such controlled drainage may reduce peak discharges and limit nutrient loads to surface waters, but have the additional advantage that they allow to actively control the groundwater levels and soil moisture conditions at an agricultural field (Ayars et al., 2006).

The concept of Climate Adaptive Drainage (CAD) is a controlled drainage system that allows to remotely manage the drainage basis through internet. Technically, the Climate Adaptive Drainage system consists of coupled subsurface drains, of which the drainage basis can be controlled. The equipment installed allows remote and continuous management of the drainage basis, to control the water discharged to the surface water by the outlet of the CAD-system. All is coupled with a telemetry system for control, visualization of information, and data management.

The feature of the automated control of the drainage basis provides opportunities for continuous and online control of the field soil moisture conditions. In this study, we provide a basis for a management algorithm for CAD, which allows to optimize crop yield by timely anticipation on drought and/or waterlogging situations. The management algorithm focusses on anticipatory water management at the field scale, i.e. the unit scale of interest to a farmer. We combine parallel field measurements (‘observe’), process-based model simulations (‘predict’), and the Climate Adaptive Drainage system (‘adjust’) to optimize soil moisture conditions for plant growth and crop production.

In this report we first give a description of the CAD system (Section 2.2). Then we provide further theoretical background on the climate-robust simulation of different types of plant stress (Section 2.3), followed by a description of the CAD management algorithm, as developed for plot scale application (Section 2.4). Upscaling from plot to field, using a hydrological model (SPHY) is described in Section 2.5. Then, we demonstrate the application of the CAD management algorithm by some explorative simulations for fictitious situations, and for the CAD experimental field of Haaksbergen, the Netherlands (Section 2.6, Chapter 3).

We end with conclusions and discussion, aiming at bringing CAD and the management algorithm into daily agricultural practice (Chapter 4).

2 Methods

2.1 General

Controlled drainage generally focusses on maintaining specific groundwater levels. It leads to a drainage situation that suits the local crop demands, that allows to store water in the soil when needed, and that benefits the downstream water management. However, a groundwater level by itself has only an indirect effect on the soil moisture content in the unsaturated zone, and thus on the oxygen and water availability in the root zone, partly by capillary effects. Effects of other variables that determine oxygen and drought stress, e.g. precipitation, evapotranspiration, soil temperature and plant characteristics, are not accounted for by groundwater levels (Bartholomeus et al., 2012). Therefore, we focus here not on optimizing the water table, but on minimizing plant stresses, which integrates the processes in the soil-plant-atmosphere system (section 2.3) and is a more direct and relevant management objective for optimal crop growth.

Next, we combine parallel-obtained field measurements (‘observe’), process-based model simulations (‘predict’), and the Climate Adaptive Drainage system (CAD) (‘adjust’) to optimize soil moisture conditions and minimize plant stresses. The CAD management algorithm combines continuous field measurements, weather forecasts and a detailed numerical hydrological model for the unsaturated zone, to provide the optimal crest level to i) prevent oxygen stress, and ii) prevent unnecessary drainage (section 2.4). Doing so, we keep as much water within the field to minimize drought stress, but without causing oxygen stress. We extrapolate the field-scale application to the farm-scale, using the spatial explicit hydrological model SPHY (section 2.5). Finally, we demonstrate the application of the management algorithm for a fictitious agricultural maize field for both a wet and dry year for the CAD experimental field at Haaksbergen, the Netherlands (section 2.6).

2.2 Climate Adaptive Drainage system

The concept of Climate Adaptive Drainage (CAD) is a controlled drainage system that allows to remotely manage the drainage basis. Technically, the Climate Adaptive Drainage system consists of a series of conventional subsurface drains at a typical depth of 1.2 m below soil surface and at a spacing of 6 m. These drains are interconnected by a closed collector drain. This collector drain ends up in a drainage pit with an outlet. This drainage pit has equipment installed inside to remote and continuously manage the drainage basis, before drainage water is discharged to the surface water by the outlet. Figure 1 shows the schematic outline of the CAD system. The idea is to manage the drainage level of the CAD system ‘on time’, thus before agricultural crops suffer from too wet or too dry conditions, by respectively lowering and raising the drainage level.

The CAD experimental field of Haaksbergen and the CAD technical equipment are shown in Figure 2. The CAD-system can be operated manually, but is usually managed remotely. It is connected to an online telemetry system. This system can be operated through a website or an iOS App (Figure 3), by which also monitoring data can be viewed.

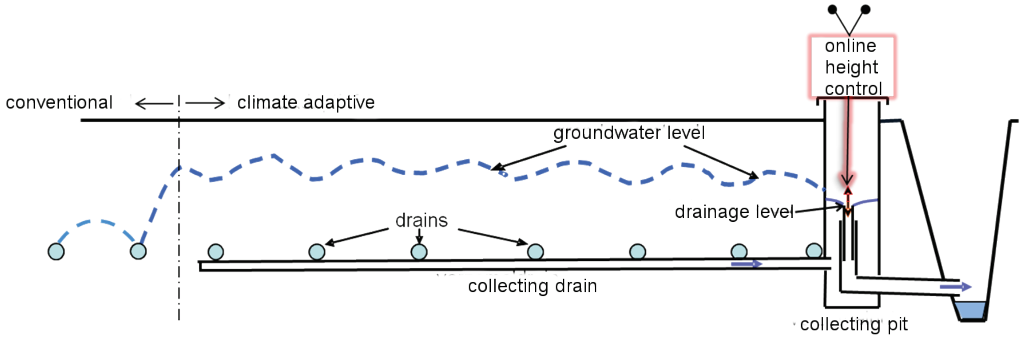

Figure 1: Climate Adaptive Drainage (CAD) system: subsurface drains, connected to a closed collecting drain, ending up in a collecting pit with drainage basis control unit, with outlet to the surface water system.

Figure 2: CAD experimental site Haaksbergen (5.5 ha area). Top left: setup of CAD and monitoring equipment (CAD-system; groundwater piezometers in green), top right: picture of the field in June 2013. Bottom left: mechanical drainage basis device installed within drainage collector pit. Bottom right: remote control unit with controlled drainage pit in the background.

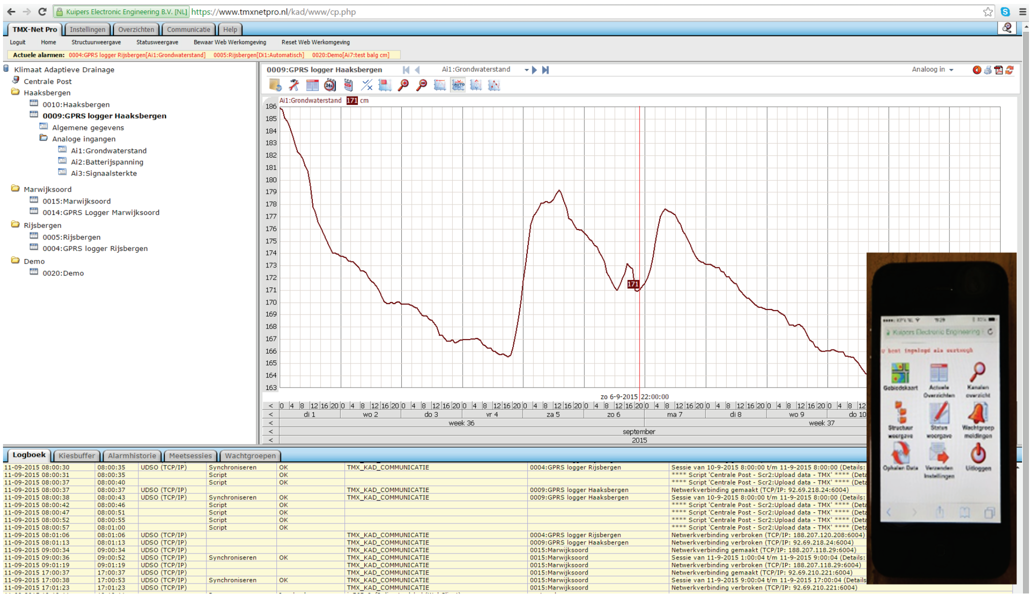

Figure 3: TMX-telemetry system for operating the CAD-system and data management and iPhone App (inset).

2.3 Process-based method for quantifying plant stress

Soil moisture directly affects plant productivity, both when it is deficient by drought stress and when it is superfluous by oxygen stress. In contrast to the process-based simulation of drought stress, remarkably little attention is generally paid to the interactions among oxygen limitation and plant performance, although it is waterlogging that farmers fear most in temperate climates. Plant roots usually obtain a sufficient amount of oxygen for root respiration directly from gas-filled pores in the soil. However, a surplus of water will lead to a shortage of soil oxygen, which reduces root respiration, negatively affecting the energy supply for plant metabolism and thus plant performance.

Under non-limiting water and oxygen availability plants transpire at a potential rate (Feddes et al., 1978). This potential transpiration depends on the atmospheric demand (global radiation, air humidity, wind speed, air temperature and atmospheric CO_2-concentration) (Monteith and Unsworth, 1990). When water or oxygen becomes limiting, however, the water uptake by plant roots and herewith plant transpiration and crop growth are reduced.

In order to optimize soil moisture conditions for crop growth, the interacting processes in the soil-plant-atmosphere system need to be considered explicitly. The widely applied dynamic Soil-Water-Atmosphere-Plant model SWAP (Kroes et al., 2009; Van Dam et al., 2008), extended with the oxygen module of Bartholomeus et al. (2008) (Bartholomeus et al., 2013) describes these processes in detail. SWAP uses the water-limited side of the commonly used Feddes-function for root water uptake (Feddes et al., 1978), based on pressure head *h* to describe the transpiration reduction due to limited soil moisture availability, and the method of Bartholomeus et al. (2008), which involves macro scale and micro scale diffusion as well as the plant physiological demand of oxygen, for the transpiration reduction due to limited oxygen availability. SWAP translates relative transpiration to relative crop yield following the linear (1:1) relationship of De Wit (1958).

Inputs required by SWAP comprise meteorological conditions, soil physical parameters according to Van Genuchten (1980), bottom boundary conditions, schematization of the drainage situation, and a file that describes the crop parameters. Daily soil moisture, temperature, and transpiration reduction, i.e. the difference between the potential and the actual transpiration due to too wet or too dry conditions, are outputs of the SWAP-model. For a detailed discussion of the SWAP model and its accuracy, we refer to Kroes et al. (2009) and Van Dam et al. (2008).

2.4 CAD management algorithm

Within the management algorithm we combine parallel field measurements ('observe'), process-based model simulations ('predict'), and the Climate Adaptive Drainage system (CAD) ('adjust') to optimize soil moisture conditions and minimize plant stress. The CAD management algorithm combines continuous field measurements, weather forecasts and the SWAP model combined with the parameter estimation code PEST (Doherty, 2010), to provide the recommended crest level that prevents i) oxygen stress, and ii) unnecessary drainage.

The management algorithm has been programmed within the open source statistical software R (R Core Team, 2013). Within this framework, input files for SWAP and PEST are automatically generated and model runs are automatically invoked.

For each day three consecutive steps are distinguished: calibration and data assimilation of SWAP to field measurements using PEST (Figure 4-I), forecast of the future hydrological conditions and plant stresses using SWAP (Figure 4-II), and estimation of the recommended crest settings (Figure 4-III) for CAD. Each of these steps is described in more detail below and in the appendix.

2.4.1 SWAP calibration procedure (Figure 4-I)

SWAP is used to provide estimates of the groundwater level, soil moisture content, drainage flux and plant stress for the future *n* days. In order to provide accurate forecasts (Figure 4-II), we follow the method of Visser et al. (2006), combining offline calibration, online calibration and online assimilation to provide i) optimal model parameters for SWAP and ii) initial soil moisture profiles for the forecast that are physically consistent and approximate/match the state (i.e. measured groundwater levels and soil moisture profiles) at the current date. For this purpose measured drainage levels are input to the model.

The calibration procedure follows three consecutive steps. Step 1: Offline calibration based on all available groundwater level and soil moisture observations, resulting in optimal estimates of the soil physical properties and drainage resistance. Step 2: Online calibration, based on data of the last 31 days, following Visser et al. (2006), resulting in optimal estimates of the hydraulic head in the deep aquifer for this period. This calibration step is required to capture the seasonality in the hydraulic head. Offline calibration results are input to this calibration step. Step 3: Online data assimilation (i.e. analysis to get the best estimate of the current state of the system), based on the same data as the online calibration, but weight is only given to observations of the last day. Doing so, the initial state for the forecast is accurately obtained. All details on this procedure are presented by Visser et al. (2006); for details on the calibrated parameters for each step we refer to the appendix (Table 3).

2.4.2 Forecast and optimization (Figure 4-II and III)

In forecast mode, drainage levels are simulated based on a given crest level. Using the calibrated optimal model parameters, the current predicted state as initial conditions and daily weather forecasts as model input, the state (daily drainage level, groundwater level, soil moisture contents, drainage flux, plant oxygen stress) is forecasted for the future *n* days (Visser et al., 2006). Based on the simulated oxygen stress and drainage flux for the forecast, the optimization routine is invoked to determine the recommended crest level of the CAD pit. This recommended crest level depends on:

1. If oxygen stress: lower crest level to discharge water
2. Else if drainage: raise crest level to retain water
3. Else: no action

The recommended crest level is calculated as follows. First, based on the simulated oxygen stress in the next *n* days a weighted cumulative oxygen stress is calculated, using a sigmoid weight function, giving more weight to the days in the nearest future (see Appendix, Figure 17). In SWAP, oxygen stress is given by Tredwet (i.e. transpiration reduction due to too wet conditions). The weighted cumulative stress equals ΣTredwet (t_n)*Weight(t_n). We assume a lower cumulative stress limit that is acceptable, determined as a fraction of the weighted cumulative potential transpiration T_{pot}: T_{red_accept} = fraction * ΣT_{pot}(t_n)*Weight(t_n). The same procedure is used to calculate the weighted cumulative positive drainage = Σdrainage(t_n)*Weight(t_n) with drainage> 0 (i.e. no infiltration).

Then, for the prevention of oxygen stress (Ad 1), the crest level is iteratively lowered until the difference between the stress at the lowest possible crest level and the stress at the adjusted level is negligible, which is either a small absolute or relative difference, or lower than the calculated accepted value. The lowest possible crest level is a fixed value.

To limit unnecessary drainage (Ad 2), the crest level is iteratively raised until the drainage flux is minimal. If in the next *n* days the oxygen stress is lower than the accepted limit, and the cumulative drainage flux is larger than minimum, the crest level will be raised until either the difference with the drainage flux at the highest crest level is very small, or the drainage flux is lower than a predefined fixed accepted value.

In the current set up of the management routine, uncertainty in future weather is handled by creating multiple realizations of future precipitation only, following the error function for precipitation obtained by Visser et al. (2006). For each realization of future weather, the forecast and optimization routine are run, which gives a range of future state variables and optimal crest levels.

Figure 5 shows an example of the forecast and optimization of the crest level for a situation with initially wet conditions.

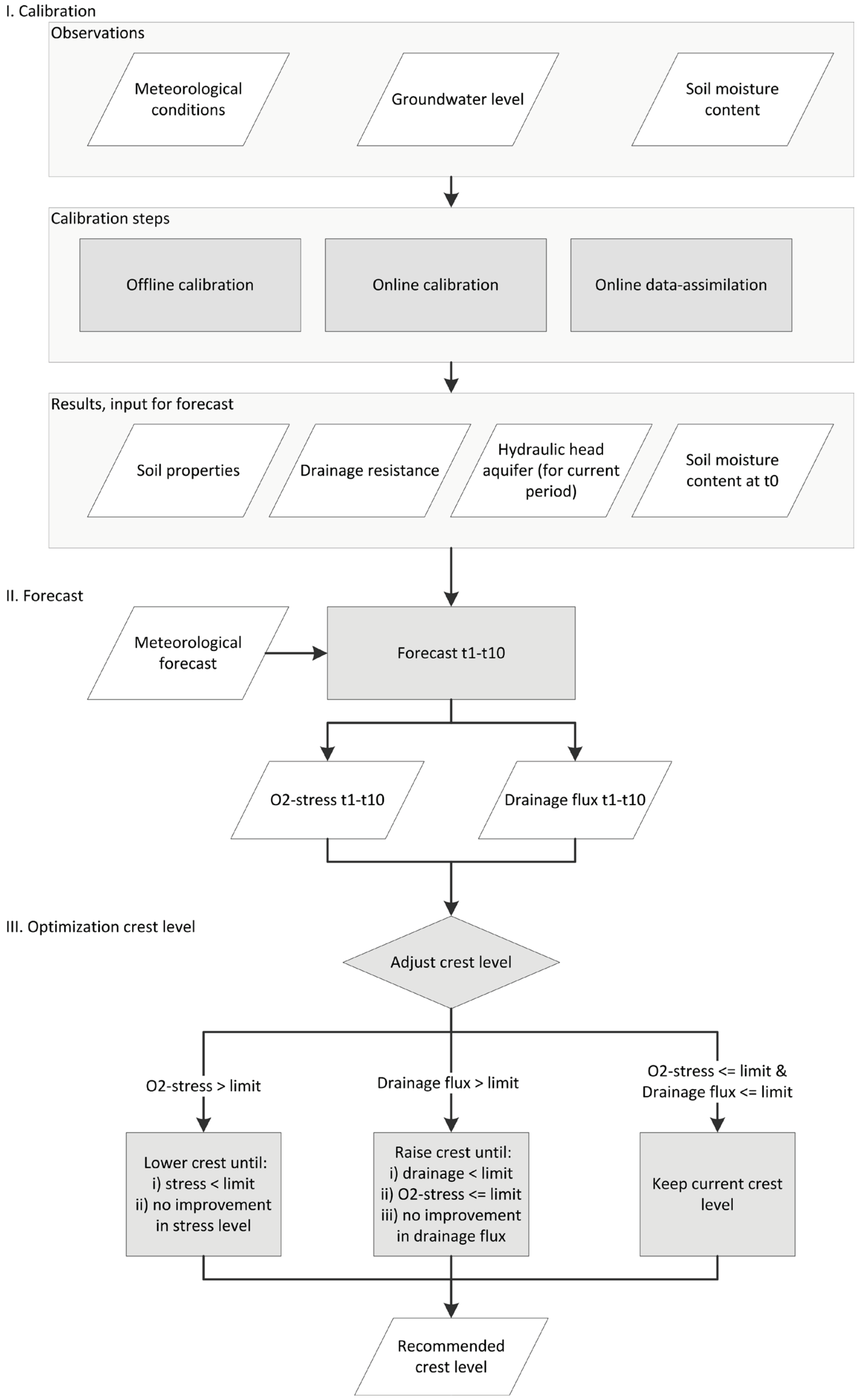

Figure 4: Estimation of the recommended crest level, based on observed groundwater levels and soil moisture conditions, process-based model simulations, and 10-day weather forecasts.

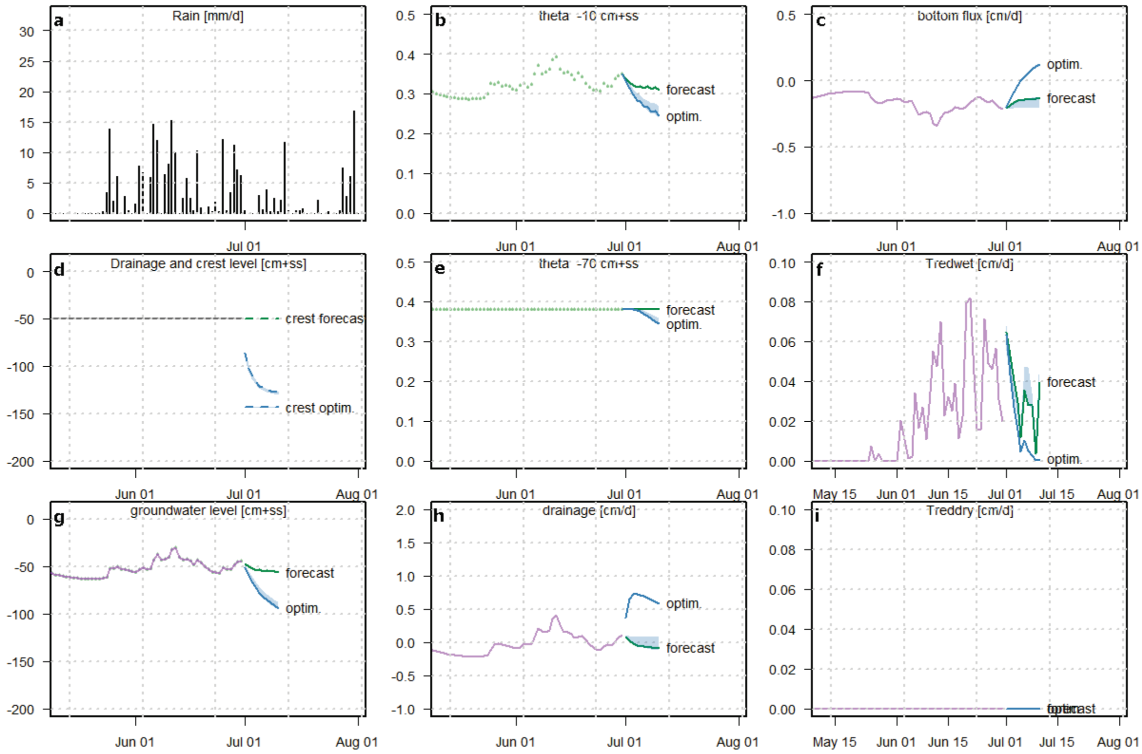

Figure 5: Example of forecast and optimization of the crest level for wet conditions. In order to limit future oxygen stress (f: Tredwet, forecast), the crest level needs to be lowered (d: crest optim.). This will increase the drainage flux (h), lower the groundwater level (g) and soil moisture content (b: theta), and limit oxygen stress (f: Tredwet).

2.5 SPHY - from plot to field and farm

Added value lies in spatial extrapolation of the results of the calibrated SWAP column by using a spatial hydrological model. In this way, it is possible to quantify and forecast the soil moisture conditions at (and beyond) the farm level, and provide a spatial assessment of the effects of a management event. The Spatial Processes in HYdrology (SPHY) model was coupled with the calibrated SWAP model. SPHY is a spatially explicit, grid-based model (Terink et al., 2014; Terink et al., 2015) and is therefore complementary to the 1-D SWAP column. SPHY combines the strengths of existing modeling approaches, resulting in a model that: (i) integrates the most important hydrological processes, (ii) is setup modular in order to switch on/off irrelevant processes and thus decreases model run-time, (iii) is relatively easily adjustable and applicable in an operational decisions support system, (iv) can easily be linked to remotely sensed data, and (v) is in the public domain. In terms of agronomy, SPHY is less detailed than SWAP and does for example not facilitate the simulation of a dynamic root zone depth and variations in root density.

SPHY allows the user to use a dynamic vegetation module based on remote sensing in order to incorporate changing vegetation cover and corresponding rainfall interception and transpiration. The use of remotely sensed NDVI for determining the crop factor (K_c) for evapotranspiration calculations is a proven methodology (e.g. Rafn et al., 2008). Figure 6 is a schematization of all hydrological processes that can be included in SPHY, depending on local conditions. The basic concept consists of a two-layer coupled ‘leaky bucket’ model, below a vegetation layer. Incoming fluxes are rainfall and upward seepage. Outgoing fluxes include evapotranspiration, interception, surface runoff, downward seepage and lateral drainage from the root zone or subsoil. Interaction between the root zone and subsoil can take place through capillary rise or percolation. Soil physical properties are important input to the model as they strongly influence these fluxes. In the current application of SPHY, the focus is mainly on root zone processes (soil moisture content, evapotranspiration) and the groundwater module is thus switched off. A detailed model description can be found in Terink et al. (2015) and at www.sphy.nl.

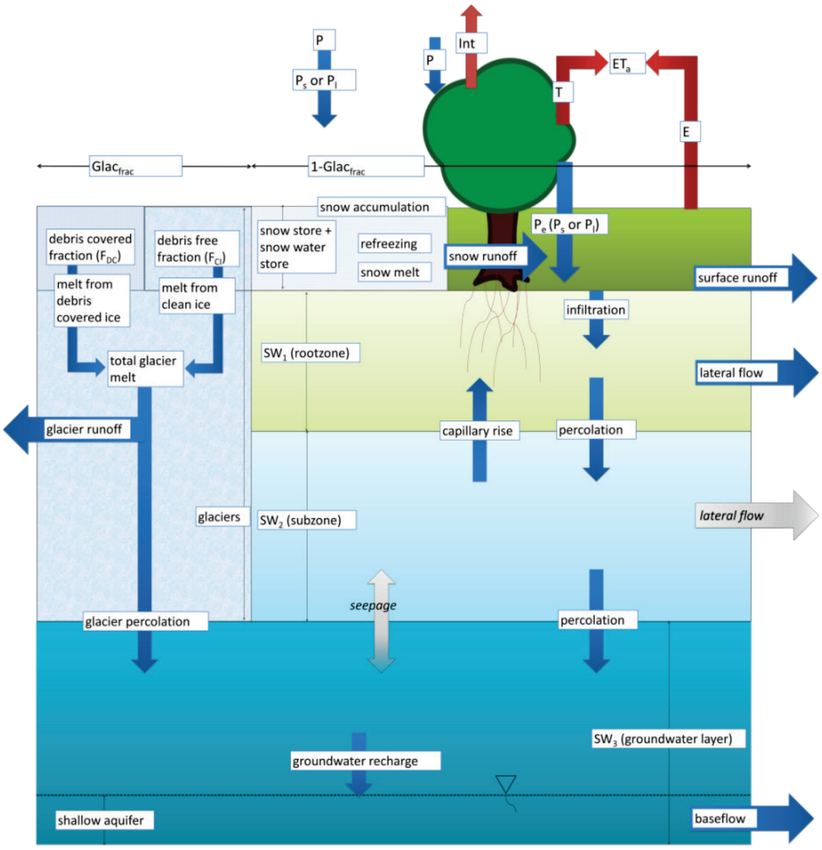

Figure 6: SPHY model concept. Several of these concepts, such as the glacio-hydrological module of the model, are optional and switched off in the current application (www.sphy.nl).

2.6 Application

We demonstrate the potential application of the management algorithm based on two cases.

At first, we applied the optimization routine for both a relatively wet (1998) and dry (2003) year for the Netherlands for a maize crop on a drained sandy soil (drainage resistance of 60d, soil physical properties of soils B1 and O2 taken from Wösten et al. (2001), fixed hydraulic head in deep aquifer = 75cm below soil surface) and compared a situation with dynamic crest control to that with a typical fixed crest of 85 cm below the soil surface (Cultuurtechnische Vereniging, 1988). The dynamic crest control concerns a fictitious modeling exercise, for which SWAP first generates current hydrological conditions given the current crest level. Then future conditions were forecast (Figure 4-II) and the optimal crest level was estimated (Figure 4-III), which were input for the SWAP simulations of the next day. This procedure, which thus only includes and demonstrates the optimization routine and not the calibration and assimilation steps, was repeated for all days within the growing season. We used meteorological data from Rekken and Twenthe stations, the Netherlands, which were provided for by the Royal Netherlands Meteorological Institute (KNMI).

Secondly, we applied the calibration (Figure 4-I) procedure for the CAD experimental field of Haaksbergen, the Netherlands. Continuous measurements were available of groundwater level and CAD drainage level (i.e. level in CAD pit) were available from 2012 onwards.

Continuous measurements of soil moisture conditions during the growing season were available from 16 June 2013 onwards. Rainfall data were obtained from the Rekken KNMI-measurement station, located 15 km from the CAD field. Data on reference evapotranspiration were obtained from the Twenthe KNMI-observatory station, which is located 24 km from the experimental site. From the measured drainage and groundwater levels followed that subsurface-irrigation through the drainage system should have taken place for most of the measurement period. For 2013 this actually was the case as additional water was actively supplied, but we doubt if subsurface-irrigation occurred for 2012 and 2014. Additionally, the soil moisture measurements, generated by six capacitance sensors in the vertical profile, appeared to be disturbed by the relatively high iron content of the soil. Besides, the measurements did not show a severe wet or dry period that resulted in significant plant water stress. Despite our restraint on the validity of our field data and the lack of a significant stress period, the available measurements are still valuable to demonstrate the technical coupling of SWAP and SPHY and to show the principle of the CAD management system.

We used the field measurements from 1 January 2012 to 31 July 2014 consecutively for offline calibration, online calibration and online data assimilation (Figure 4-I). For this procedure, reproducing measured soil moisture conditions was prioritized over groundwater levels, because soil moisture conditions impact more directly on plant functioning. Then, using future 10-day weather forecasts, and a steering event at 1 August 2014, the future hydrological boundary conditions for SPHY were estimated, for the drained fields within the region only. For the non-drained fields, SPHY simulations were based on fluxes from SWAP simulations for a non-drained situation. Soil physical parameters and bottom boundary conditions were independent of drainage and were therefore equal for the drained and non-drained situation. Finally, SPHY was used to estimate the effect of a steering event on the soil moisture conditions in the surrounding drained and non-drained agricultural fields.

SPHY calculations were performed with a spatial resolution of 25 m for the spatial domain as indicated in Figure 7. In addition to the model inputs derived from the calibrated SWAP column, SPHY was supplied with dynamic satellite-derived NDVI obtained from ‘Groenmonitor’ (www.groenmonitor.nl; WUR-Alterra), a base map of long-term averaged groundwater conditions (Waterschap Vechtstromen) and the 1:50,000 soil map of WUR-Alterra. These inputs all influenced the spatial distribution of simulated soil water conditions.

Figure 7: Location of the experimental CAD field (in red), northwest of the town of Haaksbergen. The grey rectangle represents the spatial domain of the SPHY model.

3 Results

3.1 Fixed versus dynamic crest control

Figure 8 shows simulated relative yield for a maize crop for the wet year 1998, for a fictitious situation and for a CAD crest that is fixed to 85 cm below soil surface and for dynamic crest that is established following the management algorithm. The simulations with dynamic crest control include typical management events. At the end of June the crest is lowered to prevent waterlogging, followed by oxygen stress. In August, the crest is raised to prevent unnecessary drainage and thus to retain water in the soil. For this specific example, the dynamic management of the crest level limits the potential yield reduction with ~10%. For the dry year of 2003, these differences are less pronounced (Figure 10), which is a logical result as no excess water that either causes oxygen stress or excessive drainage is input to the system. A drainage level of 85 cm below soil surface seems appropriate for most of the year.

Figure 9 shows the changes in simulated soil moisture and soil oxygen profiles within the root zone for simulations with a dynamic vs. fixed crest. Together with the atmospheric demand for water and oxygen, the availability of soil moisture and soil oxygen determines if the crop suffers from drought or oxygen stress, respectively. It are these stress conditions that we aim to minimize using the dynamic CAD-system. Figure 9 shows the effect of dynamic crest control on the soil water pressure head, the gas filled porosity and oxygen concentration at specific depths. The differences in gas filled porosities and soil oxygen concentrations are especially pronounced at the central part of the root zone.

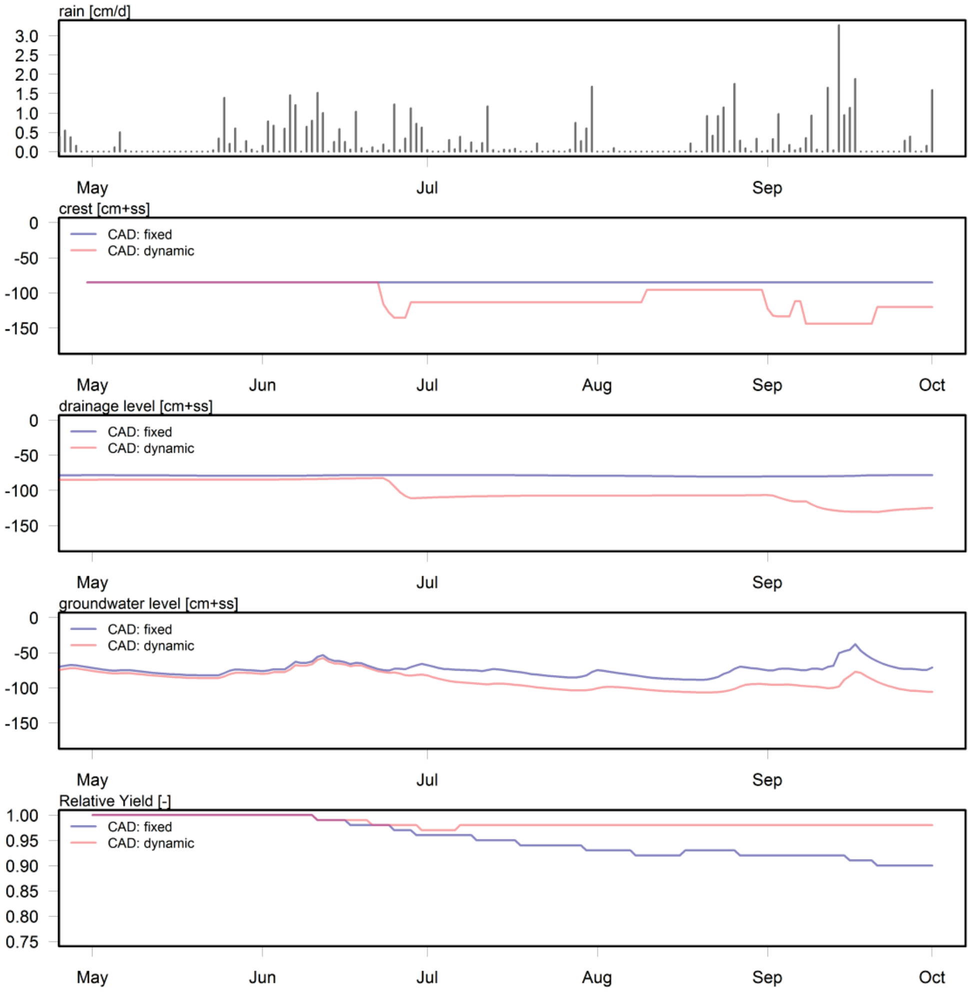

Figure 8: Example simulations for dynamic CAD crest management (red) vs. a fixed crest (blue) for the year 1998 (wet).

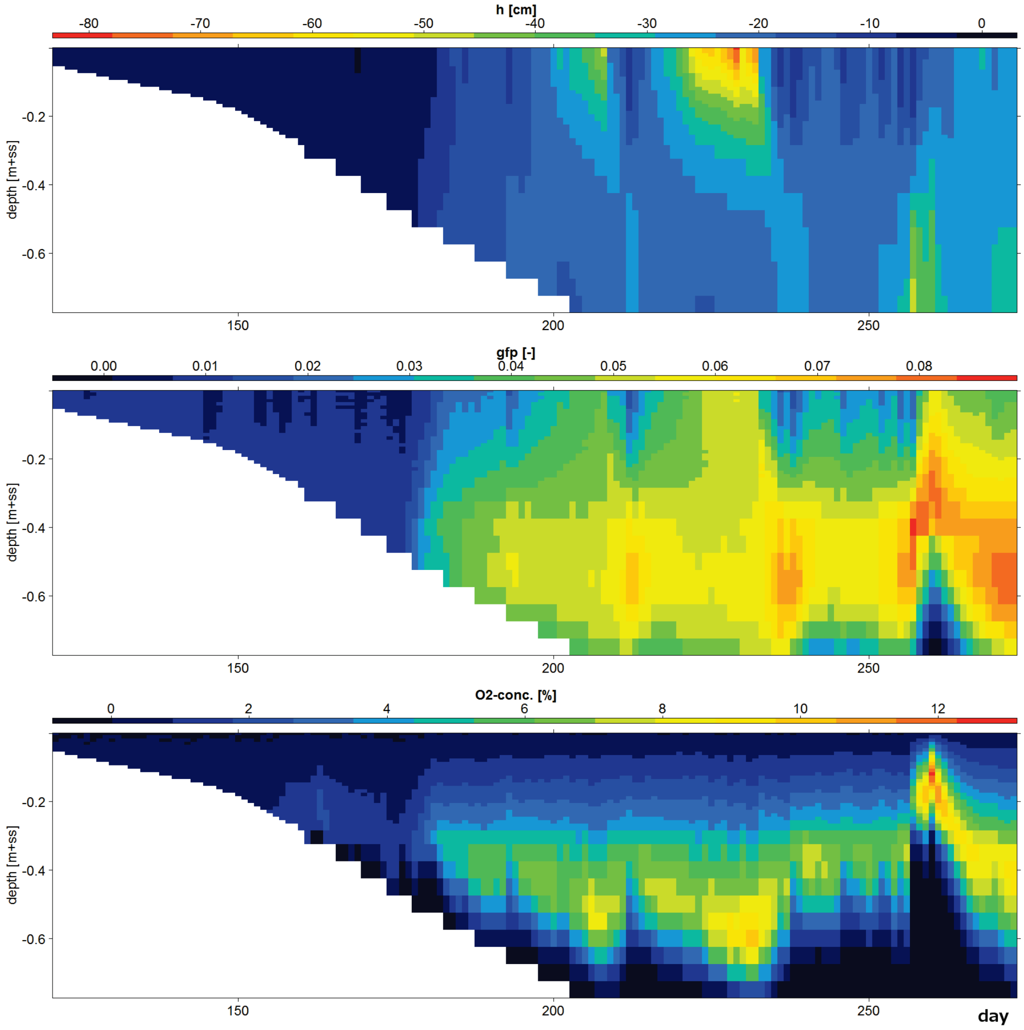

Figure 9: Differences of soil water pressure head (h), gas filled porosity (gfp) and oxygen concentration (O2-conc) in the root zone for the growing season of 1998, for simulations with a fixed and with a dynamic crest (Figure 8). Given values = results dynamic crest – results fixed crest. The root depth increases during the growing season, with a maximum depth of -0.7m+s.s. around day 200; this explains the white area in the figures.

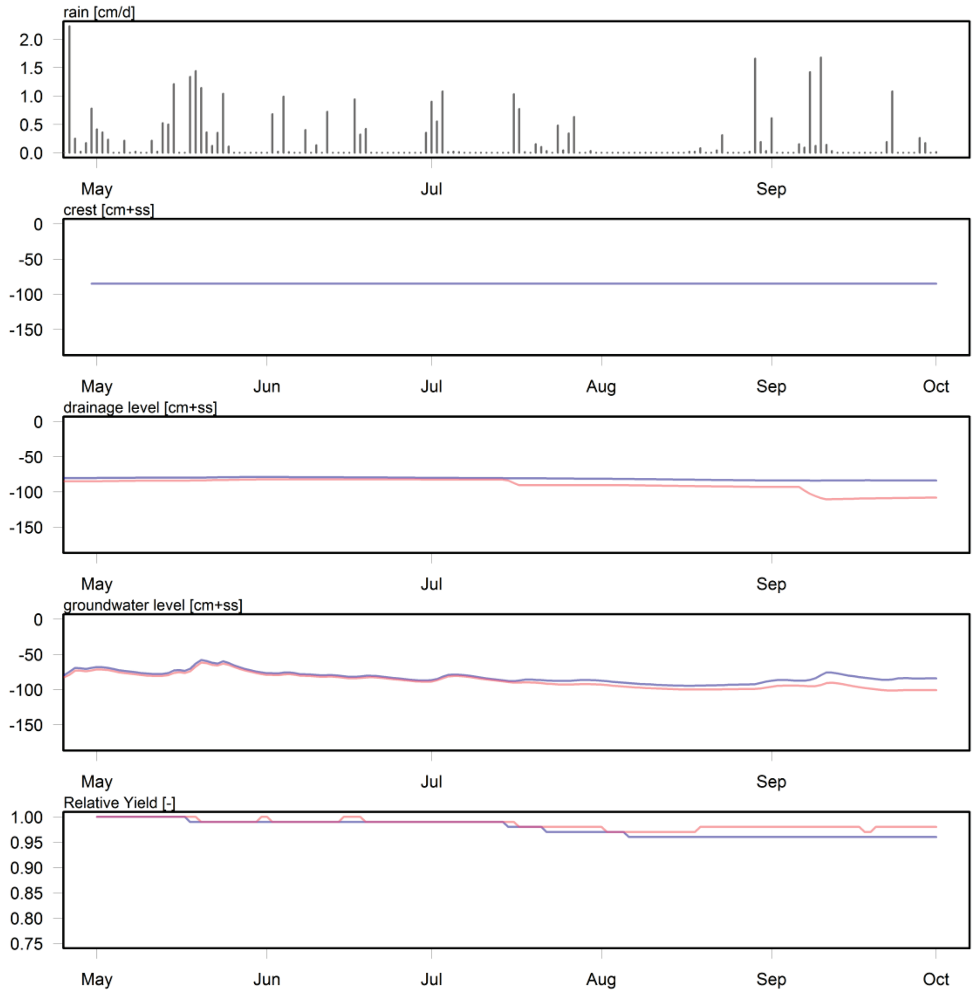

Figure 10: Example simulations for dynamic CAD crest management (red) vs. a fixed crest (blue) for the year 2003 (dry).

3.2 From plot to field-scale

Figure 11 shows the results of the calibration and assimilation steps for the Haaksbergen case. The measured soil moisture content at 70 cm below soil surface is almost constant for 2013, which is unlikely to be true given the variability in groundwater levels.

The results between offline and online calibration hardly differ, which indicates that the hydraulic head from the deep aquifer of the last 31 days (online calibration period) is close to the long term average hydraulic head: h = 123 and 127 cm below soil surface, for offline and online calibration respectively. Overall, the calibrated SWAP model (Figure 4-I) is able to reproduce measured groundwater levels and soil moisture contents well, i.e. the model properly mimics the behavior of the system. This is a prerequisite for reliable model forecasts (Figure 4-II).

Figure 12 shows the simulated future groundwater levels, soil moisture conditions and plant stresses for a range of crest levels, obtained from the uncertainty runs. The blue areas give the range of recommended crest levels, groundwater level, soil moisture content, drainage flux and oxygen stress for multiple realizations of future precipitation.

To demonstrate upscaling of model calibration on plot scale to regional scale, i.e. for the coupling of SWAP to SPHY, fluxes (bottom flux, drainage flux) are transferred from SWAP (Figure 11) to SPHY

Table 1 provides the simulated soil moisture condition and evapotranspiration for the same grid cell (located in the center of the CAD field) from both SWAP and SPHY. The values show that, despite the differences between the two models, root zone soil moisture and actual evapotranspiration are well reproduced by SPHY for this location. The spatially extrapolated results are therefore expected to be consistent with the calibrated SWAP column.

Figure 13 displays the total actual evapotranspiration E computed by SPHY for the Haaksbergen CAD field and its surroundings during the growing season of the year 2013 (May 1 – October 31). Field boundaries are often clearly visible, signifying crop type or farm management differences between fields. However, the figure shows that the 25 m spatial resolution is also sufficient to view differences in actual evapotranspiration within individual fields (during the growing season closely linked to crop production).

Table 1: Comparison SWAP vs. SPHY for simulated soil moisture content in the root zone and actual evapotranspiration E.

	SWAP			SPHY		
	2012	2013	Jan – Aug 2014	2012	2013	Jan – Aug 2014
average soil moisture content in root zone [-]	0.257	0.271	0.274	0.280	0.277	0.285
E [mm]	432	423.3	268.5	427	423.6	278.5

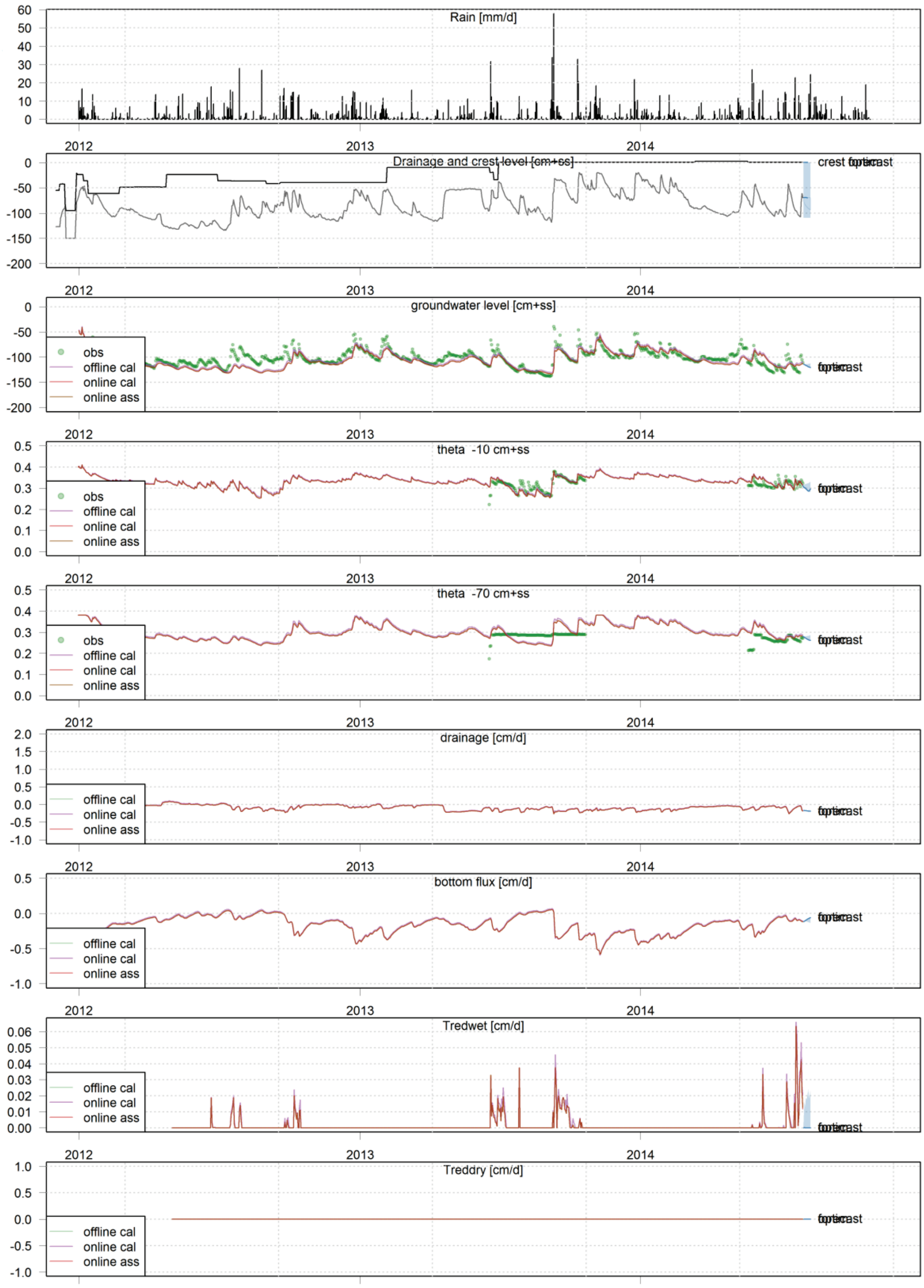

Figure 11: Example of measured and simulated (after calibration and assimilation) groundwater levels and soil moisture conditions, and simulated plant stresses for the Haaksbergen CAD test site. Please note that for this example, calibration and assimilation runs provide almost similar results (lines overlap). Theta = soil moisture content, Tredwet = transpiration reduction due to oxygen stress, Treddry = transpiration reduction due to drought stress. See also Figure 12, which zooms in on the 10-day forecast and optimization runs.

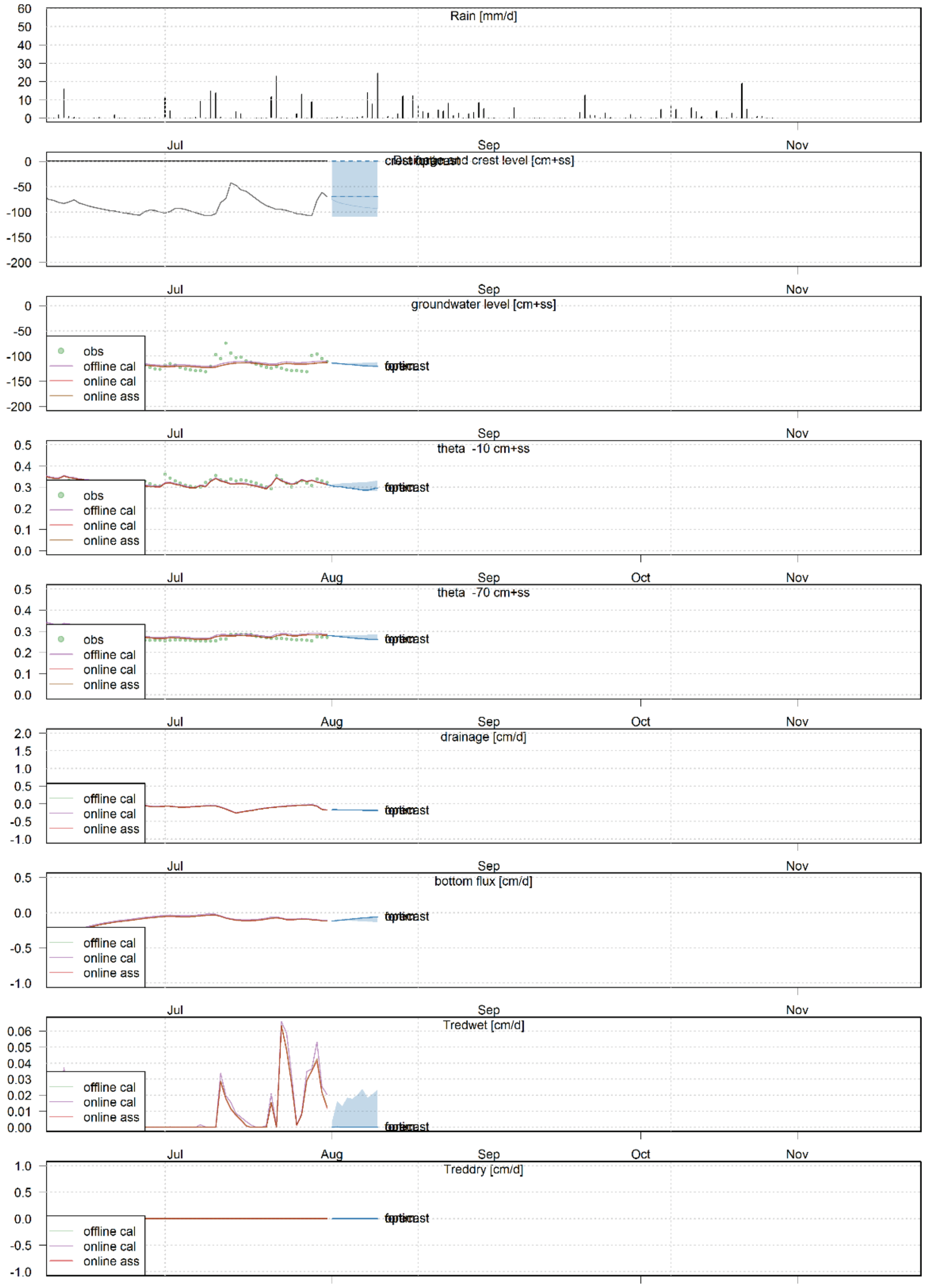

Figure 12: Same as Figure 11, but with different time scale (horizontal axis). Note that for the given weather forecast, the predicted and optimized crest level are the same (therefore the text labels overlap in the figures). For the uncertainty runs, forecast values and optimized values may differ (blue areas).

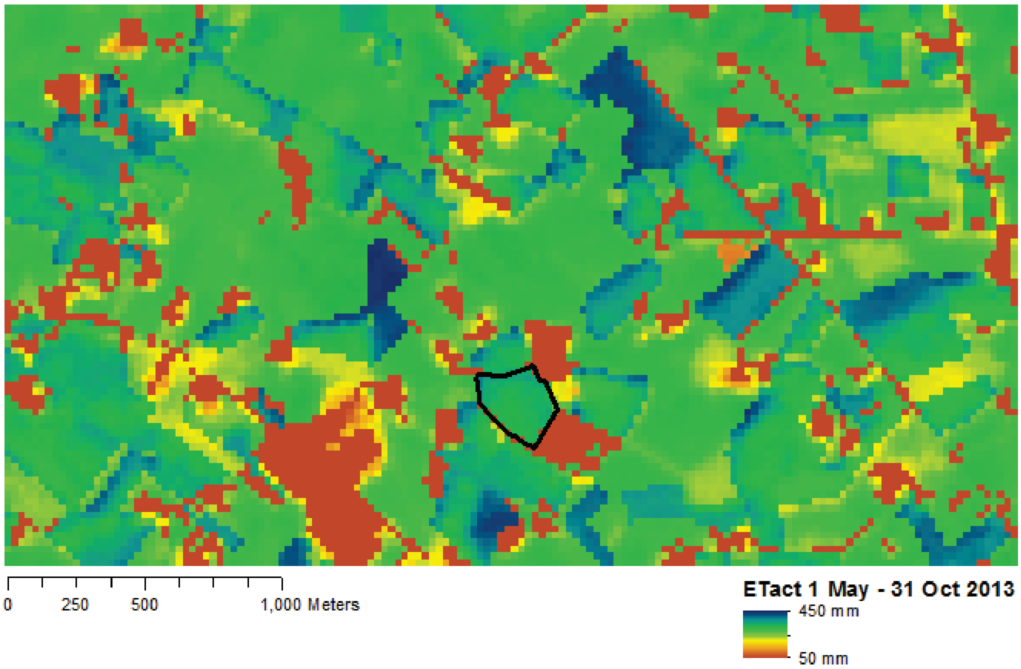

Figure 13: Cumulative regional E computed by SPHY for the maize growing season 2013 (1 May – 31 October). The Haaksbergen CAD test site is indicated by the black-coloured line.

During the period from July 7, 2013 until July 20, 2013, there was no rainfall. Therefore the model computes a steady decline of root zone soil moisture storage for these two weeks. However, development of the maize crop was at an advanced stage as indicated by measured NDVI values of around 0.7 (Figure 14), close to their peak values two weeks later.

The combination of high crop water requirements and no rainfall means that this is a typical period in which a crop could start experiencing drought stress. The effect of soil moisture retention by the CAD system is evidenced by the difference in root zone water content between the CAD field and a reference maize field nearby with a similar cropping cycle (NDVI profile), but without a CAD system implemented. Figure 15 shows how root zone soil moisture content diverges during the 14-day period for a location in the middle of both fields. A spatial map of regional root zone soil moisture content on July 20 2013, is also provided. The sharp division in root zone soil moisture content within the CAD field is caused by differing soil types.

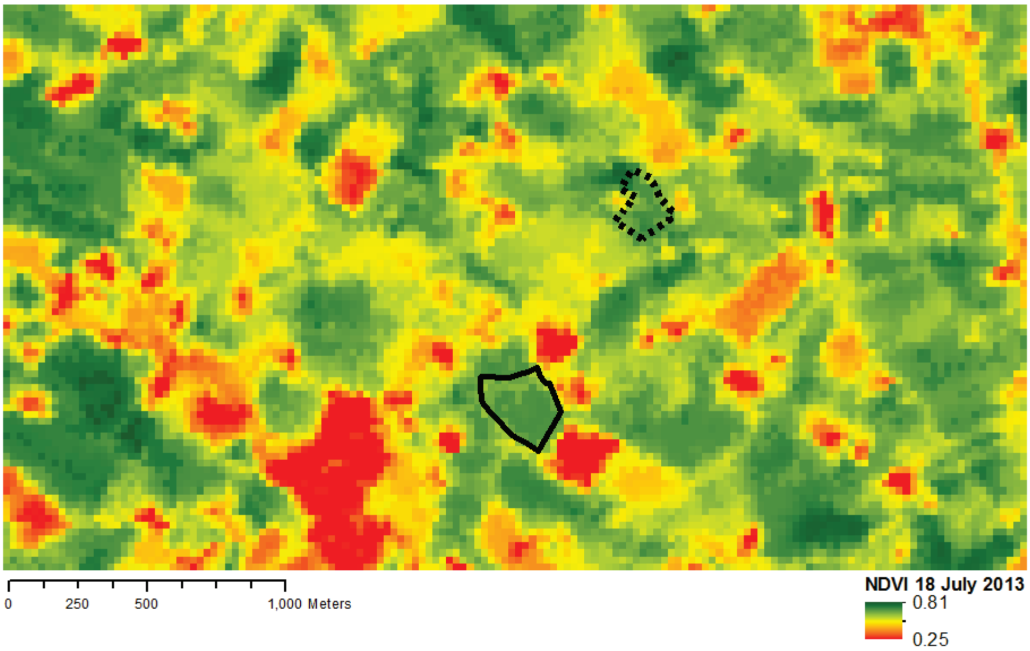

Figure 14: Regional-scale high-resolution NDVI on July 18, 2013. Locations of the CAD field and reference field without CAD are indicated on the map by the solid and dashed black lines respectively.

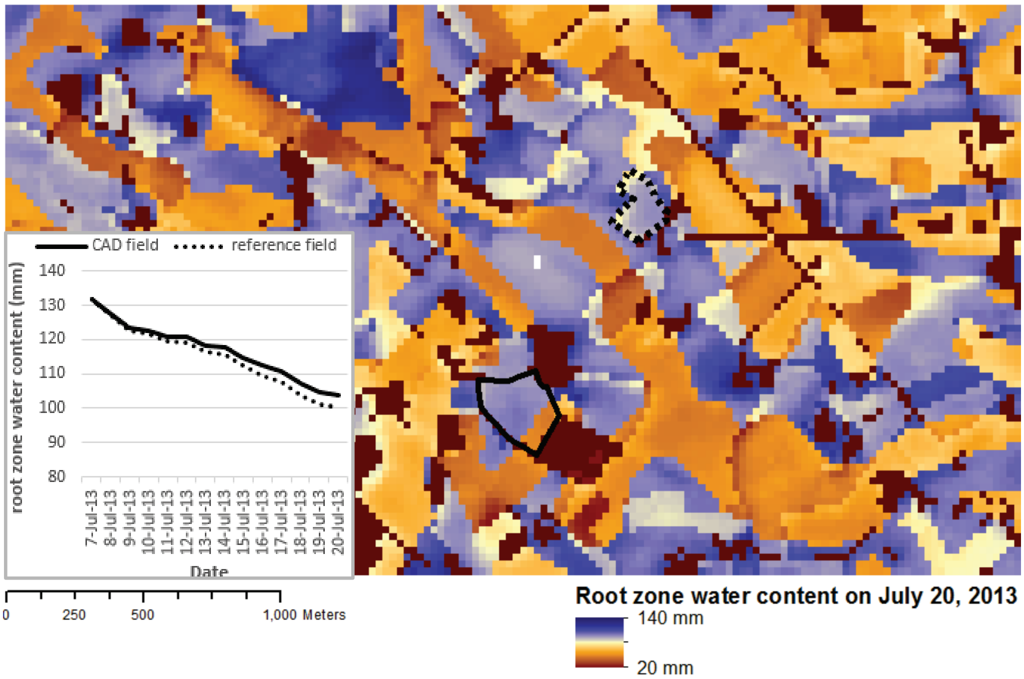

Figure 15: Spatial and temporal visualization of differences in root zone soil water content between the Haaksbergen CAD test site and a reference maize field without CAD. Locations of the CAD field and reference field are indicated on the map by the solid and dashed black lines respectively.

4 Discussion and conclusions

In this project we developed a management algorithm for the CAD Climate Adaptive Drainage system (CAD-MA). It is important to anticipate on the climate-change-induced more extreme dry and wet conditions that impact on crop growth and agricultural yield. Technically advanced controlled drainage systems like CAD allow for anticipative water management. CAD has been shown to work well in practice since autumn 2010. The possibility to actively regulate the soil moisture conditions in the root zone with CAD depends mainly on the drainage resistance of the system, since this variable determines how quickly groundwater levels respond to changes in drainage level.

Local-scale measurements on soil moisture and groundwater level are needed to provide information to successfully control the CAD-system. Our process-based CAD Management Algorithm (CAD-MA), focusing on optimal soil moisture conditions for crop growth has been set up. It potentially supports the farmer with decision support information on controlled drainage, if preferred automatically controlled. CAD-MA can be used for water supply management as well, by sprinkler or subsurface irrigation.

Our initial simulations of online management with dynamic drainage crest control gave good results, which are more pronounced in terms of optimal crop growth during a wet year as compared to a dry year. The link of the plot model SWAP to the grid-based spatial hydrological model SPHY facilitates an assessment of spatial dynamics of soil moisture and associated implications for management at the farm and regional scale. Using local-scale measurements, process-based models and weather forecasts to anticipate on near-future conditions, not only field-scale water management but also regional surface water management can be optimized, both in space and time. This benefits both farmers as well as regional water authorities.

Plot-scale measurements for field and regional scale applications are needed for CAD control. Correct, accurate, and a sufficient amount of data at suitable locations at the field site are important sources of information to successfully apply the algorithm presented here. However, these data generally introduce noise due to spatial and temporal variations in state variables. This potentially impacts the overall results in a negative way, and is therefore an important issue when setting up the field monitoring network. With respect to field data:

- We used off-site meteorological data for this project, but we should move towards local data and/or calibrated radar data on rainfall (KNMI).
- The soil moisture probes used here are based on capacitance measurements. These seemed to fail in case sensors were located in iron-rich soil layers. Unfortunately, inaccurate measurements of soil moisture contents limit the actual application of the management algorithm.
- SPHY is able to transform remote sensing information on soil moisture and evapotranspiration to improve farm- and regional-scale analysis. Technically, soil moisture data at the regional scale by remote sensing might not yet be reliable and detailed enough for online control.

With respect to further development of CAD and the management system we would like to add the following:

- Remote control of CAD is already possible: the next step is to bring the management system into full operation, with actual online management and monitoring of soil water and crop.
- Move from local-scale to regional-scale optimization procedure.
- Enhance the use of remote sensing information, e.g. by UAV (precision agriculture).
- Accurate measurements of soil moisture are important as these impact on the plant growth and soil moisture is the most important field state variable that is used for the CAD management algorithm. We could include the effect of uncertainties of field measurements on the recommended CAD crest settings.
- We included uncertainty in future rainfall data only. The system may benefit of a more advanced approach to take uncertainties in weather forecasts into account.
- Assess the implications of online drainage control in practice for:
    - individual farmer and groups of farmers;
    - regional water authorities.
- Most studies on controlled drainage focus on water quality. Therefore it may be interesting to incorporate soil water chemistry and agro-chemical emission control into management and control.
- Implement management of subsurface irrigation (Tan et al., 2002).

We made an important step towards a more anticipative water management: automated crest management of the Climate Adaptive Drainage (CAD) system, allows to anticipate on climate-induced amplifying soil moisture conditions. With opportunities to increase agricultural crop yield by 10%, our system proves to be an interesting investment for farmers or farmer in cooperation with regional water authorities.

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Appendix: Manual CAD-MA – Climate Adaptive Drainage- Management Algorithm

General

Within the TKI-project Groundwater for Crops, we developed a tool which calculates the recommended crest level of the Climate Adaptive Drainage system, using daily meteorological forecasts for the future 10 days (or any other). In this appendix we describe the setup of this Decision Support System (DSS).

The DSS focusses on anticipatory water management at the field scale, i.e. the unit scale of interest to a farmer. We combine parallel field measurements ('observe'), process-based model simulations ('predict'), and the Climate Adaptive Drainage system (CAD) ('adjust') to optimize soil moisture conditions. The DSS has a core of the field-scale SWAP model (Soil-Water-Atmosphere-Plant), extended with a module for the simulation of oxygen stress for plant roots. Continuous measurements of soil moisture content, groundwater level and drainage level are used to calibrate the SWAP-model each day and to optimally reproduce the actual soil moisture conditions by data assimilation in the first step (Figure 4- I). During the next step, near-future (+10 days) soil moisture conditions and drought and oxygen stress are predicted (Figure 4- II). Finally, optimal drainage levels to minimize stress are simulated, which can be established by CAD (Figure 4 - III). This process is visualized in Figure 4.

Input

The DSS has been programmed within the open source statistical software R (R Core Team, 2013). Within this framework, input files for SWAP and PEST are automatically generated and model runs are automatically invoked. The user only has to provide input values and files in a separate screen (Figure 16). Example input files are provided with the system and consists of measured drainage, crest and groundwater levels, soil moisture contents and locally measured precipitation data. Moreover input files for the SWAP-simulations should be provided (*.swp, *.dra and *.crp). Generation of these files, and the variable ranges for the PEST-optimization, requires specialist knowledge.

Each R routine has been programmed such that the *.swp and *.dra files of SWAP are automatically made suitable for PEST. PEST is run from the R-scripts. Common installation of PEST is required (including adding PEST to the system path).

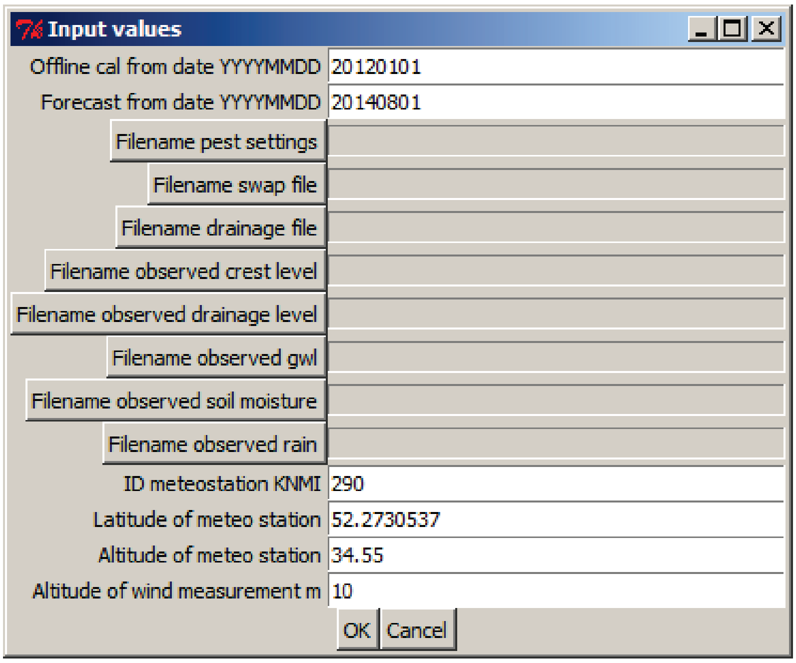

Figure 16: Start screen for the optimization tool, where input values and files should be provided.

Table 2: Description and user instructions for input files used in the optimization routine

File	Description	Instructions for file set up and possible changes
pest settings (*.xlsx)	Main input file for the PEST settings	The 'parameters'-tab contains the hydrological and soil physical SWAP-variables that will be optimized during calibration (Figure 4-I). Only the values in columns PARVAL1 (first estimate of parameter value) and PARLBND and PARUBND (parameter values lower and upper bound, respectively) should be adjusted to the specific case studied. Some parameters are 'tied', which means that they are linked to another parameter. During the calibration process, only the latter parameter is adjusted while the ratio with the tied parameters remains the same. To reduce the number of parameters during optimization, K0 (KSAT in the *.swp file) of the lower layer is tied to that of the top layer (following Visser et al. (2006)) and the also Ksat (KSAT_EXM in the *.swp file) values of the top and lower layer are tied to that variable. Additionally, the infiltration resistance (RINFI) is tied to the drainage resistance (RDRAIN).
observed crest levels (*.dat)	Measured crest levels	Provide measured crest levels (cm+reference level) in the following format: Date;LEVEL 02-Dec-2011;-55.5 03-Dec-2011;-55.5
observed drainage levels (*.dat)	Measured drainage levels	Provide measured drainage levels (cm+reference level) in the following format: Date;LEVEL1

		02-Jun-2014;-55.5 03-Jun-2014;-55.5 etc.
observed gwl (*.dat)	Measured groundwater levels	Provide measured groundwater levels (cm+reference level) in the following format: Date;Gwl 02-Jun-2014;-55.5 03-Jun-2014;-55.5 etc.
observed soil moisture (*.dat)	Measured soil moisture contents	Provide measured soil moisture contents (0-1 [-]) and depth (cm+reference level) in the following format: Date;Depth;Theta 02-Jun-2014;-10;0.223 02-Jun-2014;-70;0.175 03-Jun-2014;-10;0.265 03-Jun-2014;-70;0.234 etc.
observed rain (*.dat)	Measured precipitation depths	Provide measured precipitation [mm/d] in the following format: DD;MM;YYYY;rain;wet 18;06;2013;1;0.083 19;06;2013;2.6;0.042 (use of measured precipitation is currently disabled)

Calibration procedure (Figure 4-I)

In order to improve the forecasts, we follow the method of (Visser et al., 2006), combining offline calibration, online calibration and online assimilation to provide i) optimal model parameters and ii) initial soil moisture profiles for the forecast that are physically consistent and approximate/match the observations at t0. Citing Visser et al. (2006): *"Observations of meteorological input (precipitation and evapotranspiration) are used to advance the model to the current day, i.e. to reconstruct the state (groundwater level and soil moisture profile) at the current day as accurately as possible. Next, weather forecasts are used as input to the model, such that with the current predicted state as initial condition, the state is forecasted for the coming days."*

The calibration procedure follows three consecutive steps:

1. Offline calibration:
   - Estimate soil physical properties (Van Genuchten parameters n and α, and K_0 and K_{sat} (Table 3)
   - Estimate drainage resistance
2. Online calibration
   - Estimate actual hydraulic head in deep aquifer; required to capture seasonality
   - based on last 31 days, following Visser et al. (2006)
   - Equal weight to all observations in these days
3. Online assimilation
   - Get best (i.e. matching observations and physical consistent) initial soil moisture state values for forecast
   - Only weight to last observation, i.e. only last observation is used for calibration

Table 3 gives the SWAP parameters that are optimized for each calibration or assimilation run.

Table 3: Parameters optimized and used during each of the calibration steps, and parameters used for the prediction and optimization step. 'X' indicates that a parameter is optimized in the specific calibration step; numbers refer to the calibration/assimilation step from which the parameter value is taken.

Parameter	Description	1. Offline calibration	2. Online calibration	3. Online assimilation	4. Forecast and optimization
AQAVE	Average hydraulic head in underlaying aquifer [cm]	**X**	**X**	**X**	**2.**
K0 top layer	Saturated vertical hydraulic conductivity (fitted) [cm/d] (KSAT in *.swp)	**X**	1.	1.	1.
K0 sub layer	Idem	**X ('tied' to K0 top)**	1.	1.	1.
Ksat top layer	Saturated vertical hydraulic conductivity (measured) [cm/d] (KSATEXM in *.swp)	**X ('tied' to K0 top)**	1.	1.	1.
Ksat sub layer	Idem	**X ('tied' to K0 top)**	1.	1.	1.
Alfa top layer	Van Genuchten Shape parameter alfa of main drying curve [1/cm]	**X**	1.	1.	1.
Alfa sub layer	Idem	**X**	1.	1.	1.
Npar top layer	Van Genuchten shape parameter n [-]	**X**	1.	1.	1.
Npar sub layer	Idem	**X**	1.	1.	1.
DRARES	Drainage resistance [d]	**X**	1.	1.	1.
INFRES	Infiltration resistance [d]	**X ('tied' to DRARES)**	1.	1.	1.
Initial soil moisture profile, i.e. soil moisture contents for each SWAP-layer					**3.**

Forecast and optimization

During the calibration steps, measured drainage levels are input. In forecast mode, drainage levels are simulated based on a given crest level (extended drainage option in SWAP). Based on the initial soil moisture conditions of the assimilation step, 10-day weather forecasts (temperature, reference evaporation and precipitation), and crop characteristics of the current day, future conditions are simulated. Note that if there is no crop present at the previous day, forecasts cannot be done (in the current version of the algorithm, crop conditions for the forecast are taken from the previous SWAP run).

Based on the simulated soil moisture conditions for the forecast, the optimization routine is invoked to determine the optimal crest level of the CAD pit. This optimal or recommended crest level depends on:

1. prevention of oxygen stress (Tredwet) → lower crest to loose water
2. no oxygen stress and cumulative drainage is larger than zero → higher crest to retain water
3. no oxygen stress and no water loss through drainage → do nothing, keep current level

In the subroutine forecast.R SWAP is run with the crest level of t0 and the meteorological forecast of the next *n* (max 10) days. The crop conditions for t1-t10 are equal to those at t0, i.e. there is no crop development with the next *n* days. Based on the simulated oxygen stress in the next *n* days a weighted cumulative oxygen stress is calculated, for which Tredwet_t1 has a higher weight than Tredwet_t10. A sigmoid weight function is used (Figure 17). The weighted cumulative stress equals ΣTredwet(t_n)*Weight(t_n). We assume a lower cumulative stress limit that is acceptable, determined as a fraction of the weighted cumulative potential transpiration T_{pot}: T_{red_accept} = fraction * ΣT_{pot}(t_n)*Weight(t_n). T_{red_accept} has a minimum value of 0.001 cm.

The same procedure is used to calculate the weighted cumulative positive drainage = Σdrainage(t_n)*Weight(t_n) with drainage> 0 (i.e. no infiltration).

Then, for the prevention of oxygen stress (Ad 1; Figure 18 and Figure 20), the crest level is iteratively lowered until the difference between the stress at the lowest possible crest level and the stress at the adjusted level is negligible, which is either a small absolute or relative difference, or lower than the calculated accepted value (T_{red_accept}). The lowest possible crest level is a fixed value.

To limit unnecessary drainage (Ad 2; Figure 19 and Figure 21), the crest level is iteratively raised until the drainage flux is minimal. If in the next *n* days the oxygen stress is lower than the accepted limit, and the cumulative drainage flux is larger than zero, the crest level will be raised until either the difference with the drainage flux at the highest crest level is very small, or the drainage flux is lower than a predefined fixed accepted value.

It is possible to define a water supply rate by defining WSCAP in SWAP_PEST.R.

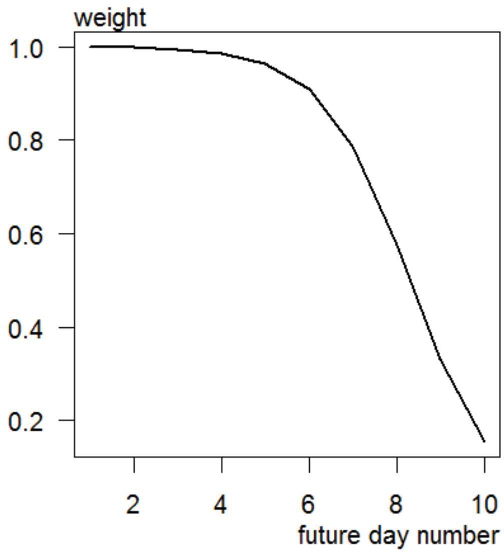

Figure 17: Weight function used in the calculation of the weighted cumulative potential transpiration and weighted cumulative drainage. The shape of the function can easily be altered in R_swap_pest.R. With the given sigmoid function, the forecast conditions for 10 days in the future, get a lower weight in the optimization scheme than conditions of the next day.

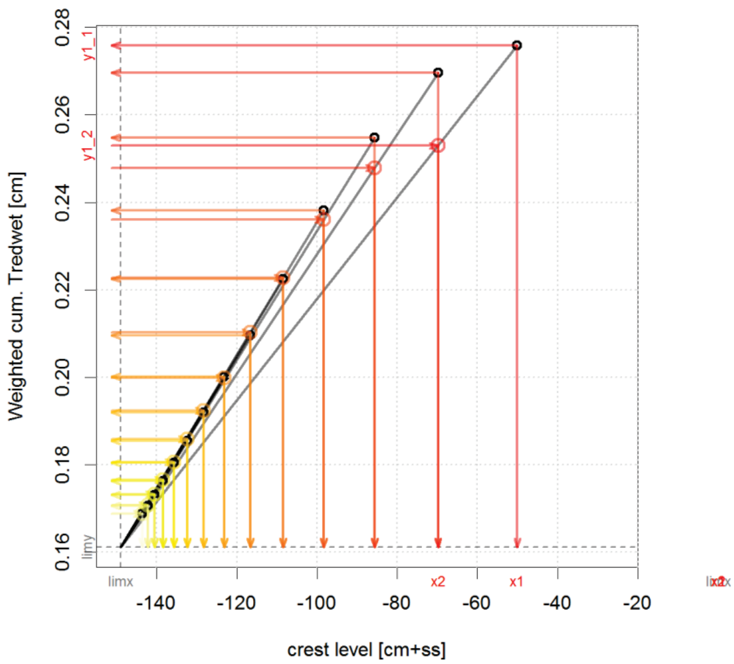

*Figure 18: Optimization routine, if Σweighted Tredwet > limit. First, the lowest possible stress level (limy, see y-axis) is calculated, by running SWAP with the lowest possible crest level (limx, see x-axis). Then, the next crest level is derived by i) calculate y-value by a fraction of the difference between y1_1 (the current weighted cumulative Tredwet) and limy: y1_2 = limy + factor*abs(y1_1-limy)), ii) calculate next x value from a linear relationship between (x1,y1_1) and (x2, y1_2), iii) run swap with this x value, which gives a new yn_1 value. This procedure is repeated until: abs(y1_1-limy)<1e-3 (i.e. very small absolute difference) or abs(y1_1-limy)<=myfactor2*limy (i.e. very small relative difference with lowest possible value) or y1_1<=limy.accept (i.e. very small difference with accepted value) or (x1_2<minx) or (x1_2>maxx)) (i.e. next estimate of crest level below lowest or above highest possible crest level) or nrow(it.out)>100 (i.e. too many iterations)*

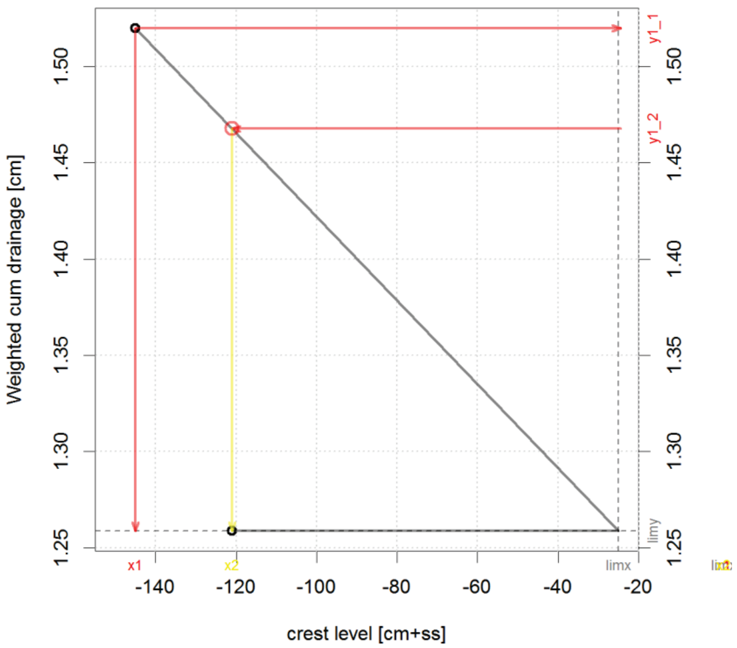

*Figure 19: Optimization routine, if Σweighted positive Drainage > limit. First, the drainage flux (limy, see y-axis) at the highest possible crest level (limx, see x-axis) is calculated with SWAP. Then, the next crest level is derived by i) calculate y-value by a fraction of the difference between y1_1 (the current weighted cumulative drainage) and limy: y1_2 = limy + factor*abs(y1_1-limy)), ii) calculate next x value from a linear relationship between (x1,y1_1) and (x2, y(1_2), iii) run swap with this x value, which gives a new yn_1 value. This procedure is repeated until: abs(y1_1-limy)<= factor*abs(limy) (i.e. very small relative difference with lowest possible value) or abs(y1_1) <= abs(limy.accept)) (i.e. smaller than accepted value) or sum(str.out[,"Tredwet"]*myweights)>Tredwet.cum.accept (i.e. weighted cumulative Tredwet larger than accepted weighted value or (x1_2<minx) or (x1_2>maxx)) (i.e. next estimate of crest level below lowest or above highest possible crest level) or nrow(it.out)>100 (i.e. too many iterations).*

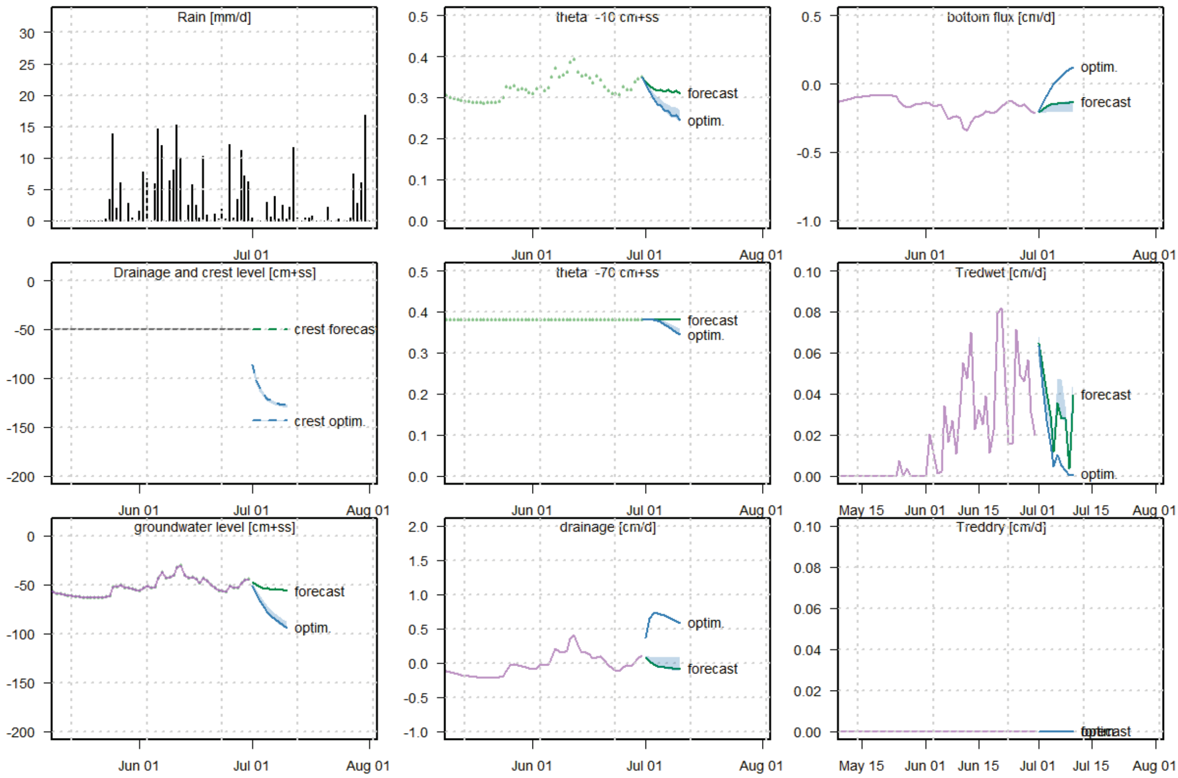

Figure 20: Example of forecast and optimization of the crest level for wet conditions. In order to limit future oxygen stress (Tredwet, forecast), the crest level needs to be lowered (crest optim., see also Figure 18). This will increase the drainage flux, lower the groundwater level and soil moisture contents (theta), and limit Tredwet..

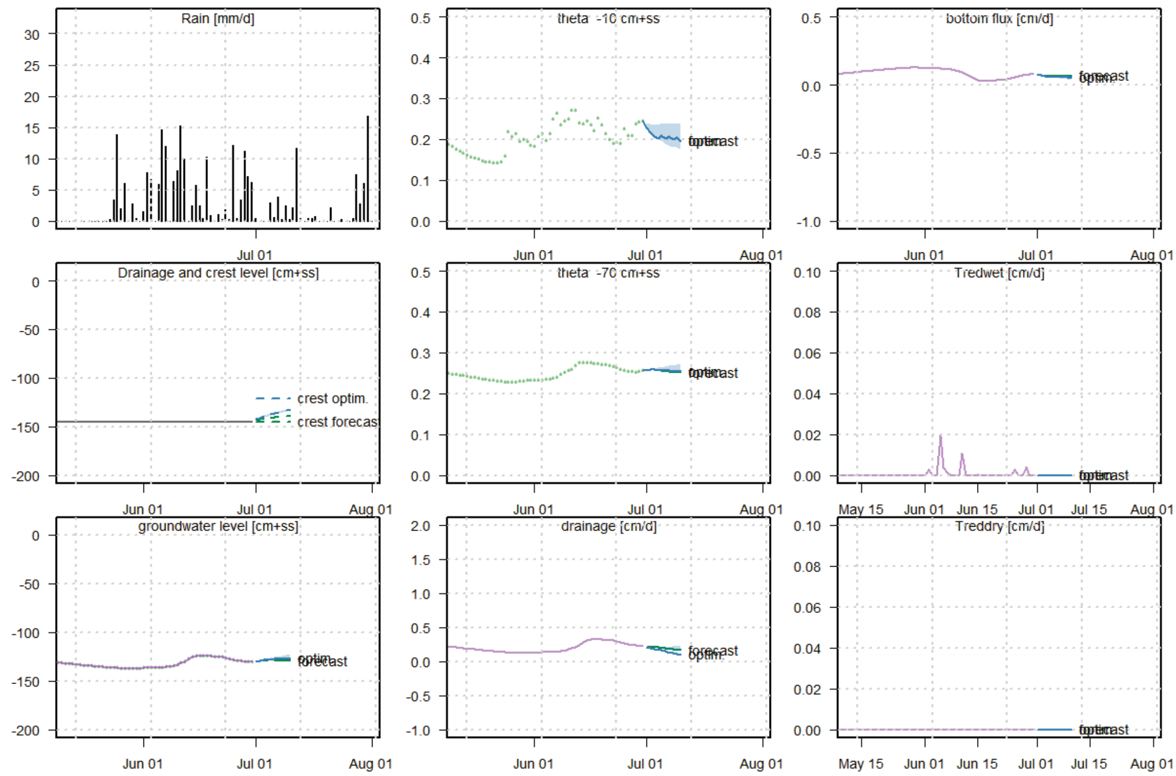

Figure 21: Example of forecast and optimization of the crest level for conditions with superfluous drainage. In order to limit the future drainage flux (forecast), the crest level needs to be increased (crest optim., see also Figure 21).

File description of CAD-MA

name	description
R_swap_pest.R	MAIN FILE: - provide minimum and maximum crest level, surface water supply capacity (can be improved in next version) - call routines for calibration, assimilation, forecast and optimization
runmeteo.cmd	call meteo.exe
runswap.cmd	call executable to run swap with specific *.swp file
runswap_forecast.cmd	idem
runswap_init.cmd	idem
runswap_optim.cmd	idem
meteo.exe	executable to generate swap meteo files
swap.exe	swap executable
ETrefcalcs_functions_data_TKIKAD.R	calculate meteorological variables, including reference evaporation according to Makkink and Penman-Monteith
forecast.R	prepare forecast files and run forecast
get_param_offlcal.R	get optimized parameters from offline calibration; used as input for next calibration run
initial_swap_run.R	prepare swap files and execute initial swap run
load packages.R	load R packages
makepestcontrol.R	make pest control file
meteo_forecast.R	make meteo files for foreast
offline_calibration.R	run offline calibration
online_calibration.R	run online calibration
online_dataassimilation.R	run online data assimilation
optimization_20141008.R	run optimization
plot_results.R	plot results
R_swap_pest_fileprep.R	read input files and move relevant files to simulations folder (automatically generated)
R_swap_pest_functions.R	definition of specific R functions
readexcel.R	read input data from excel file
store_results.R	store results in matrix