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Development and test of usability of an operational crop growth system for farmers

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TKI Farmers'App (final report)

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11202523-000

Title

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Client	Project	Attribute	Pages
Centraal Beheer Achmea, APELDOORN Waterschap Aa en Maas, 'S-HERTOGENBOSCH Waterschap Vechtstromen, COEVORDEN	11202523-000	11202523-000-BGS-0013	87

Keywords

Real-time forecasting, soil moisture, groundwater, crop production, data assimilation, remote sensing, Delft-FEWS, MetaSWAP, WOFOST, iMOD.

Summary

The goal of this project was to demonstrate the possibility to develop a real-time forecasting system for crop production, enabling water boards, farmers and the insurance broker to improve their services and possibly reduce costs. The setup of both the Aa & Maas and Vechtstromen models within the “Grow with the Flow” operational system shows promising initial results. The value of the system was demonstrated by comparing model results with measurements in the field during the growing season. We successfully finalized the system and demonstrated the possibilities of application for a wet (2016), ‘normal’ (2017), and dry (2018) season.

This project was executed with funding from the TKI-programme and contributions by Achmea (Agro), Deltares, and the water boards Aa & Maas and Vechtstromen. Wageningen Environmental Research and Milan Innovincy contributed to the project as subcontractors.

Results out of this project are:

- Despite a number of data services, farmers have a need for system that can transform multiple data sources (including monitoring data and model results) into information. With this information, farmers can optimize their processes.
- Several domains have been identified where integrated information from multiple sources can add value for farmers in taking business decisions.
- The connection between the coupled iMODFLOW-MetaSWAP-WOFOST models and Delft-FEWS provides a realistic historical simulation of daily output based on observed meteorological data, as well as the forecasting of a number of hydrological and crop growth parameters.
- The model results for both soil moisture and groundwater levels for the Aa & Maas pilot area provide a good indication of trends at most of the locations. For the Vechtstromen model, however, some locations are either too wet or too dry.

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References
To refer to this report please use the following description:

Snippen, E. (et al), Development and test of usability of an operational crop growth system for farmers – Farmers App (Final report), February 2019. Deltares, The Netherlands.

Version	Date	Authors	Initials	Review	Initials	Approval	Initials
	May 2019	E. Snippen		P. Ker Rault		H. van der Klis	

Status
final

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Appendices

1 Introduction

By combining the latest technological developments in the field of ICT, hydrological models, crop models and satellites, it is possible to develop a real-time forecasting system for crop production, enabling water boards, farmers and the insurance broker to improve their services and possibly reduce costs.

Therefore, a joint project proposal was made by the following project partners: Achmea (Agro), Deltares and the water boards Aa & Maas and Vechtstromen. Wageningen Environmental Research and Milan Innovincy were also involved in the project as subcontractors. During the project, it was renamed to: Grow with the Flow (GwtF).

1.1 Scope of the project

The aim of the project was to:

- Set-up a real-time hydrogeological and crop modelling forecasting system that feeds the Farmers' App with relevant groundwater, soil moisture and crop production data using a coupled model;
- Compare the model results for historical runs to measured data to test them for practicality;
- Test the usability of these data with the pilot farmers and the water boards involved; and
- Test the usefulness of these data for the determination and tracking of crop damage.

We calculated the available soil moisture and crop yield with a 100 m x 100 m resolution using the coupled iMODFLOW-MetaSWAP-WOFOST model for the 2016, 2017, and 2018 growing seasons. The pilot areas were determined together with Achmea and the two water boards involved in this project. For the Aa & Maas area, the pilot area of the Raam was selected; for the Vechtstromen area, the upstream catchment of the Vecht area of Ommen (towards the German border) was selected. These areas were chosen due to the high concentration of Achmea's clients in the respective areas in combination with other activities carried out by water boards in these areas within a knowledge program for the high sandy soils (Lumbricus).

The models were integrated into Delft-FEWS for the real-time forecasting of hydrological parameters and crop yield. The output from Delft-FEWS is then sent to an app, which is presented for feedback to a selection of farmers in the pilot area.

1.2 Approach

The project was divided in two phases. In phase 1, we developed the operational forecasting system. In phase 2, we compared the results from historical simulations with the same models (using the same forecasting feature from the system developed in phase 1, although with historical meteorological data instead of future forecasted data). The initial states of the models and some parameters were modified in order to improve the results. Details about these activities and future recommendations are provided in this report.

The following steps describe the activities that were carried out:

Phase 1: Setup the operational forecasting system

1. Select the most suitable pilot areas, preferably with a dense monitoring network of groundwater levels and soil moisture;
2. Prepare the regional iMODFLOW-MetaSWAP-WOFOST models for the selected pilot areas and do first trial runs of the models;
3. Integrate the models into a Delft-FEWS system for real-time forecasting. Delft-FEWS consists of a sophisticated set of configurable modules for building a hydrological forecasting system customised to the specific requirements of an individual organisation;
4. Export the relevant model outputs from the Delft-FEWS system, such as groundwater levels, soil moisture, and crop yield to the app;
5. Workshop with farmers about the app; and
6. Refine the app to farmers' needs.

Phase 2: Improve the model results by:

7. Calibrate the initial states of the model based on historical groundwater level and soil moistures measurements; and;
8. Evaluate the app with farmers.

1.3 Project team

Deltares is an independent knowledge institute for applied research in the field of water, subsurface and infrastructure, and is working on innovative solutions and applications worldwide for people, the environment and society. Deltares develops the system for 'real-time' prediction of hydrological conditions and the link with models for crop growth. In the models soil, crop, and meteorological data are used to generate current insight into the expected yields and the changes after, for example, damage to the crops.

WEnR is the environmental research institute of Wageningen University and Research (WUR), which conducts research worldwide in the area of healthy food and living environment. WEnR develops the crop module WOFOST and the unsaturated zone model (MetaSWAP). WEnR supports the application of the models in this project, and contributes to the optimization of these models in the study areas.

Milan InnoVincY BV (MI) is a Dutch-based provider of spatiotemporal computing and analysis for the international agricultural industry. By capturing time series based multispectral images and performing analysis to enable crop growth modelling and anomalies modelling. In the project MI develops the app that transforms the information from the models into information for farmers on a plot level.

Water boards in the Netherlands are amongst others responsible for the water management in a certain area. The water boards Aa & Maas and Vechtstromen developed the hydrological models for their management area, based on information about the current water level and detailed area information for it water management. The models have been developed as part of the Lumbricus project. The water boards also supply the validation of the system with their data model calculations in this project.

Achmea - with its brands Interpolis and Avéro Achmea - is the largest agricultural insurer in the Netherlands. Achmea has extensive experience with crop testing and helps to calibrate the results from the models. Achmea is in this project also responsible for the involvement of stakeholders (farmers) to test the usability of the information of the operational crop development system provided by the Farmers App.

1.4 Report outline

The structure of the report is as follows. Chapter 1 describes the outline of the project. Chapter 2 describes the chosen pilot areas and their main characteristics for this project. Then the used software and input data for the operational crop development system is described in Chapter 3. After that the outcome of the model runs will be compared to available in situ measurements in Chapter 4 explains the basic calibration and validation of the system. Chapter 5 gives the recommendations for future improvements by using data assimilation techniques. The design and development of the app used to inform farmers in the area about the conditions of the soil and crop development are described in Chapter 6. The evaluation of the use of the cop growth information is discussed in Chapter 7. This report closes with an overview of the main conclusions and recommendations.

2 Selection of pilot areas and models

To design the “Grow with the Flow” operational system, existing models that have previously been calibrated and validated were selected. Two pilot areas were selected to first develop the system: one within the management area of Waterboard Aa & Maas, and one within the management area of Waterboard Vechtstromen.

A description of the models that were selected for the pilot and the definition each of the pilot areas are provided below.

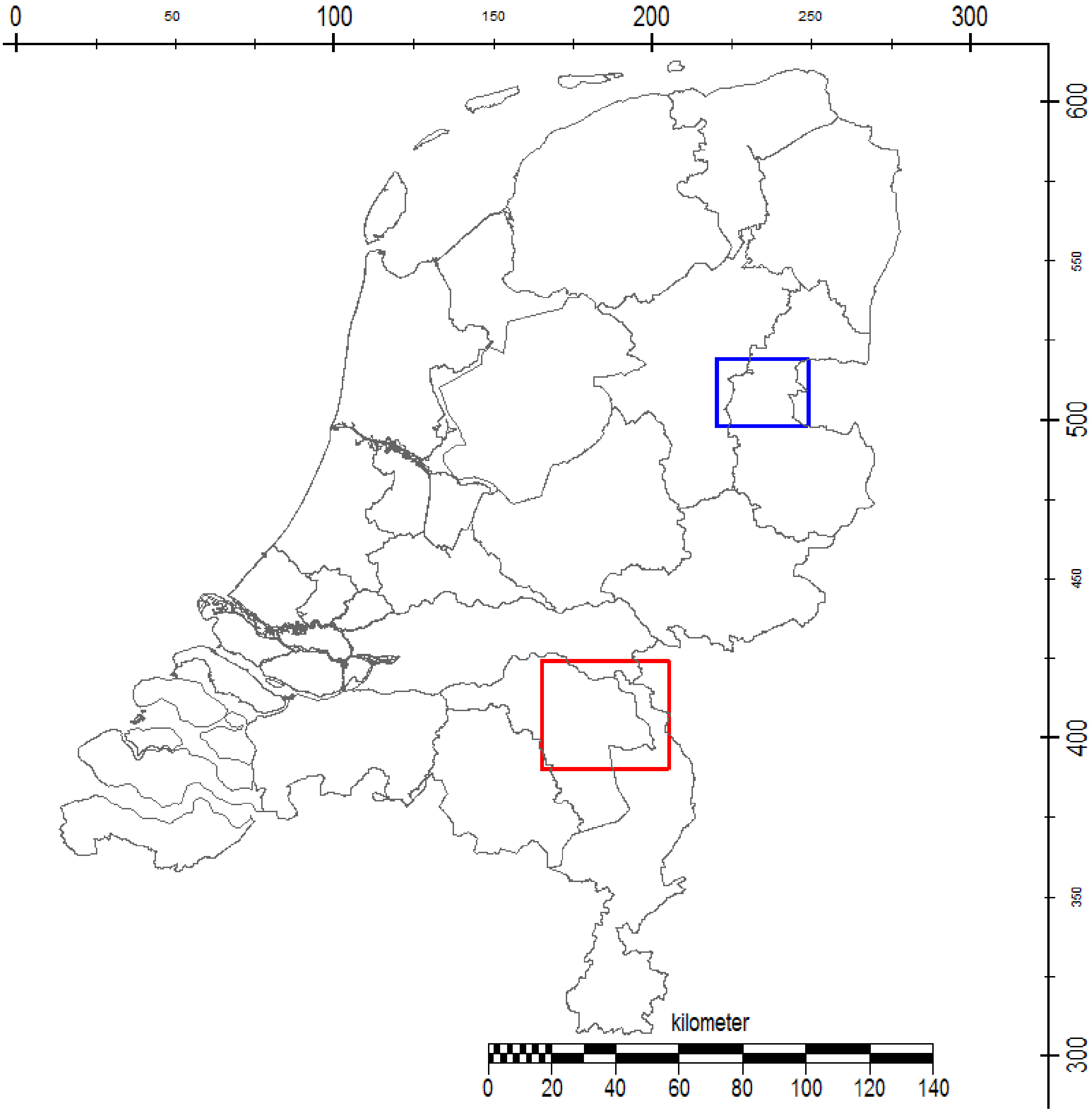

Figure 2.1 Location of pilot areas for Waterboard Aa & Maas (red box) and Waterboard Vechtstromen (blue box)

2.1 Waterboard Aa & Maas

For the pilot area, a pre-existing iMODFLOW-MetaSWAP model in use by Waterboard Aa & Maas was selected. A copy of the model was taken from their servers in June 2018; modifications to the model after that date have not been taken into account for the development of the “Grow with the Flow” system. Based on the location of a number of clients of Achmea and the availability of monitoring data, it was decided to use the Raam area in this pilot. A map showing the extent of both the Raam area and the model boundary is provided in Figure 2.2. Note that the legend indicates the surface elevation in metres above mean sea level (mamsl).

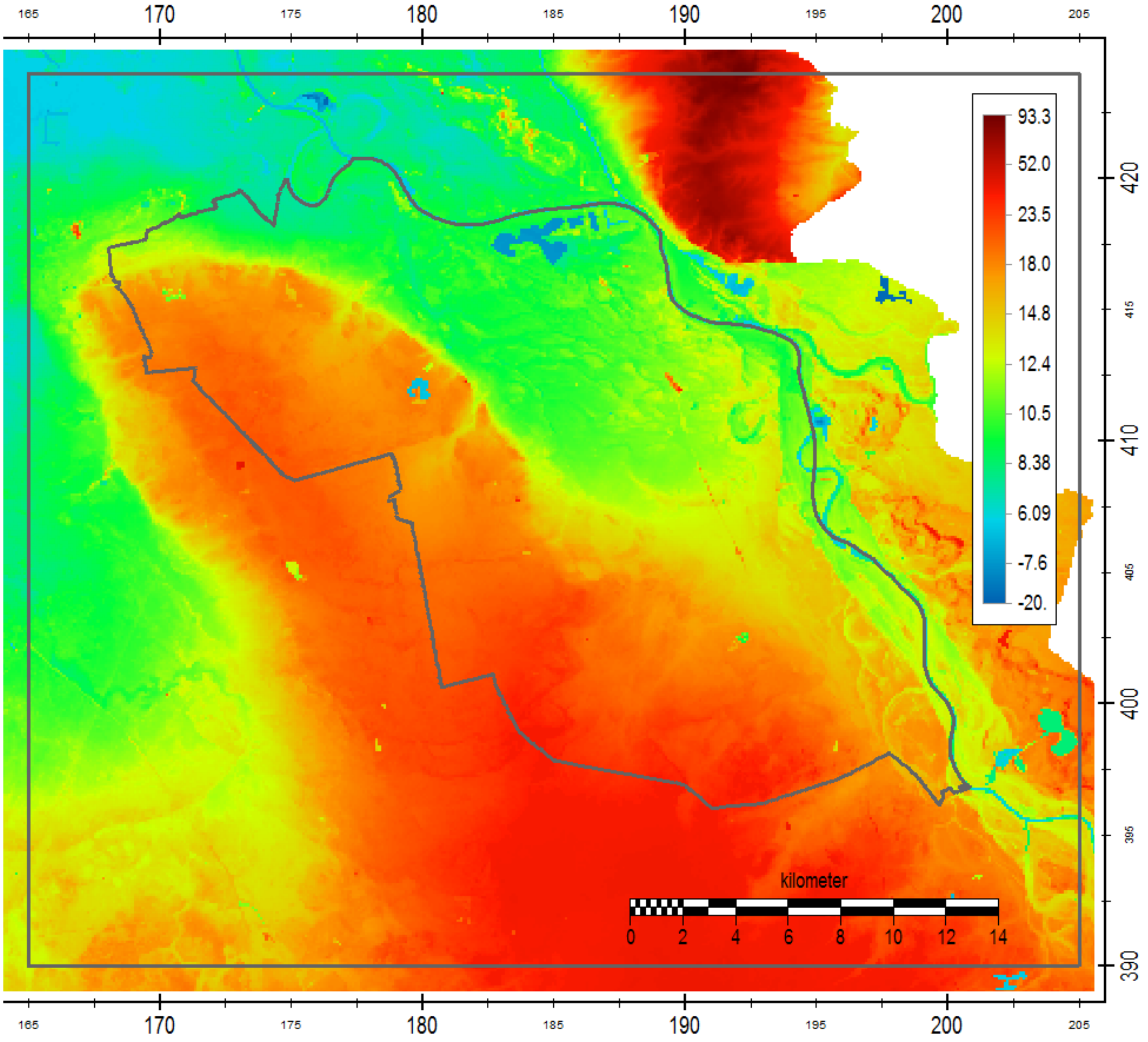

Figure 2.2. Extent of the Aa & Maas model for the “Grow with the Flow” system (outer boundary) and extent of the Raam area (inner boundary)

2.2 Waterboard Vechtstromen

For this pilot area, the iMODFLOW-MetaSWAP-WOFOST model developed as part of the LUMBRICUS project was selected. A map showing the extent of the model boundary is provided in

. Note that the legend indicates the surface elevation in mamsl.

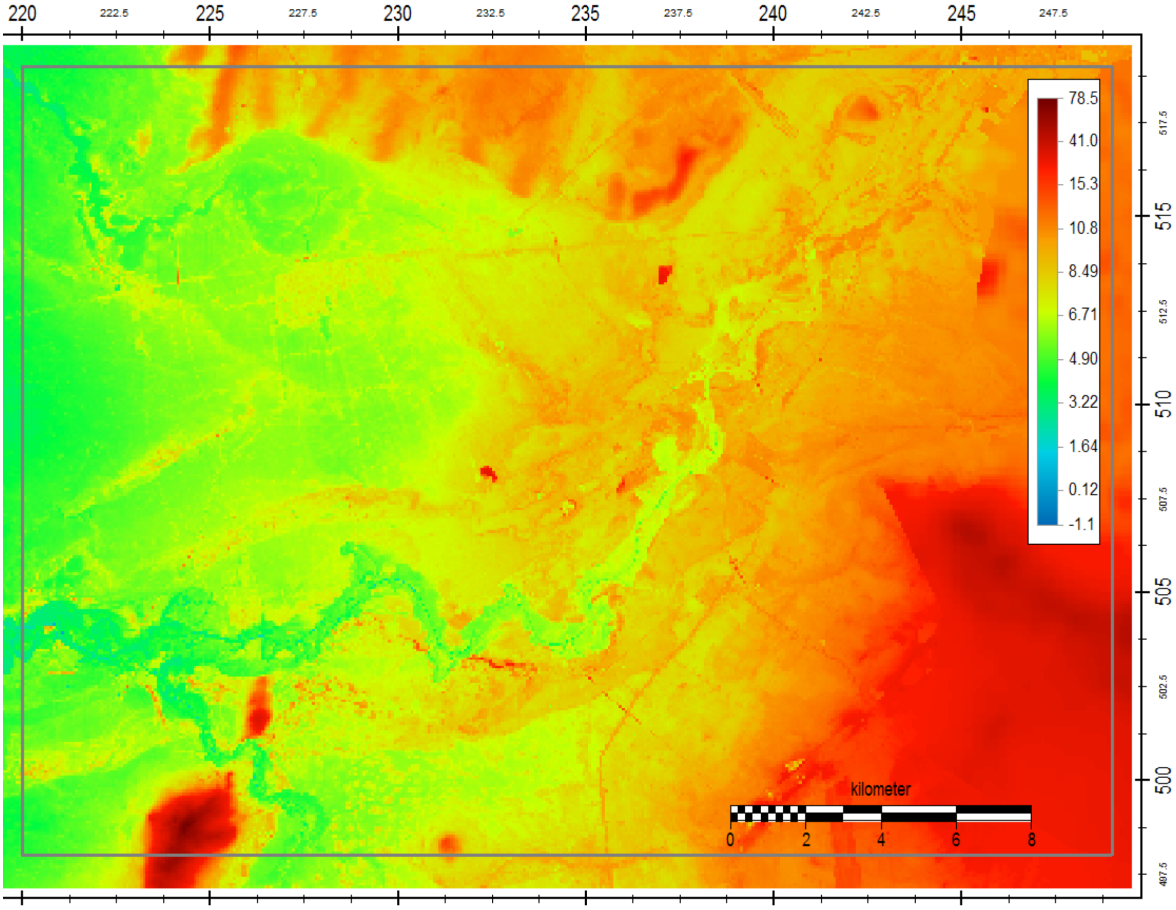

Figure 2.3 Extent of the Vechtstromen model for the “Grow with the Flow” system

3 Description setup operational system

3.1 Introduction

In Figure 3.1 an overview of the system set-up is given. In the centre of this Figure Delft-FEWS is located. Delft-FEWS is responsible for data import, data processing and making sure that the models can run so that the model results can be imported back into Delft-FEWS. These results can then be shared to the outside world by using build-in export functionality.

In this Chapter the forcing data are discussed (see 3.2) followed by an introduction to the model and its components (see 3.3). A short description of the important role of Delft-FEWS to connect the outside data with the model is given in Section 0. The development of the App for farmers is given in chapter 6.

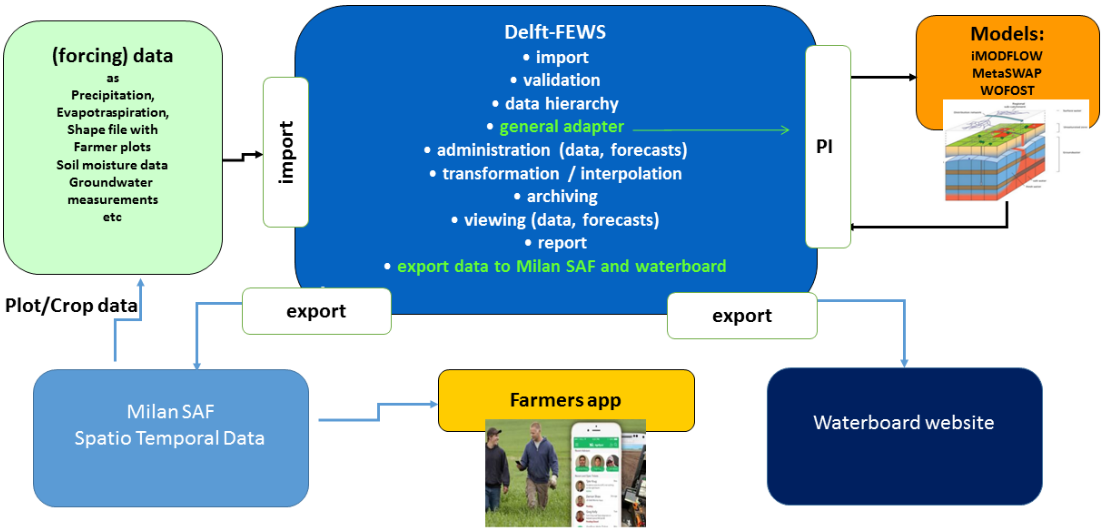

Figure 3.1 Overview of the Grow with the Flow system

3.2 Forcing data (model input)

The MODFLOW, METASWAP and WOFOST model requires a total of 9 different input parameters in order to be able to run a calculation. In an operational system these data need to be imported and processed with regular intervals so that the model can be used to create up-to-date historical simulations and forecasts.

In this pilot project we have selected two openly available data feeds: KNMI-Synopsis for historical simulations and DWD-ICON-EU data for creating forecasts. Additionally we have also used historical KNMI-24hrs-timeseries to run simulations for the years 2016, 2017, 2018. A brief description of these three data sources is given below.

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3.2.1 KNMI-SYNOPS

The KNMI owns an automated measurement system for meteorological data. In the Netherlands there are 35 weather stations located on land and 10 on sea in order to measure parameters such as precipitation, temperature, humidity, wind speed and radiation. These data are collected every second but the KNMI makes them available in time steps of 10 minutes.

In the Delft-FEWS system this KNMI-SYNOPS data forms the basis for the operational historical simulations of the model. The scalar data needs to be converted to the correct (model) time step and to the correct (model) grid definition.

3.2.2 KNMI-24hr timeserie

The KNMI-24 hr timeserie are based upon the measurements between 0-24 o'clock (hrs UT). The most recent data in this data feed can be unreliable since it might be not validated however for a historical simulation these data can be regarded as reliable.

In the Delft-FEWS system this KNMI-24 hr timeserie data forms a reliable back-up data feed for when there is no KNMI-SYNOP data to do a historical run. We have used these data to run a simulation for 2016, 2017, 2018 to verify the plausibility of the outcomes of the system. The data is converted to the correct (model) grid definition to be used by the model.

3.2.3 DWD-ICON-EU

Germany's National Meteorological Service, the Deutsche Wetterdienst (DWD), is the producer of the ICOsahedral Non-hydrostatic (ICON) Numerical Weather Prediction model[1].

The DWD develops and runs different numerical weather prediction (NWP) models for global and regional weather predictions. One of the latest models is the global forecasting model ICON (ICOsahedral Non-hydrostatic) of which the high-resolution ICON-EU is an important component. The ICON-EU model provides detailed forecasts for Europe. The model has a forecast length of +120 hours. The cells are 6.5 kilometres wide.

The ICON forecasts are made available through the DWD's open data portal (https://opendata.dwd.de/). Open ICON EU data is currently used in the Delft-FEWS application for the forecast run in this project because the service is free-of-charge service. A large number of parameters is available including those used most often in hydrological forecasting.

The forecasts are available to a lead time up to 120 hours in one-hour time steps for the first 78 hours. After that, its temporal resolution decreases to three hours. The spatial resolution of the products varies: ICON-global has an effective mesh size of approximate 13 kilometres globally, whereas ICON-EU is made available in a resolution of 0.0625 degrees in both longitudinal and latitudinal direction. Over Delft, which is more or less in the centre of the ICON-EU domain, this coincides with a resolution of approximately 4 by 6 kilometres in longitudinal and latitudinal direction, respectively[2].

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[1] Amendment to the Deutsche Wetterdienst Act in force since 25 July 2017. Available from https://www.dwd.de/EN/press/press_release/EN/2017/20170725_amendment_to_the_DeutscherWetterdienst.pdf

[2] Some background information can be found at https://www.dwd.de/EN/research/weatherforecasting/num_modelling/01_num_weather_prediction_modells/icon_description.html

Both ICON-global and ICON-EU are made available through a set of grib2 files. These files are available approximately 3.5 hours after the forecast initialization time[3], which are 00UTC, 06UTC, 12UTC and 18UTC[4]. The ICON-EU files can be readily imported by a Delft-FEWS application; currently, the ICON-global files need to be remapped (from icosahedral grid to rectangular grid) prior to import.

3.3 The MODLFOW-METASWAP-WOFOST model

The model consists out of three different components MODFLOW, METASWAP and WOFOST.

3.3.1 MODFLOW

MODFLOW is a popular open-source groundwater flow model distributed by the U.S. Geological Survey. For over 30 years, MODFLOW has been widely used by academics, private consultants, and government scientists to accurately, reliably, and efficiently simulate groundwater flow. In this project, an innovative Deltares version of MODFLOW (called iMODFLOW) was used (coupled with two other models – see description below). iMODFLOW is characterized by fast, flexible and consistent high resolution and sub-domain modelling techniques. It enables very large, high resolution groundwater modelling. Results include the groundwater heads of the various aquifers. More information about this model can be found at: https://oss.deltares.nl/web/imod/home

3.3.2 METASWAP

MetaSWAP can model both shallow and deep groundwater levels; it is intended for regions with an undulating topography and unconsolidated sediments. Its strength lies in modelling the unsaturated zone and shallow subsurface. MetaSWAP covers plant-atmosphere interactions and groundwater. Results include the fluxes to and from the unsaturated zone. More information about this model can be found at: ftp://ftp.wur.nl/simgro/doc/

3.3.3 WOFOST

WOrld FOod STudies (WOFOST) is a crop growth model for the quantitative analysis of the growth and production of annual field crops. WOFOST can be used to calculate attainable crop production, biomass, water use, etc. for a given location. Calculations are made based on local soil type, crop type, weather data, and crop management factors (e.g. sowing date). Results include the time of crop initiation, time of crop emergence, root zone depth, leaf area index, and water demand.

The oxygen stress model simulates the availability of oxygen for water uptake by roots. For situations with limiting oxygen availability the root zone development can be retarded and the uptake of water for crop growth is reduced. This has an impact on the crop development. For information about the model coupling and calibration we refer to Walsum & Kroon, 2018 (in prep, see also Appendix D).

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[3] For example: the 00UTC forecast can be downloaded from the web as of approximately 3:30am UTC.

[4] ICON EU is available at 03UTC, 09UTC, 15UTC and 21UTC also, noting that the forecast lead times at these cycles is limited to 30 hours.

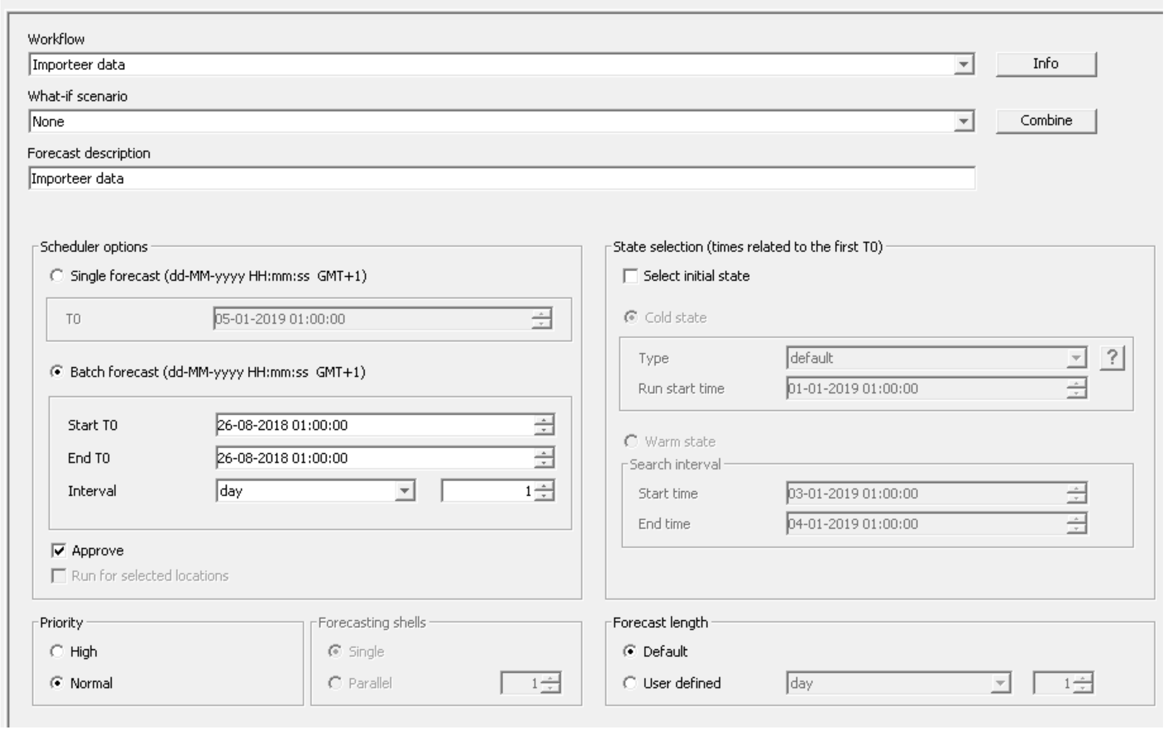
3.4 Delft-FEWS system

3.4.1 Introduction

Delft-FEWS provides an open shell system for managing forecasting processes and/or handling time series data. Delft-FEWS incorporates a wide range of general data handling utilities, while providing an open interface to any external (forecasting model). The modular and highly configurable nature of Delft-FEWS allows it to be used effectively for data storage and retrieval tasks, simple forecasting systems and in highly complex systems utilising a full range of modelling techniques. Delft-FEWS can either be deployed in a stand-alone, manually driven environment, or in a fully automated distributed client-server environment. Initially the system for this project is built as stand-alone application. More information about this model can be found at: https://www.sciencedirect.com/science/article/pii/S1364815212002083?via%3Dihub

3.4.2 Import of data

The data that was described in paragraph 3.2 must be imported by Delft-FEWS before it can be used by the model. To do so we have created a specific *import.xml* workflow in which we have defined separate modules. In these modules the imports are described.



Workflow: Importeer data

What-if scenario: None

Forecast description: Importeer data

Scheduler options
○ Single forecast (dd-MM-yyyy HH:mm:ss GMT+1)
T0 05-01-2019 01:00:00
● Batch forecast (dd-MM-yyyy HH:mm:ss GMT+1)
Start T0 26-08-2018 01:00:00
End T0 26-08-2018 01:00:00
Interval day 1
☑ Approve
☐ Run for selected locations

State selection (times related to the first T0)
☐ Select initial state
● Cold state
Type default
Run start time 01-01-2019 01:00:00
○ Warm state
Search interval
Start time 03-01-2019 01:00:00
End time 04-01-2019 01:00:00

Priority
○ High
● Normal

Forecasting shells
● Single
○ Parallel 1

Forecast length
● Default
○ User defined day 1

Figure 3.2 Screenshot of "Import data" workflow in Delft-FEWS. This workflow will import the available KNMI and DWD data

We have configured the imports in such a way that the from the different data feeds is all stored in same units. In Figure 3.3 below an example of the “raw” import data is shown for the location Heino.

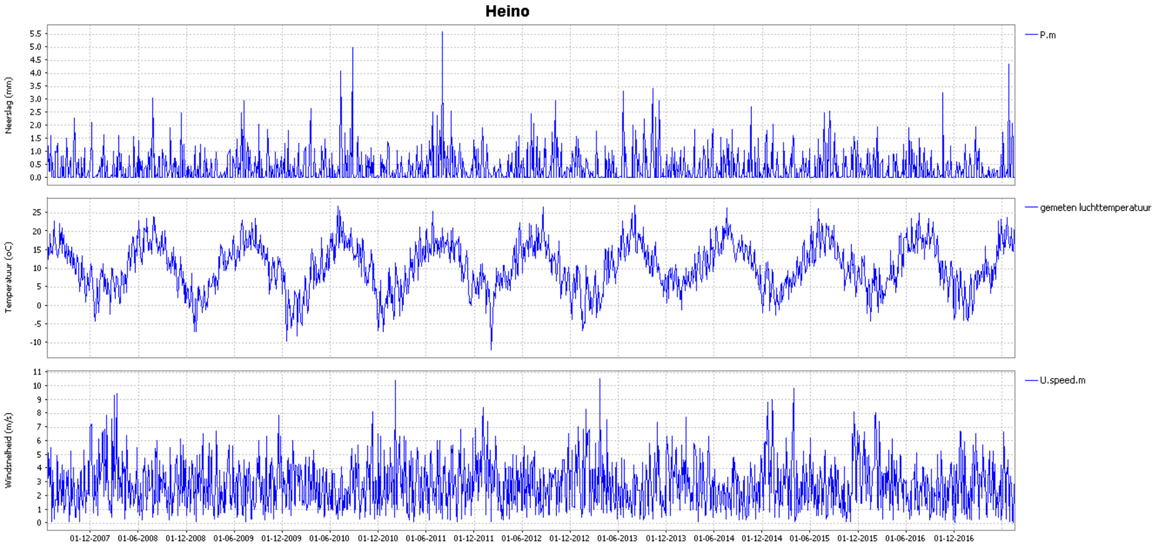


Figure 3.3 Example of scalar timeserie imported by Delft-FEWS

3.4.3 Pre-processing

The data must be processed before it can be used to run the model. This is done in the workflow *Run_MMW_<region>_prep_historical.xml* workflow. The model only requires a single timeseries per parameter to be able to run a calculation. In the pre-processing workflow we make sure that this data is always there. For operational forecast the steps to create timeseries for the model are summarized below:

a. Aggregate the scalar KNMI-Synops data from an hourly time step to a daily time step. The current system uses a daily time step for modelling; as such, the model requires input files with a daily time step.
b. Interpolate the KNMI-Synops data from scalar timeseries to a gridded timeseries. This grid is equal to the model extent.
c. Interpolate the KNMI-24 hr timeserie data from scalar timeseries to a gridded timeseries. This grid is equal to the model extent. The KNMI-24 hr timeserie are based upon the measurements between 0-24 o’clock (hrs UT). The most recent data in this data feed can be unreliable since it might be not validated.
d. Merge the data from KNMI-Synops and KNMI-24 hr timeserie to a single timeseries. In general the KNMI-Synops has priority over the KNMI-24 hr timeserie from an operational forecasting point of view. This means that the merged timeseries will ignore the data from the KNMI-24 hr timeserie wherever KNMI-Synops data is available.

Results presented in this report are based on historical simulation. For this purpose the KNMI-24 hr timeserie can be regarded as equally reliable as the KNMI-Synops-data. The calculations are made after some time, in which the KNMI-24hrs timeserie have been validated.

In some cases data must be modified in order to create a timeseries that follows the model requirements. The KNMI-Synops data does not contain evaporation data. We have added a PCRaster transformation to the Delft-FEWS configuration in order to calculate a value for evaporation based upon other available timeseries. The humidity is important as a relative humidity (%) but an absolute humidity is required by the model, we have added the following calculation to derive this humidity using the timeseries for relative humidity (RH) and temperature (T):

```
<expression>(RH /100) *(0.611*(exp((17.27 * T.) /(T + 273.3))))</expression>
```

The values for minimum and maximum temperature are simply selected from the 24 hour data recorded daily. The average temperature is set to be the mean of those two values.

The KNMI-24 hr timeserie has similar build-in tricks to complete all parameters. The humidity is calculated as described above. This data feed only contains an average daily temperature, the minimum and maximum values are 3.5 degrees lower or higher. There are no values for radiation, as a result we decided to use a look-up table per month.

```
<data value="1210" monthofYear="January"/>
<data value="3460" monthofYear="February"/>
<data value="6910" monthofYear="March"/>
<data value="12270" monthofYear="April"/>
<data value="15900" monthofYear="May"/>
<data value="15900" monthofYear="June"/>
<data value="15550" monthofYear="July"/>
<data value="12960" monthofYear="August"/>
<data value="7950" monthofYear="September"/>
<data value="4320" monthofYear="October"/>
<data value="1560" monthofYear="November"/>
<data value="520" monthofYear="December"/>
```

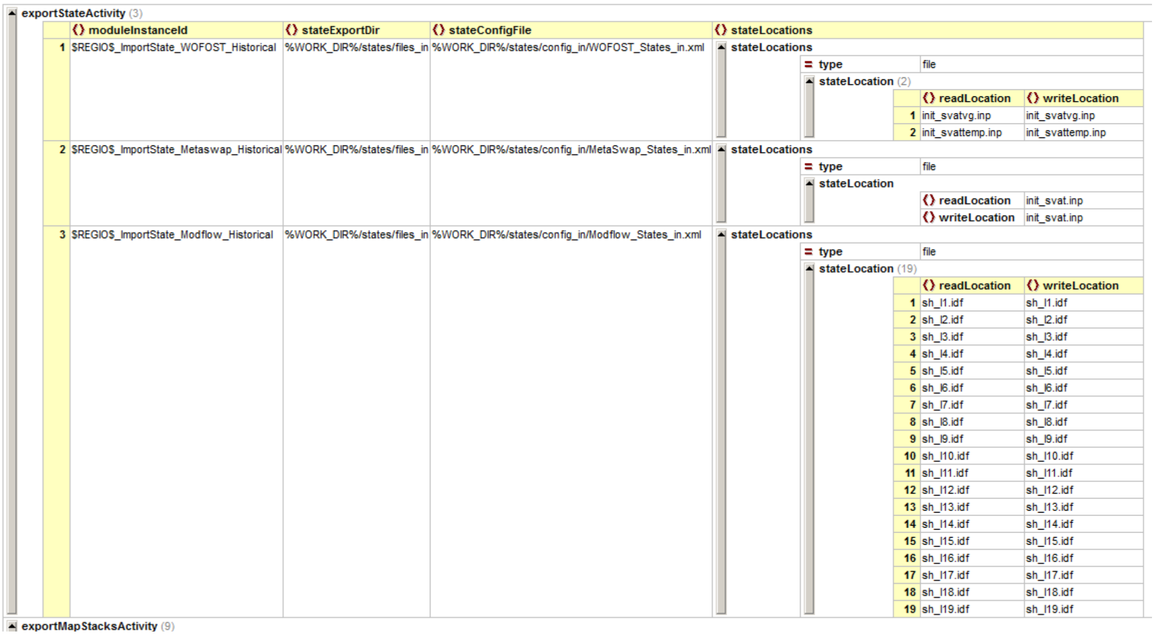
After the pre-processing is finished we are able to feed the model with gridded timeseries for each of the different parameters.

3.4.4 Model run

A model run consists of three different steps.

The first step is to export data from Delft-FEWS to the coupled model using a ‘module’ (module Template_ExportToMMW_historical.xml). This module exports a time series with the nine parameters required by the model from Delft-FEWS to a specific folder. The model then uses these parameters and begins its calculations. In addition, restart files are exported to the model. These restart files are needed to make sure that the model starts from the correct state. This is important because the files contain the history of the historical simulations (e.g. in a very dry year, the model should take this information into account when it starts its calculations). The restart files are used to transfer this information.

In the figure below the exportStateActivity for the Aa & Maas model is shown. The WOFOST model requires the files init_svatvg.inp, init_svattemp.inp. The MetaSWAP model requires the file init_svat.inp. The IMODFLOW model requires the groundwater heads sh_l*.idf for all the layers in the model (here 19).



exportStateActivity (3)

	moduleInstanceId	stateExportDir	stateConfigFile
1	$REGIO$_ImportState_WOFOST_Historical	%WORK_DIR%/states/files_in	%WORK_DIR%/states/config_in/WOFOST_States_in.xml
2	$REGIO$_ImportState_Metaswap_Historical	%WORK_DIR%/states/files_in	%WORK_DIR%/states/config_in/MetaSwap_States_in.xml
3	$REGIO$_ImportState_Modflow_Historical	%WORK_DIR%/states/files_in	%WORK_DIR%/states/config_in/Modflow_States_in.xml

stateLocations

1 stateLocations

type = file

stateLocation (2)

	readLocation	writeLocation
1	init_svatvg.inp	init_svatvg.inp
2	init_svattemp.inp	init_svattemp.inp

2 stateLocations

type = file

stateLocation

readLocation	init_svat.inp
writeLocation	init_svat.inp

3 stateLocations

type = file

stateLocation (19)

	readLocation	writeLocation
1	sh_l1.idf	sh_l1.idf
2	sh_l2.idf	sh_l2.idf
3	sh_l3.idf	sh_l3.idf
4	sh_l4.idf	sh_l4.idf
5	sh_l5.idf	sh_l5.idf
6	sh_l6.idf	sh_l6.idf
7	sh_l7.idf	sh_l7.idf
8	sh_l8.idf	sh_l8.idf
9	sh_l9.idf	sh_l9.idf
10	sh_l10.idf	sh_l10.idf
11	sh_l11.idf	sh_l11.idf
12	sh_l12.idf	sh_l12.idf
13	sh_l13.idf	sh_l13.idf
14	sh_l14.idf	sh_l14.idf
15	sh_l15.idf	sh_l15.idf
16	sh_l16.idf	sh_l16.idf
17	sh_l17.idf	sh_l17.idf
18	sh_l18.idf	sh_l18.idf
19	sh_l19.idf	sh_l19.idf

exportMapStacksActivity (9)

Figure 3.4   Example of FEWS configuration where model input is prepared for the model to run (step 1)

The next step is to run the model by kicking of the important batch files (this is done in the module *Template_run_historical.xml*).

executeActivities

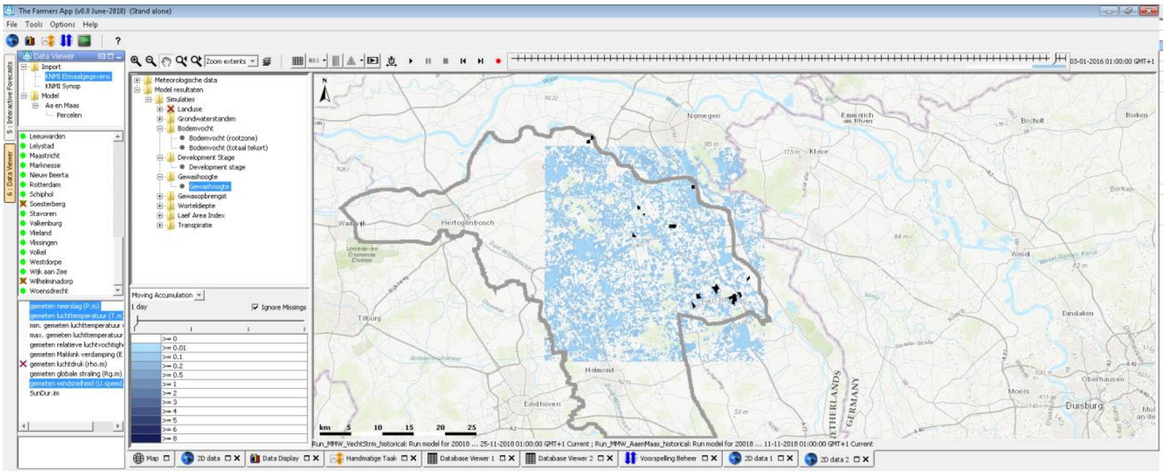
executeActivity (2)

	command		timeOut	ignoreDiagnostics
1	command executable	 %WORK_DIR%/bin/run_metaswap.bat	21600000	true
2	command executable	 %WORK_DIR%/bin/post.bat	300000	true

shutDownActivities

Figure 3.5   Example of FEWS configuration where is defined to start model runs (step 2)

The last step in this process is to import all relevant model results into the Delft-FEWS database and additionally to pick up the latest restart files. This is done in the modules Template_ImportresultsMM_historical.xml and template_ImportresultsW_historical.xml for importing the results. The modules Template_ImportState_Wofost_Historical.xml, Template_ImportState_Modflow_Historical.xml, Template_ImportState_Metaswap_1_ Historical.xml and Template_ImportState_Metaswap_2_Historical.xml are used to import the most recent restart files.



```
Run_MMW_VechtStrm_historical: Run model for 20018 ... 25-11-2018 01:00:00 GMT+1 Current ; Run_MMW_AaenMaas_historical: Run model for 20018 ... 11-11-2018 01:00:00 GMT+1 Current
```

Figure 3.6 Example of the model results in FEWS (step 3)

3.4.5 Post processing

The model results are all provided in a grid. For analyses it is useful to see the results on a plot level. In the module Template_postprocess_toplots_Historical.xml we calculate the average results in a polygon using the gridded model results as input for this spatial interpolation.

An example of this post-processing step is provided in Figure 3.7.

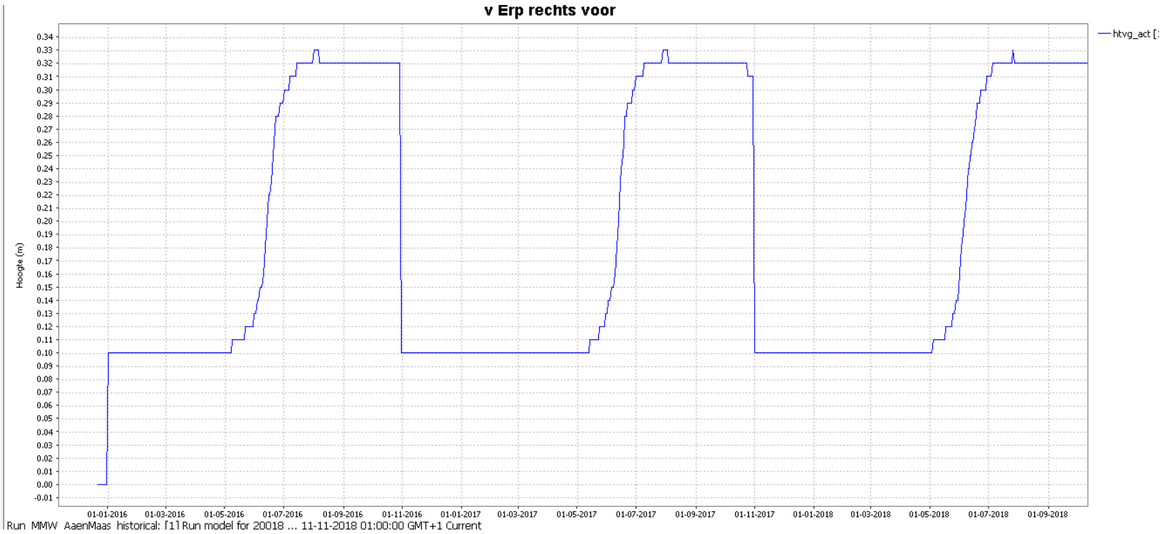


Figure 3.7 Example of post processing step to show and export results

4 Calibration and verification

This chapter describes the results of the model. Before starting the runs the crop info has been checked for the pilot farmers with the RVO database manually (boerenbunder.nl). In future, the feedback from farmers about the following year's planned crops could be added to get more accurate results on a plot level. In practice, the information from farmers was difficult to compare with the model and historical crop yield data from the farmers. Therefore, we decided to focus in this project on ground measurements and available soil moisture data. The comparisons have been executed by Deltares in close cooperation with Wageningen University to verify the implementation of the model in the FEWS-system.

4.1 Modifications to the models

This section describes the modifications that were made to the original models stated above. Modifications that apply to both models are first described, following by specific modifications to the Aa & Maas model and the Vechtstromen model.

4.1.1 General modifications

For the purpose of the pilot, it was decided to model both areas with a resolution of 100 m x 100 m. This decision was made considering computational time and space requirements to both run the simulations and save the results.

For both models, the meteorological parameters used as input for the unsaturated zone (CAP package) are not provided by fixed files, but automatically updated by Delft-FEWS on a daily basis. To prepare this data, Delft-FEWS first looks at the Royal Netherlands Meteorological Institute's (*Koninklijk Nederlands Meteorologisch* Instituut – KNMI) synoptic scalar data for the historical period and at the German Meteorological Institute's (*Deutsche Wetter Dienst – DWD*) ICON-EU synoptic scalar data on a 3-hourly basis for the forecast period. In case of the historical run, the KNMI-24hr-timeserie can be used as a back-up data feed in case the synopsis data is unavailable. In order to run the model, the Delft-FEWS configuration has the functionality to merge time series, create a back-up time series based on monthly values, and interpolate within the time series to get rid of gaps in the synopsis data. The data are then interpolated to the extent of the model grid. The flow chart for this data selection process is provided in Figure 4.1.

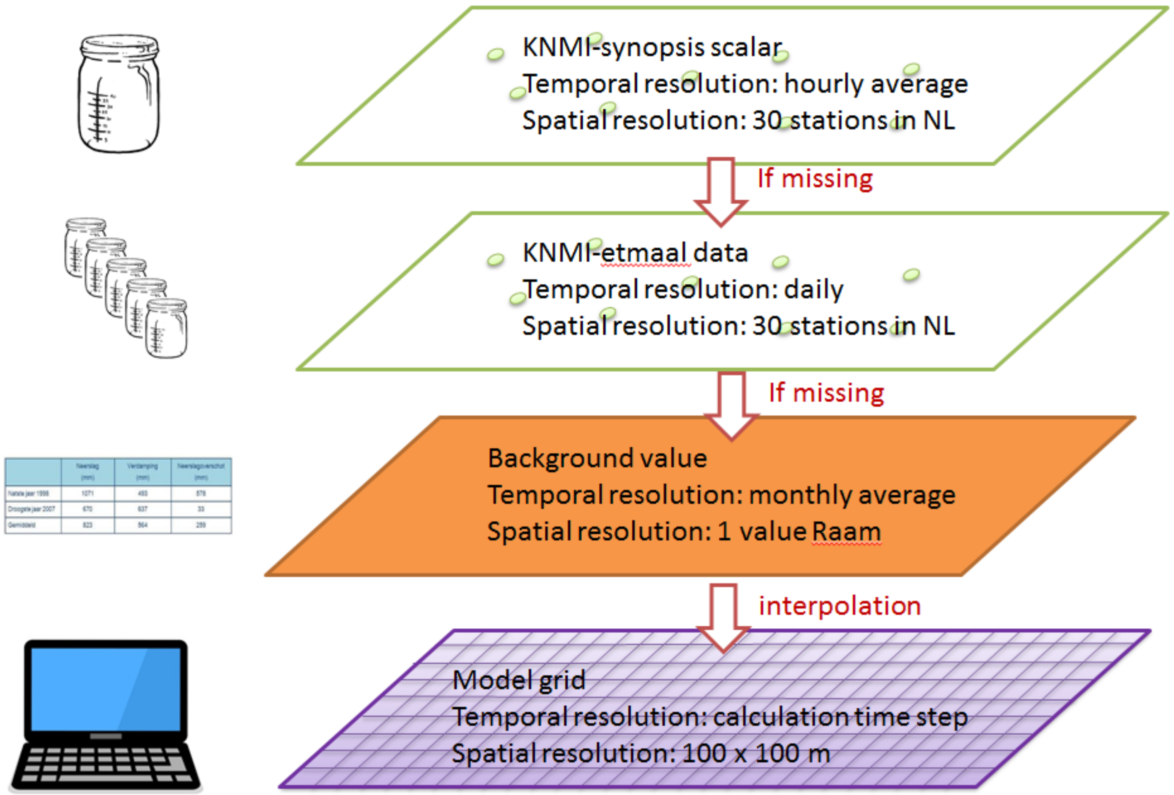
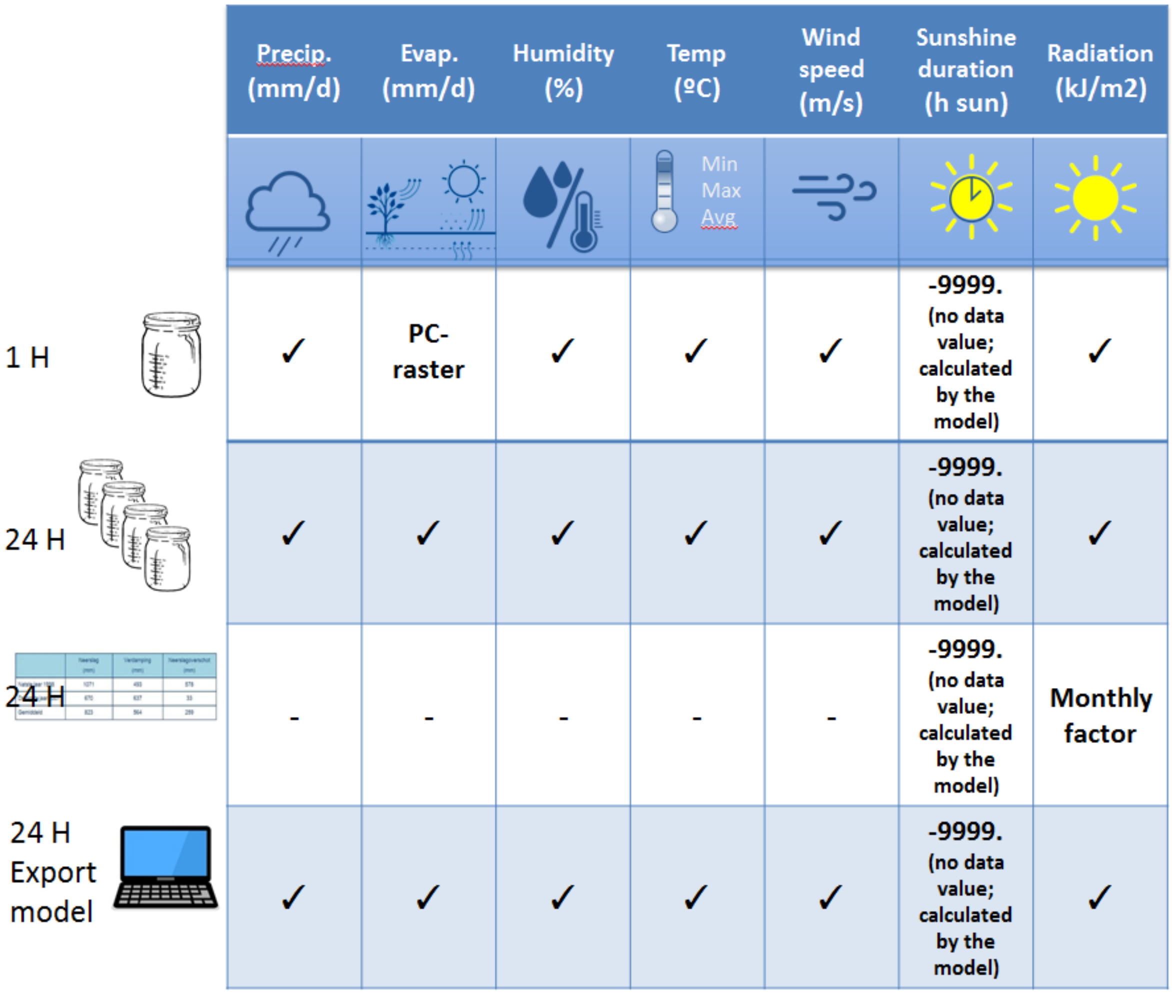


Figure 4.1 Flow chart to determine meteorological data available for the “Grow with the Flow” operational system

Based on this flow chart, the data available for the “Grow with the Flow” operational system, per input parameter, is provided in the “Grow with the Flow” operational system.



	Precip. (mm/d)	Evap. (mm/d)	Humidity (%)	Temp (ºC)	Wind speed (m/s)	Sunshine duration (h sun)	Radiation (kJ/m2)
				Min Max Avg			
1 H	✓	PC-raster	✓	✓	✓	-9999. (no data value; calculated by the model)	✓
24 H	✓	✓	✓	✓	✓	-9999. (no data value; calculated by the model)	✓
24 H	-	-	-	-	-	-9999. (no data value; calculated by the model)	Monthly factor
24 H Export model	✓	✓	✓	✓	✓	-9999. (no data value; calculated by the model)	✓

Figure 4.2 Meteorological data used in the "Grow with the Flow" operational system

The meteorological forcing to the WOFOST model needs a measurement height as an input value to be able to determine the evapotranspiration parameters accurately. The Penman-Monteith method is applied in the WOFOST model, which depends, among other parameters, on wind speed corrected for the reference level. For both the Aa & Maas and Vechtstromen models, the measurement height was set at 10 m, what is the reference level of measurement defined by the World Meteorological Organisation (WMO).

For both models, the last known extraction from the wells (WEL package) was continued indefinitely.

4.1.2 Modifications to the Aa & Maas model

Since the baseline Aa & Maas model did not include WOFOST, this first had to be added. Parameterization as developed for the Vechtstromen model was also applied to the Aa & Maas model, with the exception that the soil physical database used for Aa & Maas is taken from "NHI_veenweide_v02". The Aa & Maas model uses the latest NHI database with 370 units (see also number of entries in area_svat.inp in the soil column). To get the model working, the following workaround has been implemented to refer to the correct database (stop model with metaswap_pause.txt, and then overwriting the area_svat.file with area_svat_deb).

The original Aa & Maas model also includes the streams (ISG package), which is not easily extended into the future. For the forecasting purposes of the “Grow with the Flow” operational system, the ISG package has been removed, and instead replaced with the river (RIV package). To create this input, the ISG package was converted to RIV on a daily basis for the year 2016. The year 2016 was chosen because it is a leap year; as such, water levels are available on a daily basis, regardless of the year being simulated. The resulting daily water levels are used in the operational system for the Maas, Niers, and Nierskanaal.

The boundary file (BND package) was also modified for the operational Aa & Maas model. During testing, an error in the layers was discovered. This was communicated Waterboard Aa & Maas, who were aware of the issue. They provided an updated set of layers, and these were tested in the system; however, the model did not converge with the new layers and additions made to the model (described above). It was thus decided to continue building the system with the older version of the layers (obtained from the Aa & Maas server in June 2018, as mentioned in Section 2.1). In order to work around this issue, the boundary file was updated so that the north-eastern part of the model would not be included in the simulations (refers to area in white in Figure 2.2).

4.1.3 Modifications to the Vechtstromen model

No additional modifications to the Vechtstromen model were made.

4.2 Monitoring data

Local monitoring data was used in order to compare and validate the results from the model. Data available for both models is described below.

4.2.1 Aa & Maas

The locations of available monitoring data for the Aa & Maas pilot area are shown in Figure 4.3. Note that the grey dots indicate locations with groundwater level data (215 locations; source: DINOloket for 213 of the locations, Waterboard Aa & Maas for the remaining 2 locations) and the white dots indicate the locations with soil moisture data (13 locations; source: Waterboard Aa & Maas). The legend indicates the surface elevation in mamsl. Additional groundwater level data is available from Waterboard Aa & Maas; however, since the purpose of the comparison made was to provide an initial assessment of the reliability of the results and suitability of the system for operational purposes, this data was not used in this study. Comparison to this data could be done in a following phase.

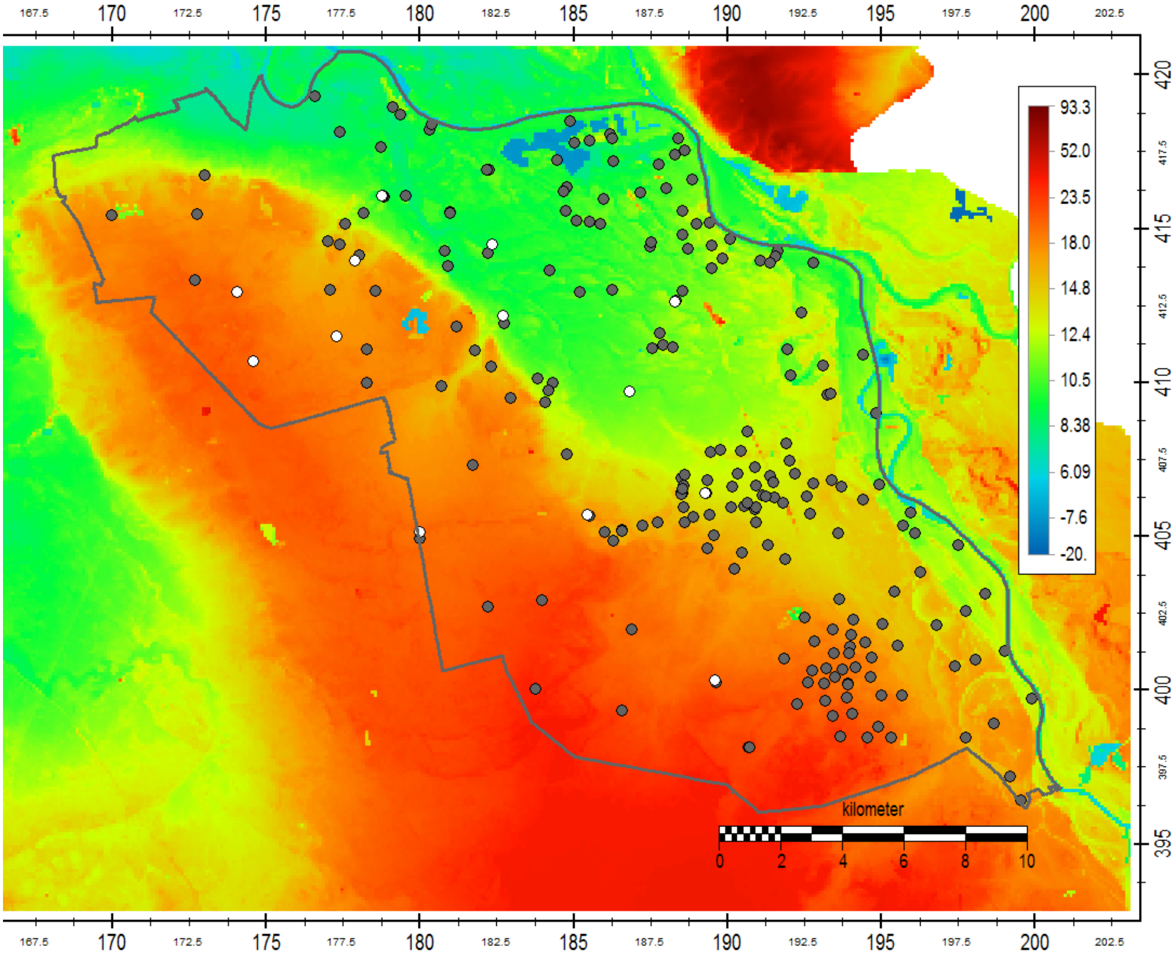


Figure 4.3. Locations of available monitoring data – Aa & Maas: groundwater monitoring data (grey dots) and soil moisture monitoring data (white dots)

4.2.2 Vechtstromen

The locations of available monitoring data for the Vechtstromen pilot area are shown in Figure 4.4. Note that the locations with groundwater level data are represented by three colours: blue (76 locations; source: Waterboard Vechtstromen), grey (57 locations; source: provincial monitoring network), and white (3 locations; source: DINOloket). The legend indicates the surface elevation in mamsl.

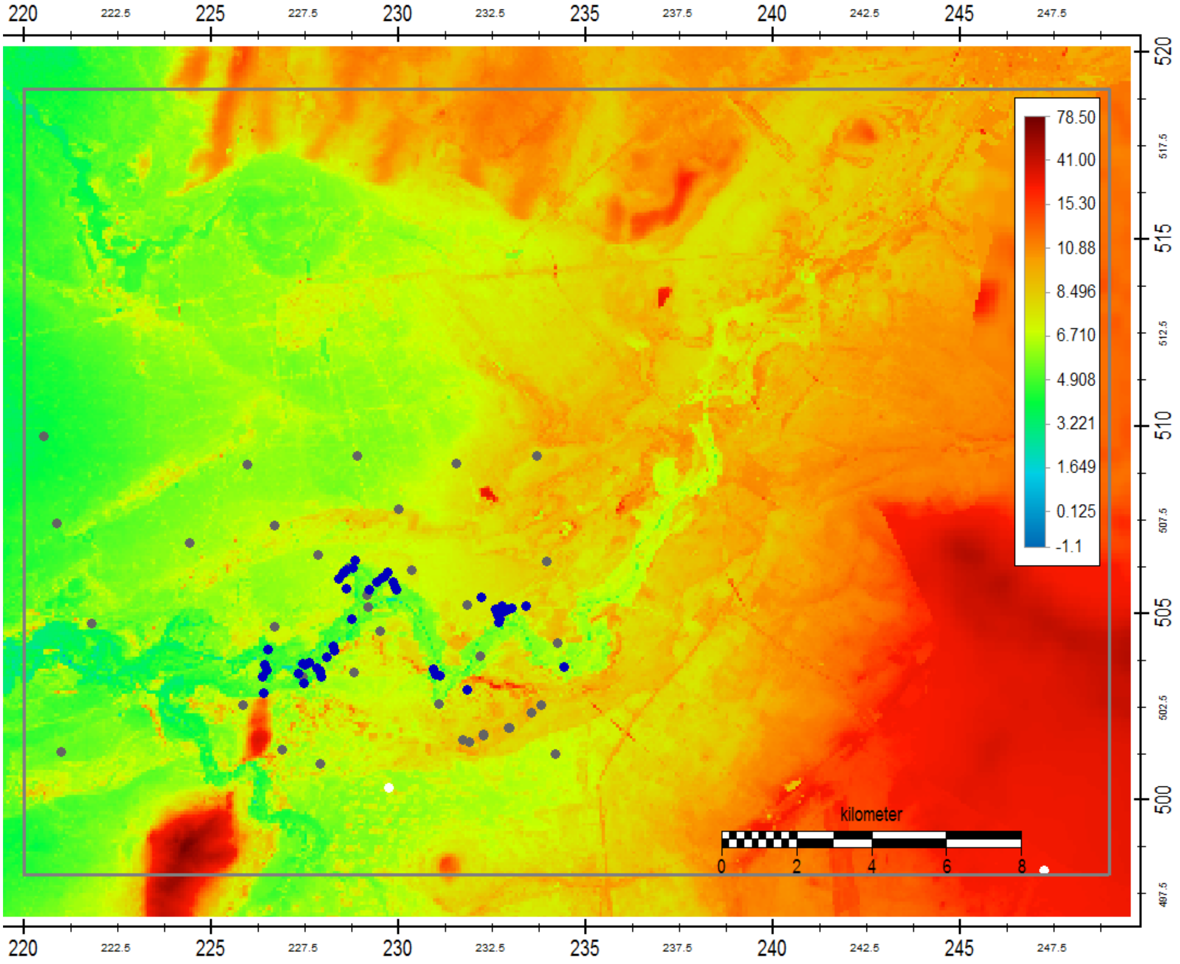


Figure 4.4. Locations of available monitoring data – Vechtstromen: groundwater monitoring data (blue, grey, and white dots)

4.3 Comparison results with monitoring data

For both Aa & Maas and Vechtstromen, the models were run for the period 2015-2018 to compare these results against monitoring data. In both cases, the model was started one year earlier than the comparison of results to allow the model to ‘warm’ up and attempt to reduce the error due to incorrect cold states at the beginning of the simulation. As such, the comparison of results for both locations for the period 2016-2018 is provided below. For Aa & Maas both groundwater and soil moisture measurements were available. For Vechtstromen a comparison could only be made for groundwater heads. However, both pilot areas have the same parameters as output in the system.

4.3.1 Aa & Maas

This section presents the results of soil moisture and groundwater heads as compared to field available measurement data, as well as a comparison of additional output parameters to data available from farmers, such as crop yield, where available.

There are 13 monitoring locations for soil moisture within the Raam area. In order to compare results, the groundwater monitoring locations from DINOloket that are closest to the soil moisture monitoring locations were selected. The corresponding location IDs, as well as comments for certain locations, are presented in

Table 4.1. Results are presented for a select number of locations, based on the comments provided in the table.
Maps showing the locations of the soil moisture and groundwater monitoring locations are provided in Figure 4.5 and Figure 4.6, respectively. The locations with results presented in this report are circled in each of the respective figures.

The comparison of soil moisture results and the nearest groundwater head measurement are provided in Figures 4.7 to 4.11. Note that for the comparison of soil moisture, both the field measurements and model results have been integrated by depth between 0 and 80 cm below surface level.

The soil moisture measurements were available at depths of 5 cm, 10 cm, 20 cm, 40 cm, and 80 cm from the surface level. The depth integration for these locations was calculated for each time step using the following formula:

$$Integrated\ depth\ (per\ location, per\ time\ step)$$
$$= \frac{\left(VWC_{5cm} * 5 + \frac{(VWC_{5cm} + VWC_{10cm})}{2} * (10-5) + \frac{(VWC_{10cm} + VWC_{20cm})}{2} * (20-10) + \frac{(VWC_{20cm} + VWC_{40cm})}{2} * (40-20) + \frac{(VWC_{40cm} + VWC_{80cm})}{2} * (80-40)\right)}{80}$$

Where:

- VWC_{5cm} is the volumetric soil water content at a depth of 5 cm;
- VWC_{10cm} is the volumetric soil water content at a depth of 10 cm;
- VWC_{20cm} is the volumetric soil water content at a depth of 20 cm;
- VWC_{40cm} is the volumetric soil water content at a depth of 40 cm; and
- VWC_{80cm} is the volumetric soil water content at a depth of 80 cm.

A similar approach was taken to integrate all of the soil moisture model results between 0 and 80 cm below surface level.

Table 4.1. Location ID and comments regarding soil moisture and nearest groundwater measurements

Soil moisture location ID	**Nearest groundwater location ID**	**Comments**	**Results presented for comparison?**
RM_SM_01	B45F1045	Could also compare to HORA001_G from Waterboard Aa & Maas in the future.	√
RM_SM_02	N/A	No groundwater monitoring location available from DINOloket in proximity to the soil moisture monitoring location. Could compare to BOVO002_G from Waterboard Aa & Maas in the future.	
RM_SM_03	B45H0138	The data from B45H0138 is not reliable for this analysis; the depth of the sensor appears to change during the period of analysis. Could compare to BOVO003_G from Waterboard Aa & Maas in the future.	
RM_SM_04	B45F0653	The data from B45F0653 is not reliable for this analysis; the depth of the sensor appears to change during the period of analysis. Nearby DINOloket locations are also B45F1048 and B45F1049; however, these locations do not provide more reliable results for comparison purposes. Could compare to REFV012_3_G from Waterboard Aa & Maas in the future.	
RM_SM_05	B45F0279	The data from B45F0279 is not reliable for this analysis; the depth of the sensor appears to change during the period of analysis. Could compare to BOVO005_G from Waterboard Aa & Maas in the future.	
RM_SM_06	B46A1603	Could also compare to TONG005_G from Waterboard Aa & Maas in the future.	
RM_SM_07	B46A1636		√
RM_SM_10	B45H0109	The data from B45H0109 is not reliable for this analysis; the depth of the sensor appears to change during the period of analysis.	
RM_SM_11	B46C0207	Using groundwater data received from Aa & Maas, not DINOloket.	√
RM_SM_12	B46C0009	The data from B46C0009 is not reliable for this analysis; the depth of the sensor appears to change during the period of analysis. Nearby DINOloket location is also B46C0246; however, the time series available at this location is insufficient to compare results.	
RM_SM_13	B46C0256		√
RM_SM_14	N/A	No groundwater monitoring location in proximity to the soil moisture monitoring location. Could also compare to BOVO014_G from Waterboard Aa & Maas in the future.	
RM_SM_15	B46C0162	Using groundwater data received from Aa & Maas, not DINOloket.	√

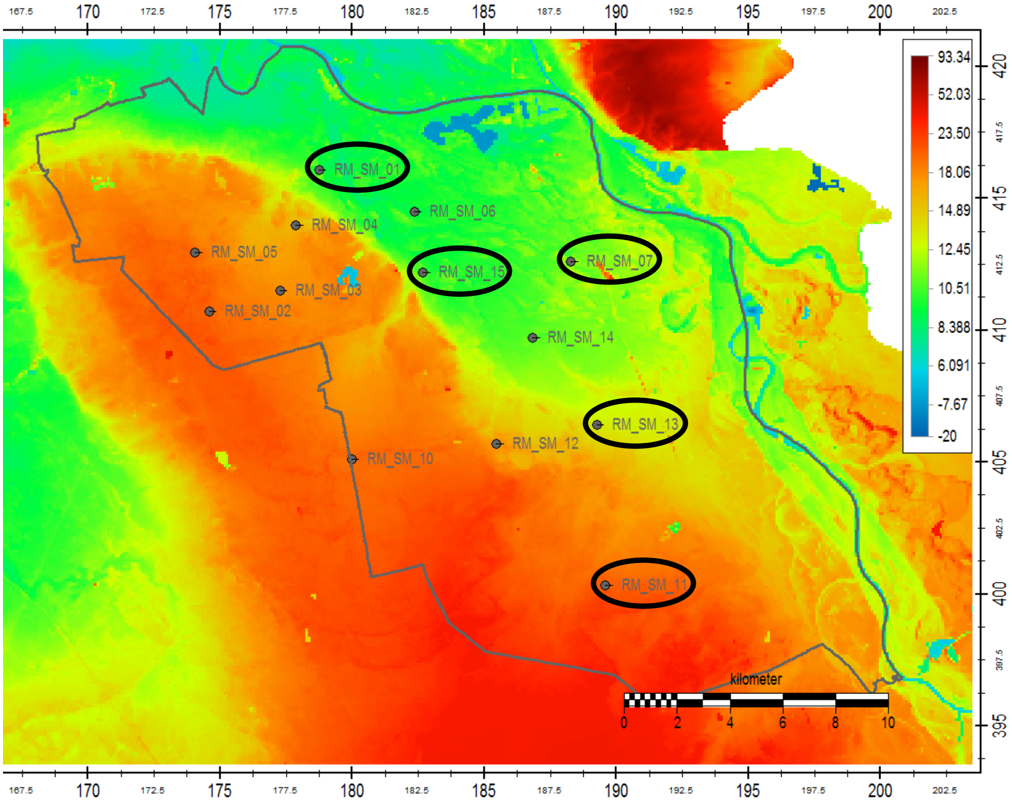


Figure 4.5. Location of the soil moisture measurements used for comparison with the model results.

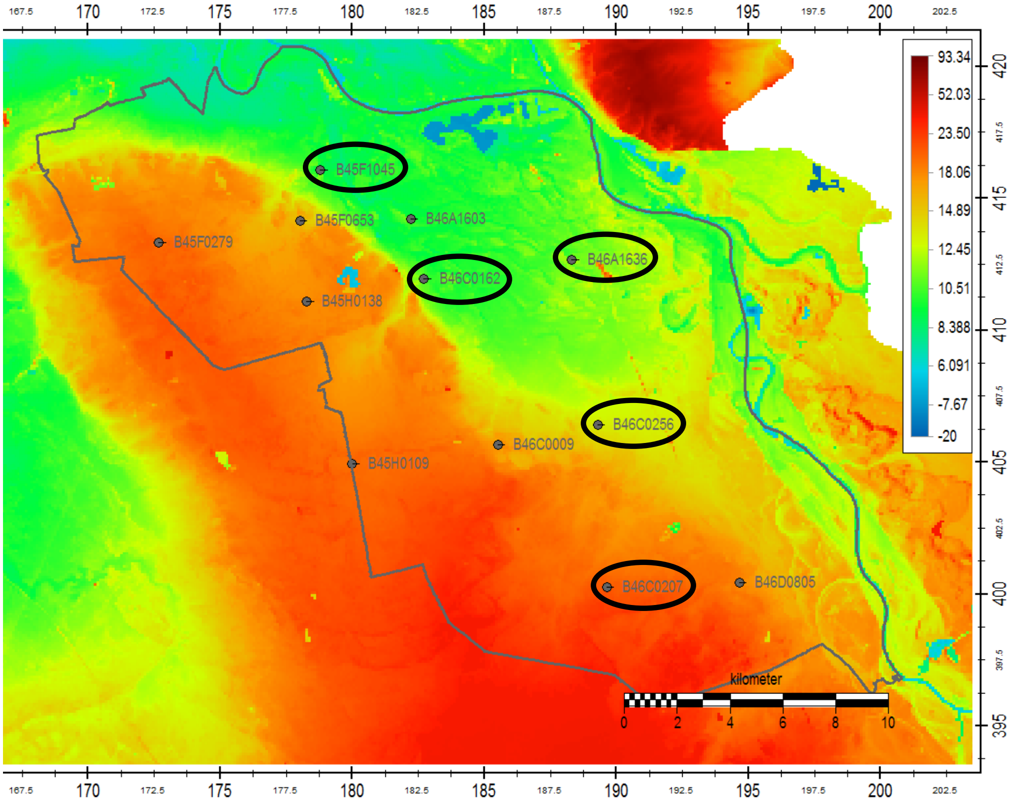


Figure 4.6. Location of the groundwater head measurements used for comparison with the model results.

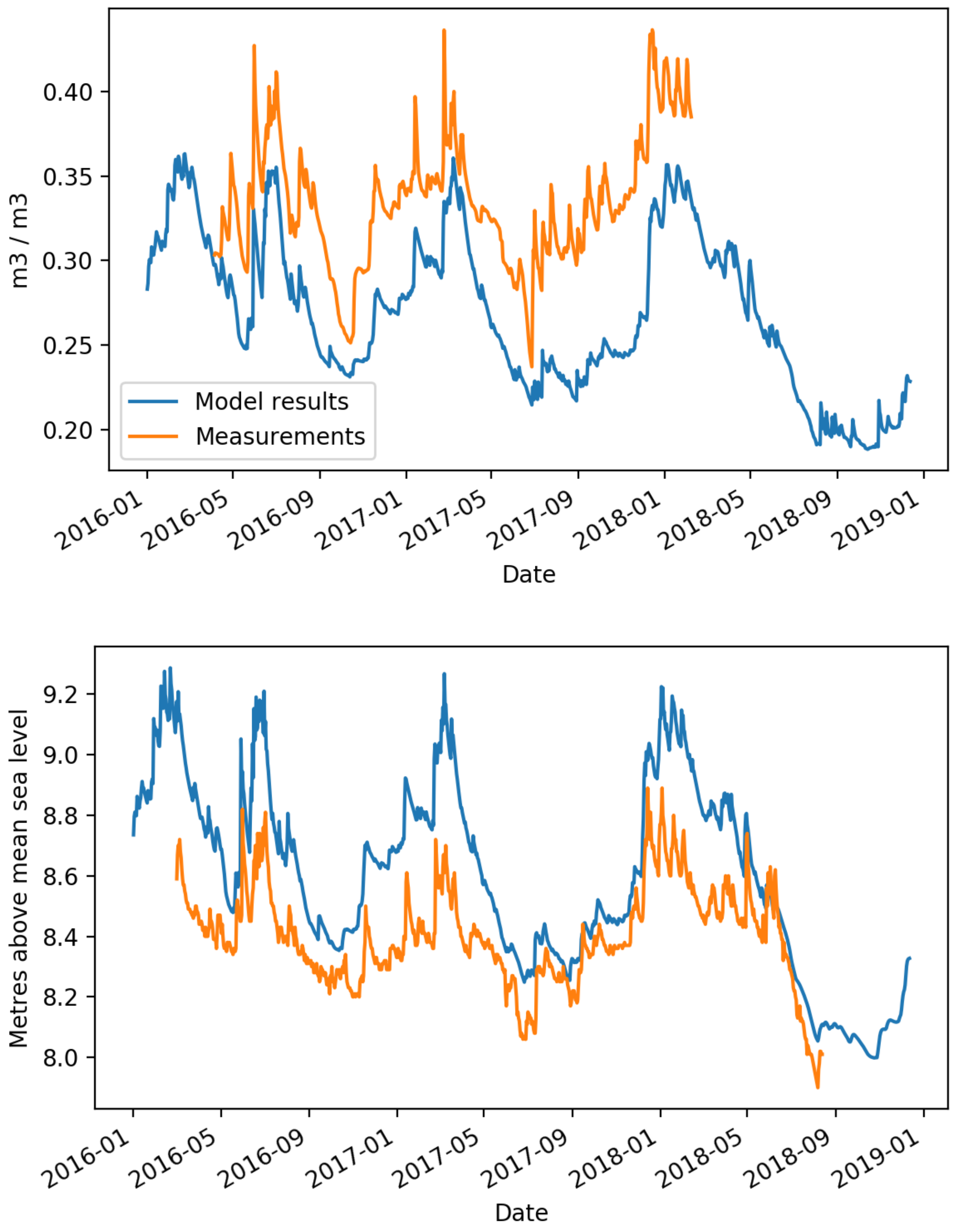
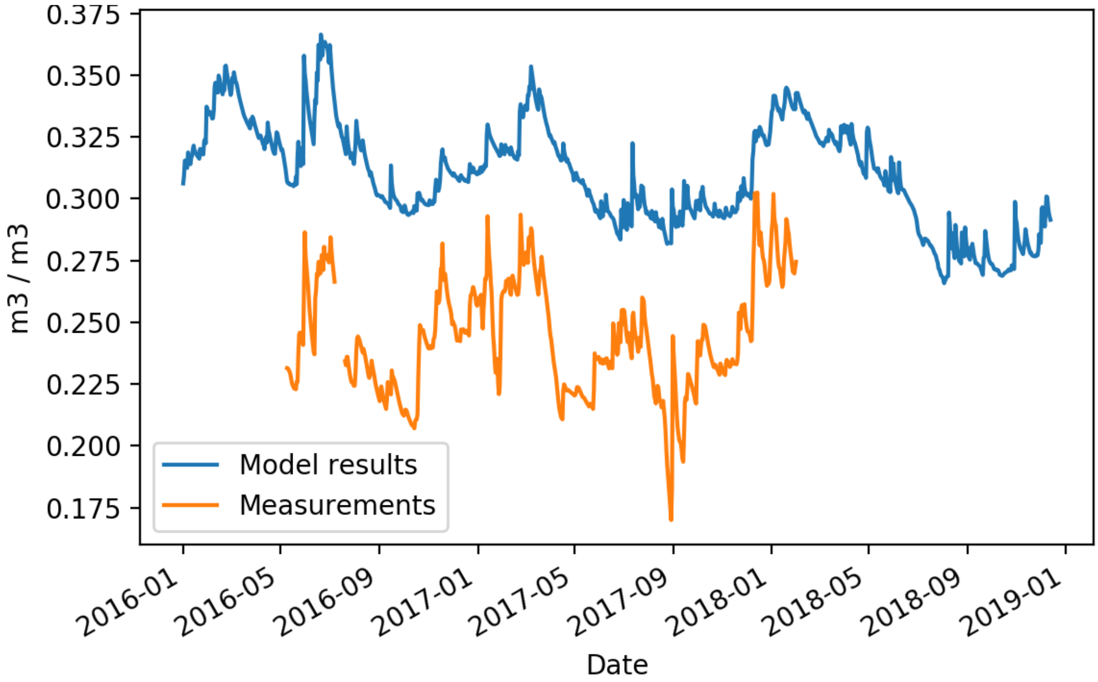


Figure 4.7. Simulated (blue) and measured (orange) soil moisture at location RM_SM_01 (top) and groundwater heads at location B45F1045, model layer 1 (bottom); surface level elevation = 9.2 mamsl.



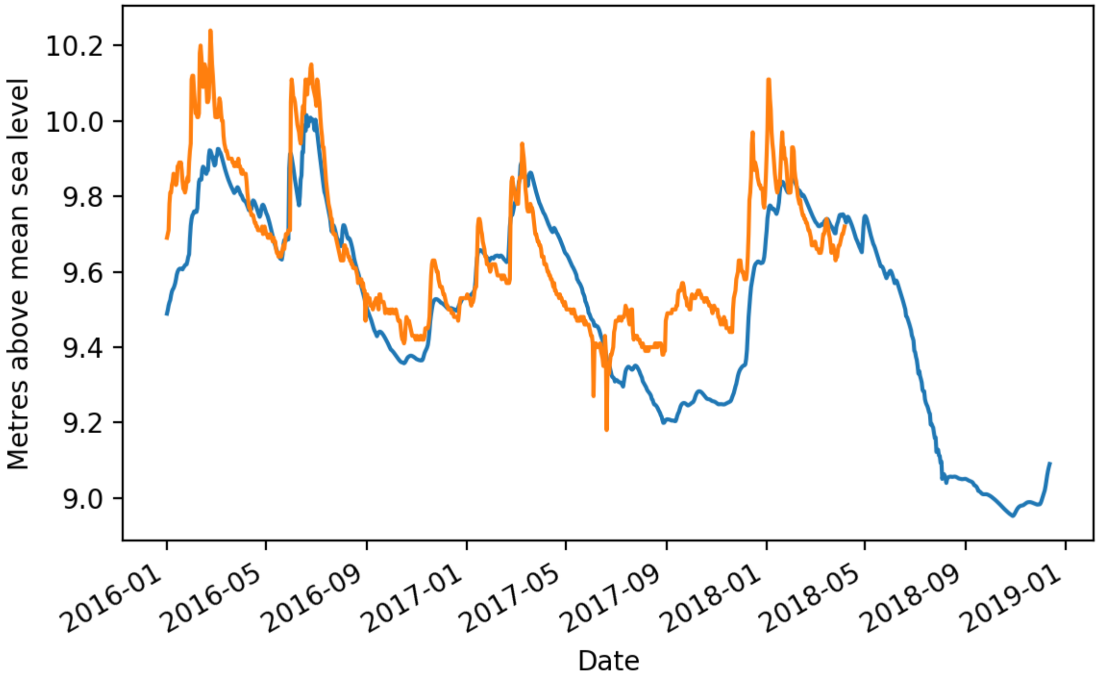


Figure 4.8. Simulated (blue) and measured (orange) soil moisture at location RM_SM_07 (top) and groundwater heads at location B46A1636, model layer 3 (bottom); surface level elevation = 11.9 mamsl.

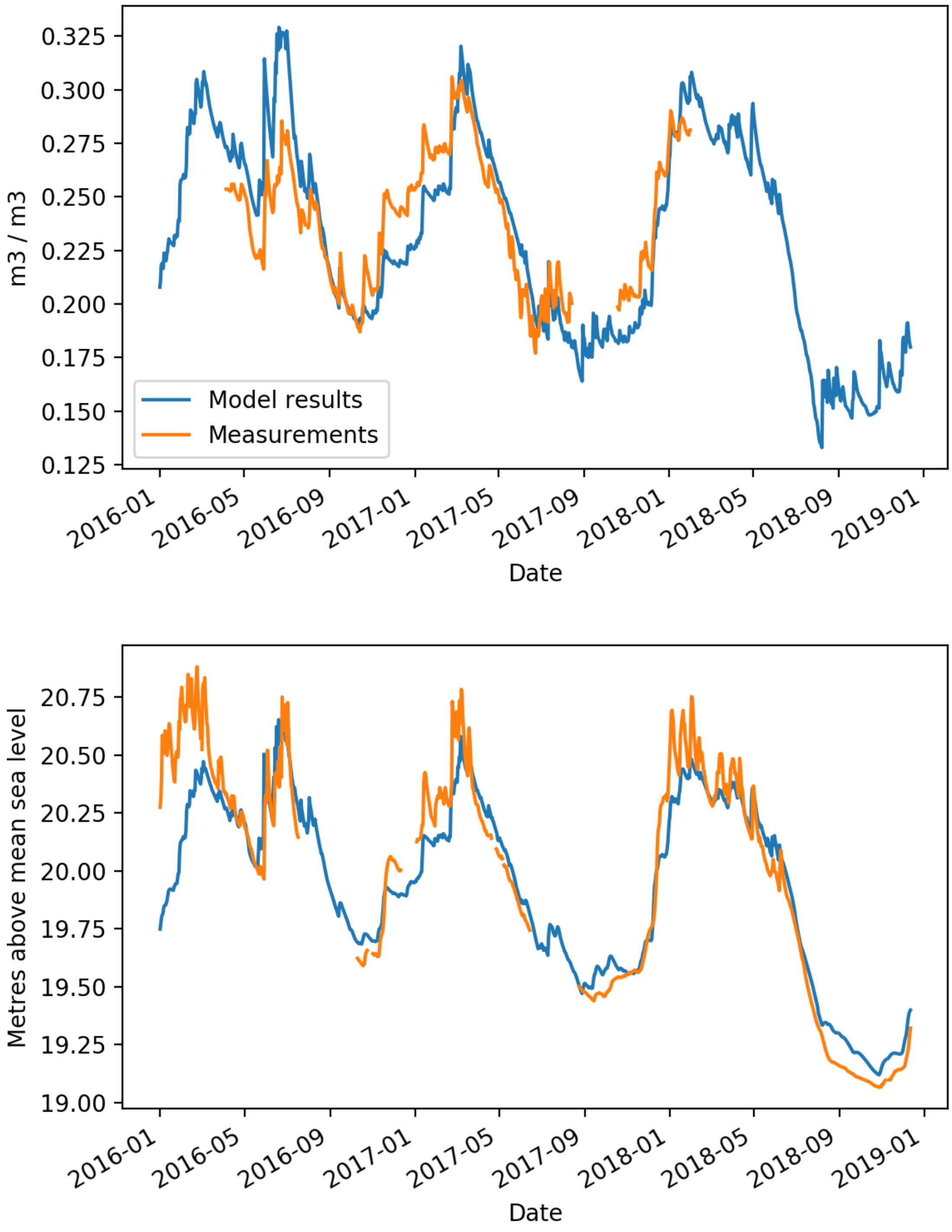
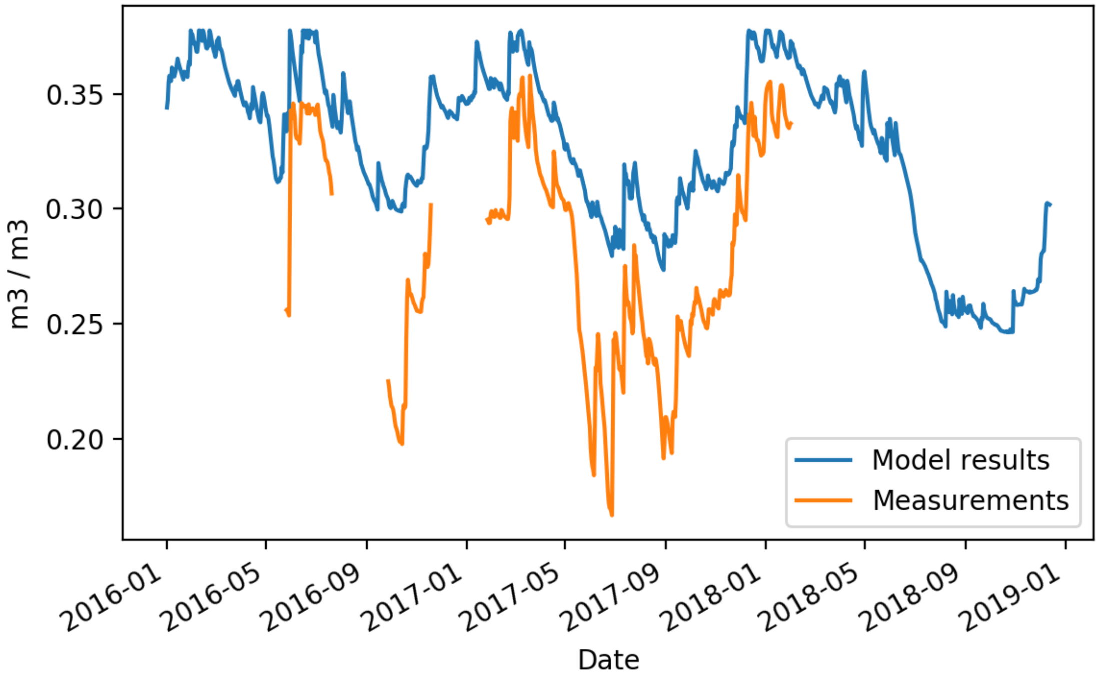


Figure 4.9. Simulated (blue) and measured (orange) soil moisture at location RM_SM_11 (top) and groundwater heads at location B46C0207, model layer 3 (bottom); surface level elevation = 21.0 mamsl.



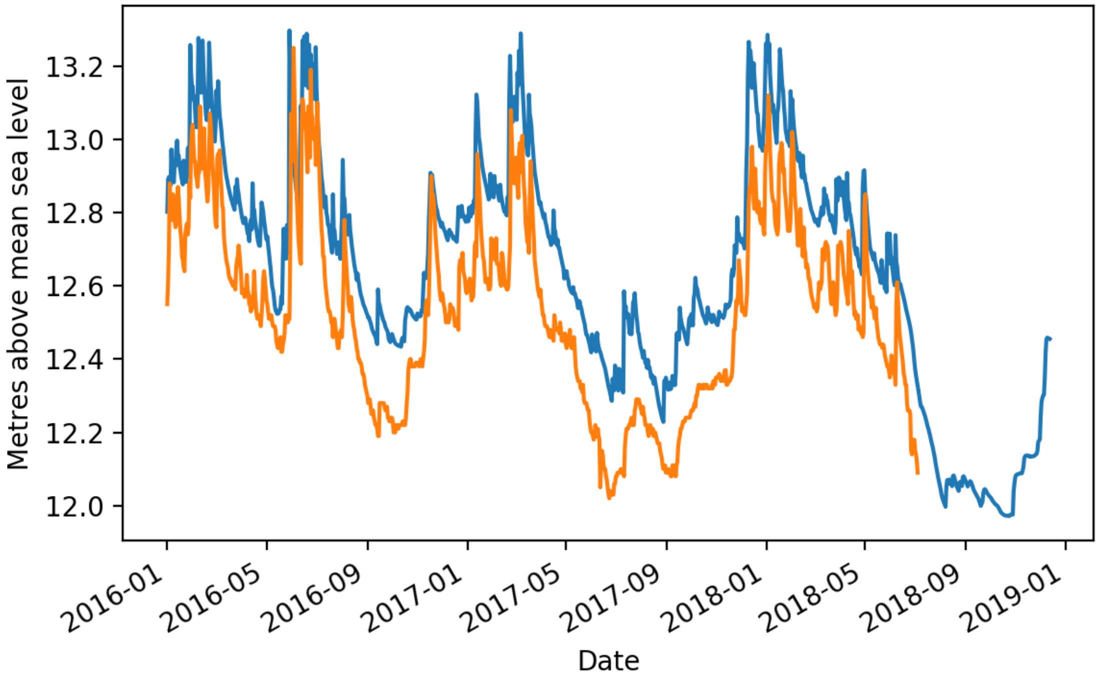


Figure 4.10. Simulated (blue) and measured (orange) soil moisture at location RM_SM_13 (top) and groundwater heads at location B46C0256, model layer 3 (bottom); surface level elevation = 13.3 mamsl.

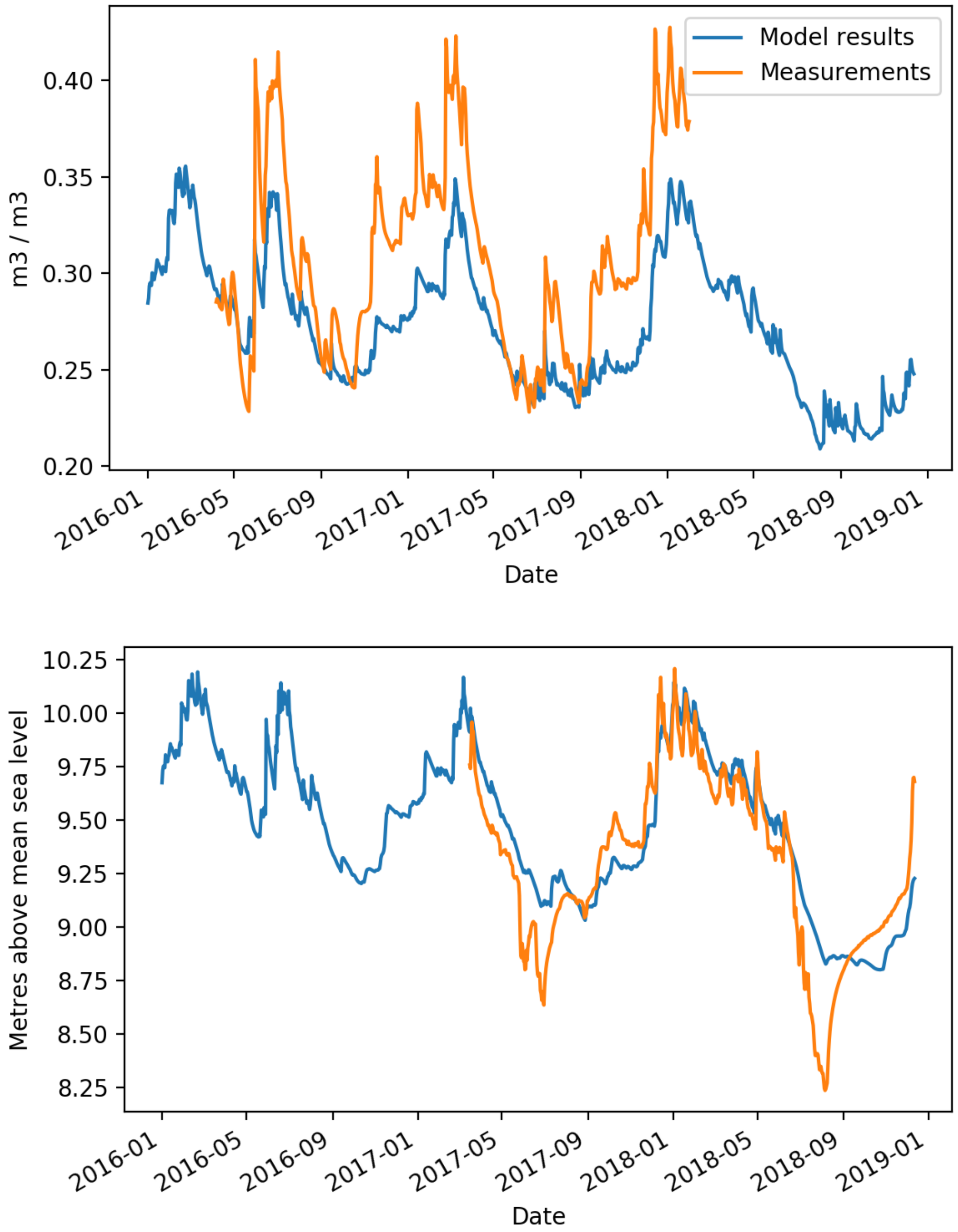


Figure 4.11. Simulated (blue) and measured (orange) soil moisture at location RM_SM_15 (top) and groundwater heads at location B46C0162, model layer 4 (bottom); surface level elevation = 10.5 mamsl.

In certain locations, the calculated soil moisture results generally provide a good fit with the measured values (SM_RM_11, Figure 4.9); however, other locations return results that are either too wet (RM_SM_07, Figure 4.8; RM_SM_13, Figure 4.10) or too dry (RM_SM_01, Figure 4.7; RM_SM_15, Figure 4.11). The location of the best fit is the highest point that is provided for comparison (elevation: +21 mamsl).

The amplitude of change in soil moisture at this location is also similar to the measurement values. This may be an indication that the calibration is best fit to higher, sandier areas (as is the case for SM_RM_11). At all of the other locations, the amplitude of the reaction of the model to changes in soil moisture content is less than that observed in the field. This provides an indication that wetting and drying processes are underrepresented for a large extent of the model.

Overall, the resulting groundwater levels provide a good indication of both the groundwater level and trend at most of the locations. For future study it would be better to calculate differences in cm, converted to m3/m3 and compare with differences. The amplitude of the measured and simulated heads in this study is in the same order of magnitude. This means that the hydraulic characteristics of the soil are captured correctly in the model. In other words, the soil water storage capacity of the model is similar to reality. There are periods of time where the observed levels decrease more than the modelled heads (summers of 2016 and 2017 at B46C0256; summers of 2017 and 2018 at B46C0162; and summer of 2018 at B46C0207). This may be due to additional groundwater pumping during the summer months that has not been taken into account in this version of the model. Another explanation is that current version of the groundwatermodel was difficult to calibrate for dry periods.

The groundwater level at B45F1045 (model layer 1, Figure 4.7) has a depth of < 1 m below the surface quickly recharges. The reaction in the model to large recharge events at this location is greater than from the measured results. For example, during each of the winter periods, the simulated results show groundwater levels that are at or above surface level. At this location, the simulated heads are often always higher than the observed heads. However, the soil moisture at the nearby monitoring location, RM_SM_01, is almost always too low as compared to the measured soil moisture. This could be due to the fact that more water is stored in the saturated zone, whereas it should be used to fill the unsaturated zone. This is also related to the estimated soil properties. Data assimilation using observed groundwater levels to correct the starting heads in the model may improve the results here.

The observation described above does not hold for the other locations that are either too wet (Figure 4.8, Figure 4.10) or too dry (Figure 4.11). For instance, in the case of soil moisture at RM_SM_13 and the nearby groundwater heads at B46C0256, the modelled results at both locations are lower than the observed measurements. The discrepancy in results here could be due to the quality of schematisation of soilparameters (e.g. combination of slightly different land, soil, and/or crop type from what is included in the model). For future study we should check how we can improve these parameters.

4.3.2 Vechtstromen

Given the large number of groundwater monitoring wells available for comparison in the Vechtstromen area, three monitoring wells from Waterboard Vechtstromen with a general overview of the results are provided here for comparison. One well from each the provincial monitoring network and DINOloket are also provided, as these datasets cover the entire period of comparison (2016-2018). These locations are provided Figure 4.12. The comparison of groundwater head measurements to modelled results are provided in Figures 4.13 to 4.17.

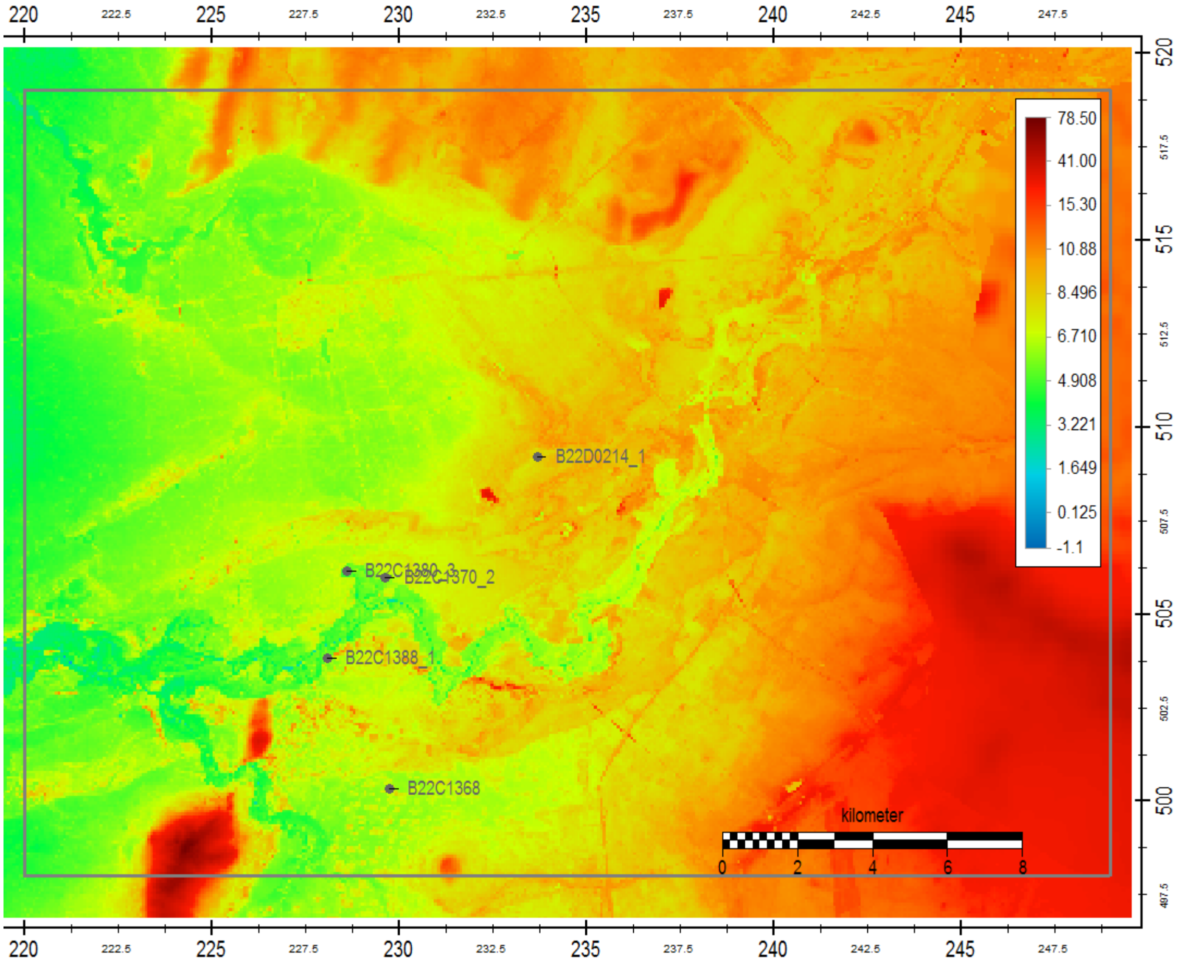


Figure 4.12. Location of the groundwater head measurements used for comparison with the model results.

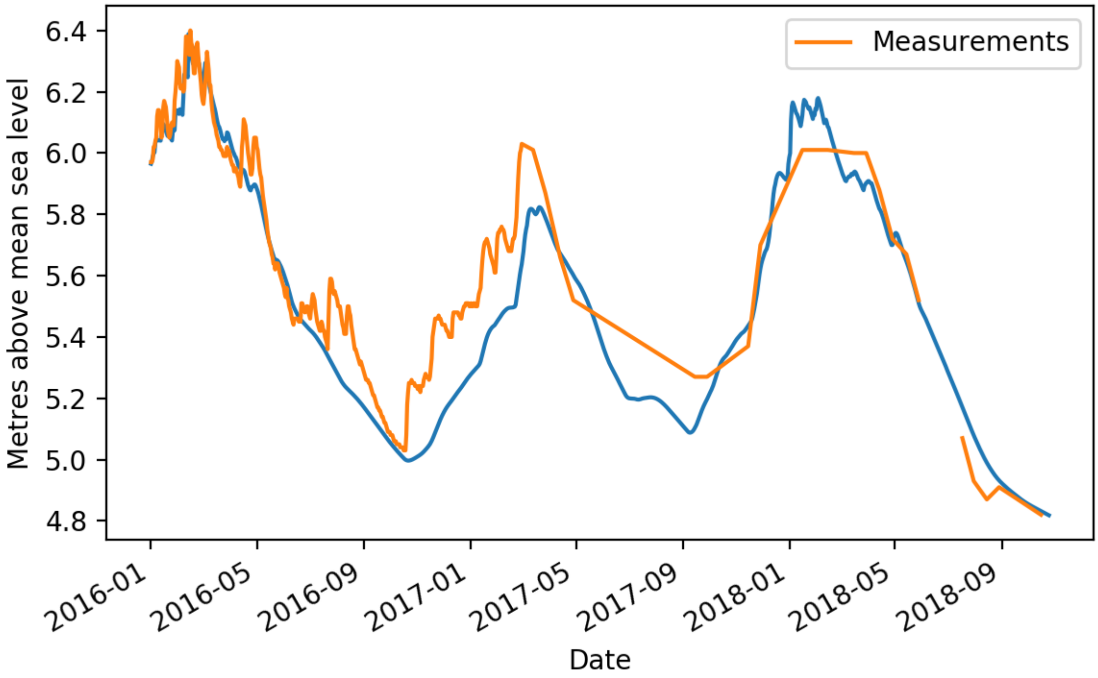


Figure 4.13. Simulated (blue) and measured (orange) groundwater heads at location B22C1368, model layer 2; surface level elevation = 7.4 mamsl.

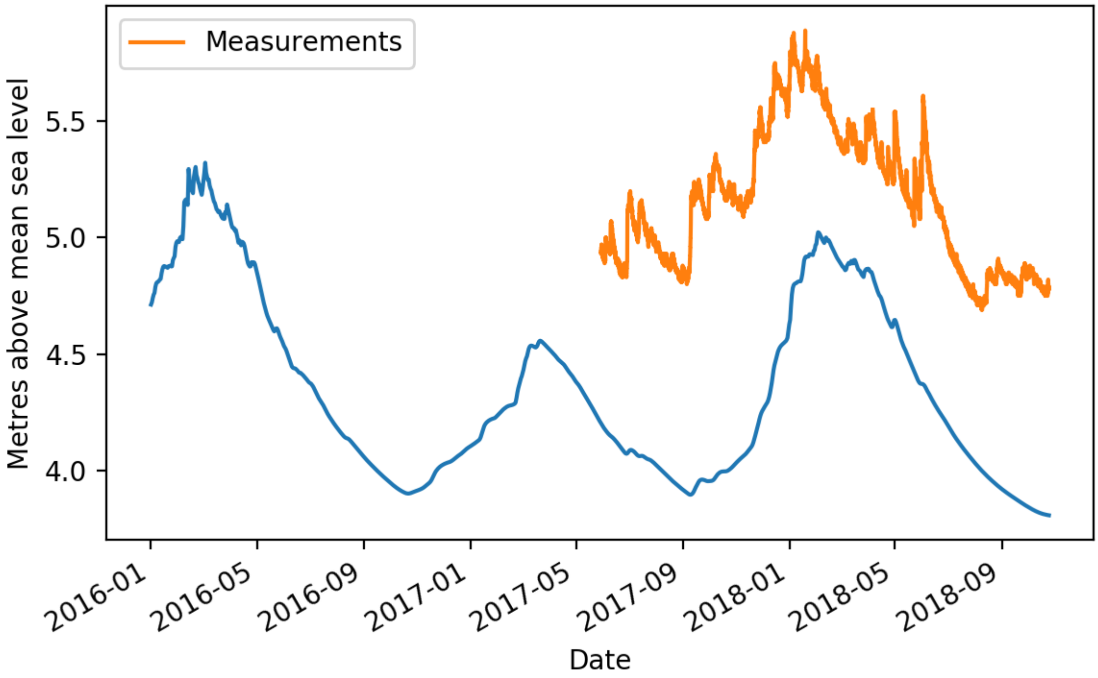


Figure 4.14. Simulated (blue) and measured (orange) groundwater heads at location B22C1370 (filter #2), model layer 2; surface level elevation = 5.68 mamsl.

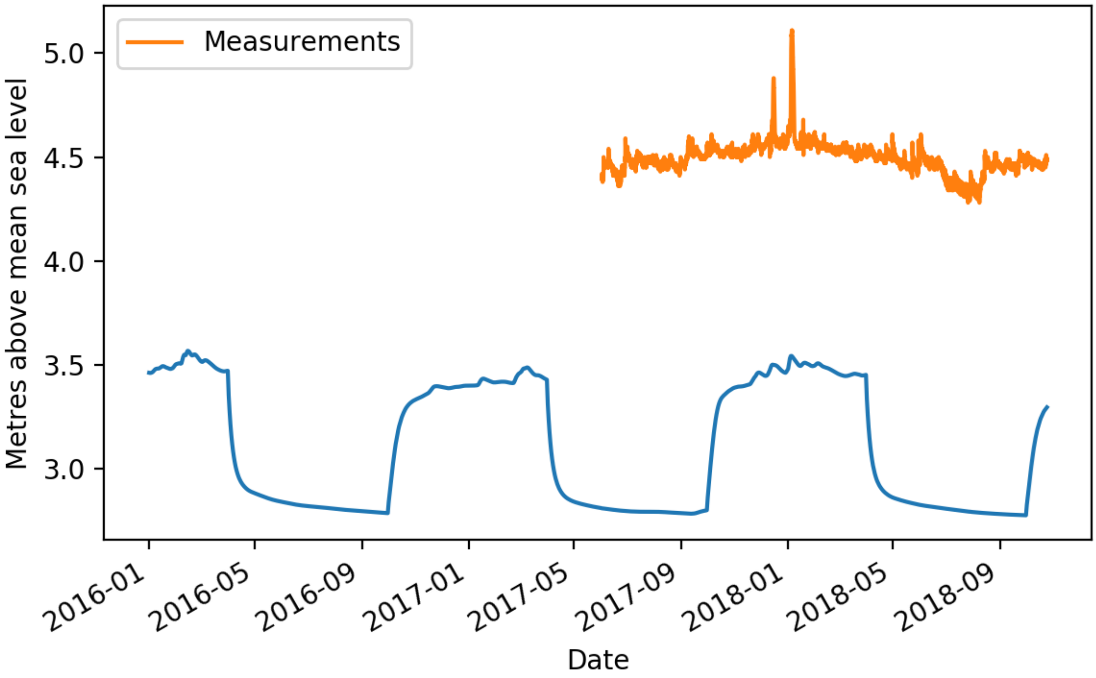


Figure 4.15. Simulated (blue) and measured (orange) groundwater heads at location B22C1380 (filter #3), model layer 2; surface level elevation = 4.46 mamsl.

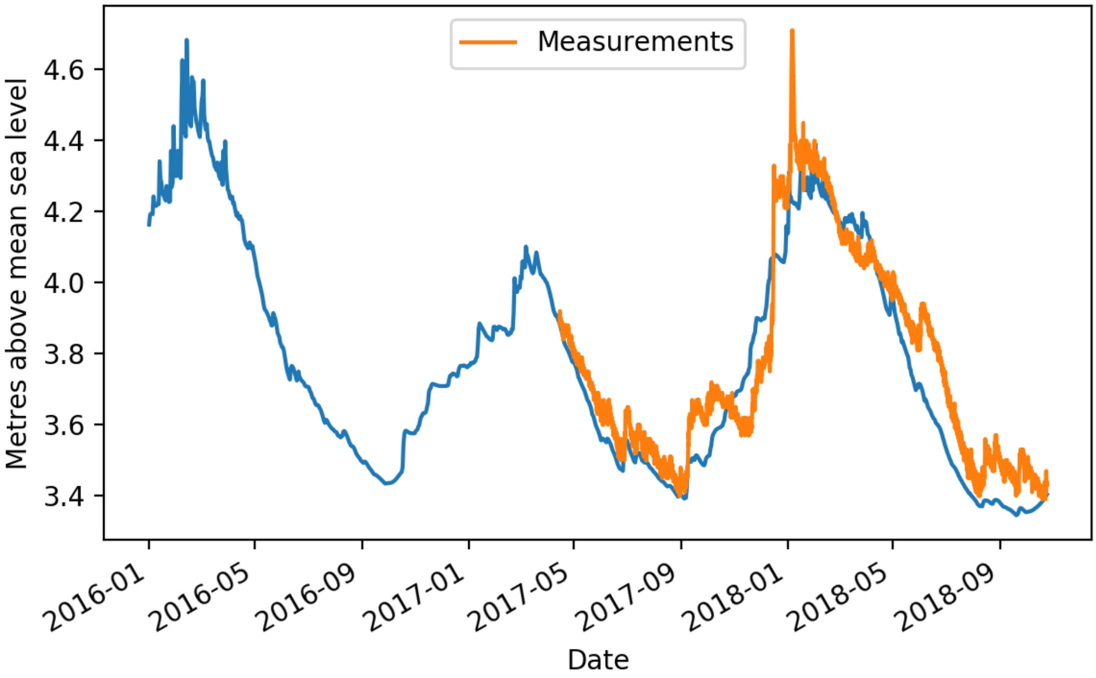


Figure 4.16. Simulated (blue) and measured (orange) groundwater heads at location B22C1388 (filter #1), model layer 2; surface level elevation = 3.93 mamsl.

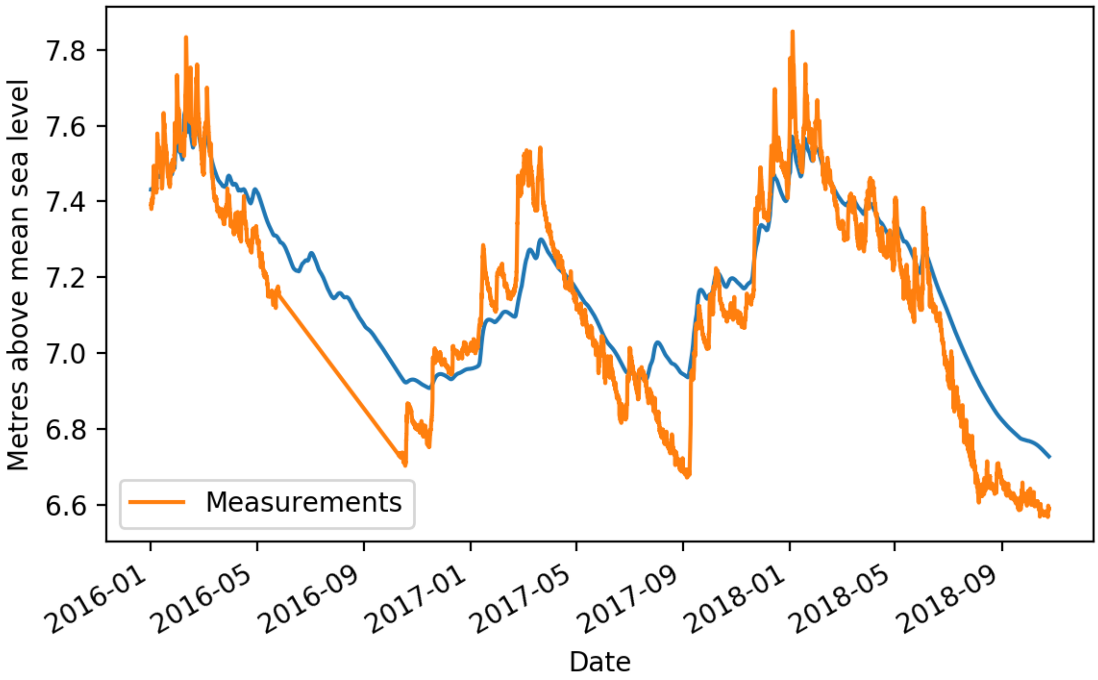


Figure 4.17. Simulated (blue) and measured (orange) groundwater heads at location B22D0214 (filter #1), model layer 2; surface level elevation = 8.64 mamsl.

Overall, the general trend of groundwater levels is represented at each of the above monitoring locations, with the exception of location B22C1380 (Figure 4.15). At this location (and other nearby monitoring locations, not presented here), the monitored groundwater levels are quite static, with only small variations a few large recharge events during the winter of 2017-2018. However, the resulting groundwater levels from the model show a distinct seasonal pumping pattern; updates to the model in these areas to better represent local conditions (e.g. pumping from wells) could improve these results.

At location B22C1370 (and other nearby monitoring locations, not presented here), despite the general trend of groundwater levels being similar, the monitored groundwater levels are consistently higher than the modelled groundwater levels and have a smaller amplitude than the modelled groundwater heads (Figure 4.14). The discrepancy in results here could be due to a difference in hydraulic characteristics of the soil from what is included in the model.

The remaining three locations analysed (B22C1368 – Figure 4.13, B22C1388 – Figure 4.16, and B22D0214 – Figure 4.17) provide a good indication not only of the trend but also of the groundwater levels themselves at those locations. There are periods where the observed levels decrease more than the modelled heads (summers of 2016, 2017 and 2018 at B22D0214), but this may be due to additional groundwater abstractions during the summer months that have not been taken into account in the model. Improvements could still be made so that the model reacts more quickly to the recharge events.

4.4 Crop yield

Within the WOFOST model, the potential and actual dry weight of stems and leaves is simulated. These parameters are dependent on the relative transpiration, which is also simulated by the model. In the simulation of the actual dry weight, temperature and oxygen stress are taken into account, whereas this is not the case for the potential dry weight.

In order to be able to understand the yield results properly, it is important to understand the land use type and basic soil characteristics, such as soil type. For example, when the land use type is grass, the model implements it as mowed grass. An option also exists for grazed grass, but this is a numerically difficult process to implement in the model and is beyond the scope of this study. The moment of mowing is triggered when the total yield (stems and leaves together) is above 4200 kg DM/ha, from the beginning of the year until day 120. Between days 120 and 213, the total yield value decreases linearly until it reaches 2700 kg DM/ha on day 213. This threshold then remains until the end of the year. In addition, the grass is mowed when the total yield stays below the threshold for more than 42 days.

A summary of various plot locations, area, harvest date, yield, and WOFOST results is provided in Table 4.2. Note that for all plots in the current model, the sowing date is May 1st of each year. This is the default in the model, and insufficient additional information was available to improve this estimate throughout the course of the project. The actual sowing date is provided for reference purposes only. The WOFOST results for actual dry weight of harvested stems and leaves and for actual dry weight of harvested storage organs are presented for the given harvest date at each plot. Note that the results are presented for indicative purposes only; an analysis on the quality of the results are not provided. Further interpretation is needed to draw conclusions about the quality of the results, such as understanding the relationship between the data provided by the farmers and the model outputs (e.g., do farmers report wet or dry yield?). Modifications to the code of WOFOST would also be needed to implement certain changes (e.g., change sowing date dynamically throughout the course of the year).

Table 4.2. Comparison of yield information to model results (provided for indicative purposes only).

Parcel name	**Crop type**	**Area (ha)**	**Actual sowing date**	**Harvest date**	**Yield (ton)**	**Yield / Area (ton/ha)**	**WOFOST: yield of stems and leaves (ton/ha)**	**WOFOST: yield of storage organs (ton/ha)**	**WOFOST: total yield (ton/ha)**
1	Winter wheat	0.45	12/10/2017	16/07/2018	3	6.67	yield information only available as of 07/08/2018		
2	Maize	0.66	24/04/2018	11/09/2018	6.5	9.85	17.91	9.99	27.90
4	Winter wheat	2.70	12/10/2017	16/07/2018	14	5.19	yield information only available as of 07/08/2018		
5	Maize	1.40	24/04/2018	11/09/2018	9.4	6.71	17.88	9.96	27.84
6	Maize	1.34	24/04/2018	11/09/2018	8	5.97	17.81	9.89	27.70
7	Maize	0.99	24/04/2018	11/09/2018	6	6.06	17.80	9.93	27.73
8	Maize	5.48	24/04/2018	11/09/2018	63	11.50	17.86	9.93	27.79
9	Maize	4.55	24/04/2018	11/09/2018	52	11.43	17.88	9.96	27.84
10	Winter wheat	3.04	12/10/2017	16/07/2018	18	5.92	yield information only available as of 07/08/2018		
77	Potatoes	2.34	25/04/2018	29/09/2018	38	16.24	7.46	4.15	11.61
Gerritsweg	Potatoes	0.64	26/04/2018	27/09/2018	17	26.56	18.18	10.28	28.46
Maurikstraat	Potatoes	1.07	26/04/2018	18/08/2018	22	20.56	17.53	12.55	30.08
Perceel 12 van Lanen	Silage maize	0.67	04/05/2018	05/09/2018	18.6	27.76	17.53	9.64	27.17
Perceel 8 de Bruin Huiskavel	Silage maize	3.24	04/05/2018	05/09/2018	171.8	53.02	17.19	9.53	26.72
Perceel Duivenbos	Silage maize	1.10	04/05/2018	05/09/2018	29.4	26.72	12.30	6.80	19.10
Udensedijk	Potatoes	8.09	16/04/2018	05/08/2018	42	5.19	yield information only available as of 07/08/2018		

4.5 Conclusions and recommendations

The setup of both the Aa & Maas and Vechtstromen models within the "Grow with the Flow" operational system has shown promising initial results. Despite large data, input, and output requirements, a connection has successfully between made between the coupled iMODFLOW-MetaSWAP-WOFOST models and Delft-FEWS. This connection enables the historical simulation of daily output based on observed meteorological data (presented here), as well as the forecasting of a number of hydrological and crop growth parameters. It provides a strong basis for the real-time forecasting of desired parameters and shows promise to be applied in an operational setting. However, care should be taken when interpreting results, taking into consideration spatial resolution of the various model inputs, assumptions made by the model, and availability of reliable measurement data to compare the results.

Overall, the model results for both soil moisture and groundwater levels for the Aa & Maas pilot area provide a good indication of trends at most of the locations. For the Vechtstromen model, most of the locations provide a good indication of the trends; however, some locations are too dry as compared to measured results, and others do not represent the monitoring data at all. Based on the observations during this project, further refinement of the models is recommended below.

4.5.1 Model improvements

In a future stage, the models could be downscaled and run at a finer resolution (e.g. 25 m x 25 m) to provide more detailed information at a plot scale. Parallel computing is recommended to be used in order to achieve this in an efficient manner; this option is not currently available with the coupled iMOD-MetaSWAP-WOFOST model and would need to be developed in future phases. It should be noted that the decision to refine the model should not be taken lightly; this is largely dependent on the purpose of the system and how the results will be used in the future in order to properly analyse the costs (additional computational time, additional refinement of input parameters needed, additional changes to model code required – including adequate testing) vs. the benefits (finer resolution of results available).

The input files for both pilot areas should be updated so that they are consistent with the most recent versions in use. A protocol should also be prepared identifying the frequency that the models will be updated as well as prior testing required before making changes to the operational system. For example, the Aa & Maas model for the "Grow with the Flow" developments was obtained from Waterboard Aa & Maas in June 2018; however, changes have since been made to the model layers and permeabilities used. After rigorous testing to ensure that the new model is compatible with the "Grow with the Flow" system, the model within the system should be replaced so that it is consistent with the most recent version in use by Waterboard Aa & Maas.

The extension of the models into the future is an aspect which would be further investigated. Within the scope of the current pilot, files from the current models were extended into the future based on the input data that was available, but without including new data. For example, pumping volumes from the wells varies over time, but no additional information was available during this pilot project. Attention should be given to updating the following model inputs on a periodic basis:

- Extractions from wells (WEL package): could be updated periodically by the model owners;
- Water levels in rivers (ISG and RIV packages): could be updated periodically by the model owners or automatically using real-time data (additional developments needed);
- Water levels in drains (DRN package): could be updated periodically by the model owners or automatically using real-time data (additional developments needed);
- Land use (CAP package): could be updated periodically by the model owners or by the farmers directly in the “Grow with the Flow” app (additional developments needed); and
- Crop information (e.g. sowing date, harvest date) (CAP package): could be updated periodically by the model owners or by the farmers directly in the “Grow with the Flow” app (additional developments needed).

A protocol should be established stating who is responsible for the updates and any troubleshooting regarding parameter updates and the frequency at which these files should be updated (e.g. automatically, weekly, monthly, yearly).

Lastly, a comparison should be made between results that include the coupling to WOFOST and without the coupling to WOFOST. For example, a coupled iMOD-MetaSWAP model could be run for the same period (2016-2018), to compare the results from this model to the results from the coupled iMOD-MetaSWAP-WOFOST model implemented in this study. This will likely be further explored as part of the Lumbricus consortium.

5 Data assimilation

Data assimilation is way to improve model results based on observational data during a forecasting process. Many data assimilation methods are available nowadays. In this chapter, we discuss the methods that are most promising for this project. Furthermore, we will propose a specific way of implementation of data assimilation in the current system. The focus of the data assimilation will be on improving the states for short-term forecasts. Data assimilation is most effective for short-term forecasts; the effect will likely not be visible in longer-term forecasts, e.g. the end of the growing season.

5.1 Available data assimilation procedures

The main data assimilation options that are applicable to our models are:

1. using the OpenDA platform to apply Kalman Filters or Ensemble Kalman Filters, or
2. Direct Insertion method.

Direct insertion is a simple technique that replaces the model states at forecast time with observed states, when available. The advantage relies in its simplicity and it is also commonly used by operators when doing manual data assimilation. Disadvantage of this method is that the correction is not propagated to the rest of the model states. Therefore, the effect is only limited to the model state itself and the propagation of the error correction in the forward model, i.e. model states that are computed form the corrected states. Alternative methods, on the other hand, such as the Ensemble Kalman Filter technique, are able to propagate the corrections to other model states. However, this is done by looking at the correlation between an ensemble of model states propagated in the forward model using MonteCarlo simulations. This means that the model needs to be run multiple times in order to assess the covariance observed states. One disadvantage of this method is the additional computational time when compared to direct insertion.

5.2 Data assimilation of groundwater heads – pros and cons

Direct insertion is more suitable for our approach, because we have groundwater heads that can be easily replaced per time step, and the results are also function of those heads. Therefore, this approach will be more efficient, computationally, and more likely to be used in the future operational forecasting of the Farmers’ App system. The effect of direct insertion of head states in the model would propagate to the rest of the model, so the assessment of data assimilation can be done looking at multiple variables as long as we have observations for those variables. When applying direct insertion it is recommended to assess the results of the data assimilation method using the comparison of the heads itself. In this way the forecasted heads are obtained for a given lead time, which can be compared with real observations. This should be done in combination with analyses of the uncertainty due to variations in the soil. Notice that in that case the uncertainty in the model results can also come from the meteorological forcing, i.e. the meteorological forecast will differ from observed meteorological data. A separate experiment can be run using the observations as ‘perfect’ forecast which would remove this part of uncertainty. This means that instead of feeding the forecasted forcing (e.g. precipitation, temperature, etc.) to the model, the observed forcing is used. In this way, the level of uncertainty of the predicted heads what is solved by the data assimilation procedure can be assessed. If, for example, the forecasted precipitation differs from what actually precipitates, the model will have a difference in the states. This difference would then be a combination of the uncertainty that was given to the model in the initial states and the uncertainty (error) of the meteorological forecast.

5.3 Data assimilation of soil moisture – pros and cons

Besides groundwater heads, we are planning on applying data assimilation also for soil moisture measurements in a later stage. However, this is more difficult than for groundwater heads, because the soil moisture that is measured is not necessarily the same parameter that is used as input for the model and / or calculated by the model. So basically, they are two different definitions calculated differently, and it wouldn’t make sense to compare them. If it is wished to compare them, there is usually a transfer function behind it, e.g. in a simple hydrological model, the observed saturation as a percentage could more or less correspond to the SM/FC (where SM is soil moisture and FC is field capacity). In the model used in the current system, there is an equivalent function for soil moisture. In this case it could make sense to make the assessment for this variable as well. Another option could be to do this also for the saturated moisture content. However, we need to make sure that we export the model state and that we apply this function before comparing it with observed data. It must be realized that the model is quasi-steady state, so the moisture profiles are built up from pieces of stationary profiles. Especially at the top there are strong deviations from reality. Hence, comparing the first 10 cm makes little sense; however, this is typically the maximum depth of the satellite observations under optimal conditions. Therefore, using remote sensing data in this case might be less reliable than in situ data. Due to all these question marks, further investigation is needed to assure soil moisture can be added in the data assimilation.

5.4 Future developments data assimilation

The implementation of the direct insertion method into the system contains different steps. We propose running a ‘simulated forecast’ for the year 2017 without data assimilation and one with updated starting heads (state variable) for each day. The data assimilation run should be based on observed measurements from DINOloket, interpolated for the area and based on the corresponding, most representing, layer for each well. After the simulations are completed, the results of both runs can be compared, to see if data assimilation improves the results on the short-term. For this the following steps need to be taken:

1. Divide observation wells based on the model layer that the well screen is in.
    a. Discuss what to do if well screen is present in more than 1 layer. Options here are to exclude the observation well or select the layer where the majority of the well screen is located and apply observation well only to that layer.

2. Prepare script to interpolate between all observation wells for a given layer for a given time step (day).
    a. There is an iMOD batch-function that can perform an interpolation based on an IPF-file. However, maybe this doesn’t work or is too slow when you have continuous measurements coming in. It might be faster to make a script that will do the trick or maybe there is a FEWS transformation module function that can take care of it.
    b. Discuss what to do if either no well is present in a given layer, or if very few measurement points are located in a given layer.
    c. Current functionalities and related speed need to be checked.

3. Set up FEWS to run model for 2017 in the same fashion as described above.
    a. Although instead of taking the output heads (result) from the previous time step, modify the input starting heads (state files) for the next simulation.
    b. To do this, use a general adapter that will take the resulting heads from the previous time step and substitute the heads at certain locations with the observed heads.

   c. Discuss whether an interpolation of neighbouring cells should be performed to smoothen the grid.

4. Repeat runs on a daily basis for 2017.

5. Plot results from baseline run with results from run using interpolation from observed heads (data assimilation run).

6. Compare difference between modelled heads (both scenarios) to observed data.
   a. Scenario (with or without data assimilation) with smaller difference between observed and modelled results is deemed to provide best results overall.
   b. Prepare script to do the comparison.

7. Based on outcome:
   a. Apply data assimilation procedure to forecast so that future predictions can be improved.
   b. Ensure that when running the forecast, the results are not purged or overwritten so that the substitution of observed values into the output grids (and possible interpolation) can be performed correctly.

8. Documentation and analysis.

6 Design and development App

6.1 The AGIF Program of Achmea

The Farmer’s app is part of Achmea’s Agro Geodata Insurance Framework (AGIF) framework, developed in cooperation with MI since 2016. The primary goals of the AGIF programme are to improve farmers’ yields and improve communication between farmers and Achmea. This is done by providing information and services by Achmea that benefit the farmer. For example, it provides agriculture-related news and tips, risk assessments and the ability to report damage quickly and conveniently for insurance claim purposes. It is a digitization of several previously manual and/or paper-based processes done within Achmea Agro, including:

1. Farmers need to specify crop plans periodically. Given this information, Achmea can send farmer insurance quotes and then finally insure the crops. The process of crop planning has been digitized as part of AGIF via the Digital Crop Registration Application (DCRA).
2. In case there is damage, farmers can send insurance claims. These claims are processed, and loss needs to be estimated. Parts of this process is already digitized in AGIF:
   - Ability of the farmer to add a claim using a mobile app (the FAPP), marking the geographical location of the claim and including metadata.
   - Ability of Achmea to review claims and assign loss adjustors via a web-based application, the Damage Assessment Application (DAA).
   - Ability to assess damage automatically and semi-automatically using remote sensing and digitization of loss adjustors’ expertise.

The FAPP, described in this section, is also part of AGIF, and it’s feature scope within AGIF is yellow in Figure 6.1.

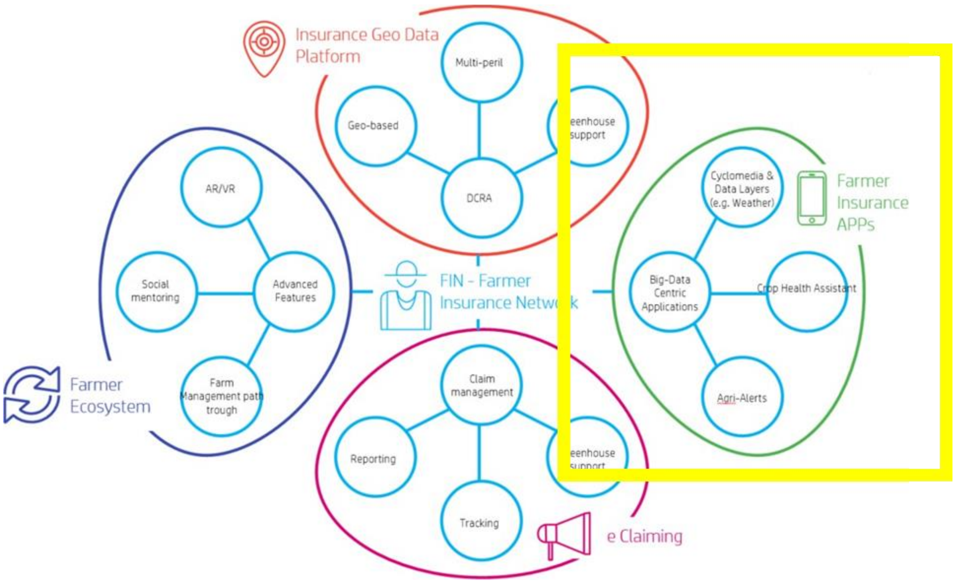


Figure 6.1 Functional map of AGIF. This figure depicts the high-level features of AGIF and how they are categorized. The Farmers App (FAPP) is yellow highlighted.

6.2 Architecture of AGIF Framework

The architecture of the AGIF framework is composed of multiple applications (e.g. DCRA and DAA described in Figure 6.1). Each application has a front-end (the software defining the user interface and interaction) which runs on the user's device and a back-end (the software responsible for business logic, transactions and storage) which runs on an AGIF server.

All applications use a layer of services which are needed across the framework, e.g.: a service for Authentication and Authorization (A&A), Graphical Information System (GIS) capabilities, Internationalization (I18N) and auditing.

Finally, AGIF makes use of the SAF developed by MI. The SAF provides a cloud-based service for multiple customers, including Achmea.

Currently, AGIF uses the SAF for geo-based data processing and analytics, including use of crop-growth models such as WOFOST and LINTUL (models developed in Wageningen University). As an example, AGIF uses SAF in order to automatically analyse losses for reported claims. Images taken by drones are analysed by SAF, input is fed into crop growth models, and loss calculations are sent back to DAA.

6.3 Extensions to Farmer App

Achmea would like to extend the Farmer App (FAPP) to deliver additional information that provides valuable and actionable insights to the farmers. Examples include: weather data, yield forecasts and soil moisture data. The models and associated user interface were developed in the Grow with the Flow (GWTF) project in close cooperation with Deltares, Wageningen Research and Milan Innovincy. At first stage GWTF-app has been developed separately, in its own portal, and not part of the FAPP to keep the project well confined, decoupled and simple to develop and test.

Once some feedback is collected, the GWTF user interface would be integrated into the FAPP. The back-end would essentially remain the same in both stages.

This information needs to be tailored to specific farmers and be accurate enough to be relevant to individual plots. It is therefore desirable to receive the data exported from the coupled models in the FEWS system and transform it so that it can be served to individual plots.

6.4 FAPP and SAF

The FAPP is using the Spatiotemporal Agribusiness Framework (SAF), as developed by MI. The SAF is a general purpose framework (i.e., not specific for Achmea) which implements a set of technologies for processing agriculture and agribusiness related data, consolidating, transforming and aggregating it, including the ability to split and scope for individual geographical features (such as individual plots). It is then possible to perform analyses of data over time, and activate machine-learning, mechanistic and other types of models for performing assessments and predictions.

SAF contains a database of plots, whose source is a database of Achmea that stores the digital crop plans of farmers. This database contains both the geographical coordinates of the plots, as well as metadata such as the crops, varieties and owners.

The SAF is a Software as a Service (SaaS) and provides an Application Programming Interface (API) for:

1. Developing data collectors that are capable of pulling input data from external sources. For example, public websites;
2. Pushing input data into it from other applications or systems; and
3. Pulling output data from it.

The SAF is capable of two types of processing chains: online and offline. Online processing occurs as part of an application user interface request for information, or in other words, the user initiates the processing and will usually expect a result in near real-time (a sub-second response time). The SAF receives the request, executes the processing, and returns the results.

In offline processing, all of the processing chain is done in the background, not bound to an application workflow. The outputs are then stored and become available for applications to use. This provides an optimization over the online method, for cases that the processing is computationally intense, which would result in an unacceptably high latency. The main downside is of course that the system needs to perform processing for all possible inputs (in our case, all plots), even for rarely accessed data. Another downside is that changes or updates to the input data or configuration can result in re-computation of all the previously computed data.

The SAF is capable of combining the two methods and performing some computations, possibly ones that are more intense, offline; the rest can be done online.

Within the GWTF project, the processing chain from FEWS to the FAPP is designed to work as follows: (see also Figure 6.2)

6.4.1 Chain A: Executed periodically offline.

- Check if new data is available. If so:
  1. Download the data, in NetCDF format. NetCDF is a binary format that encodes output from FEWS as a grid or as multi-variable timeserie. Each data point in the grid describes an N x N squared area (in phase 1, N = 100 meters). Metadata of the NetCDF contains the Geo envelope of the image (the coordinates of the boundaries, which can be used to compute the coordinates of each pixel, or to find the pixel that correlates to a given coordinate (a.k.a, image2ground and ground2image).
  2. Convert NetCDF to GeoTIFF, which is the SAF “native” format for geo-centric grid data.
  3. Store the GeoTIFF data – tag it with the correct timestamp (the time at which the information was acquired, not necessarily the time it was downloaded).
  4. FEWS also provides plot averaged data for some of the variables. This data is downloaded as well, then parsed and stored in the SAF database. This data is also tagged with the correct timestamp (data are shown in detail in appendix B)
- If no new data is available, no processing occurs until the next check. The period in which new data is checked for is configurable (currently once a day).

The app’s user interface, whenever requested by the user, calls the SAF API, while specifying which variables are required for display, for which plot(s) and for which point(s) in time, and so the following processing chain is performed online:

6.4.2 Chain B: plot ID(s), time, list of requested variables (input).

- Fetch the relevant GeoTIFF(s) based on the time and requested variables.
- Retrieve the list of requested plots from the database. For each plot:
  1. Crop image by plot: superimpose the plot boundaries over the GeoTIFF grid, and filter the pixels contained in the plot.
  2. Apply aggregations for some of the parameters: based on the land use preloaded pixel map, filter out pixels whose land use match the plot's designated crop. If there is more than one such pixel, compute weighted averages over the requested variables. The weights of the averages are the percentage of the surface of each pixel being occupied by the plot.
  3. Store the result in the database, (key is plot + time). This is an optional optimization available in the SAF in order to speed up subsequent queries. In either case, the result is sent back the API caller.

The following (Figure 6.2) is a visual description of steps in chain B, which transforms an image and a plot to plot-based analytics.

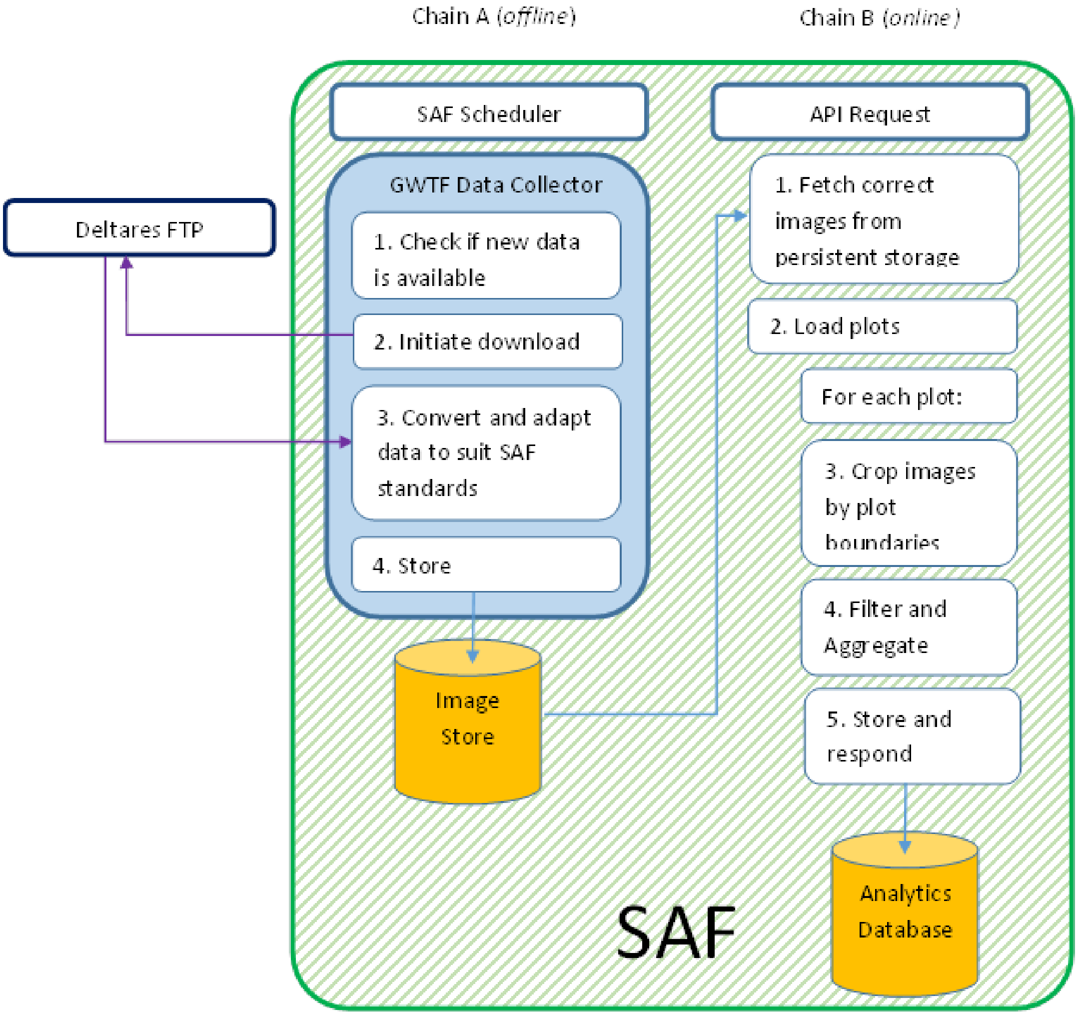


Figure 6.2 GWTF processing chains

6.5 Functional description of the FAPP

For the first step in the development of the FAPP the following requirements were identified: (the final specifications can be found in Appendix C)

The user should be able to:

- Identify and authorize himself
- View the plots of his digital crop plan (for the current year)
- Select a plot and receive (visualised) data for this plot
- View basic meteo data for the selected plots:
  - Temperature (time series), actuals and 5-day forecast
  - Precipitation (time series), actuals and 5-day forecast
- View basic plot and crop data:
  - Land use (crop info), as used by WOFOST (model input)
  - Soil type (Model input) (map or single value)
- View available moisture for plant in root zone
  - pF value (if possible) or other metric to express available water
- View crop water use
  - Evapotranspiration (time series), actuals and forecast
  - Calculated water deficit (time series) actuals and forecast
- View crop development
  - Growth stage (time series), forecast
  - Dry matter production (stem, leaf, root)
  - Yield prediction (stem, lead, root) at harvest moment
  - Calculate/estimate gross yield after moisture correction
  - This requires manual input of estimated moisture content
  - Or: visual representation of gross yield at a variety of moisture content levels

The functional requirements are translated into user stories and screen designs (see appendix C). Due to new insights and some technical or functional constraints the final specifications may differ from the initial described functional requirements.

This document is the final specification for the FAPP system development.

6.6 Technical description of the FAPP

The following diagram (Figure 6.3) depicts the architecture of the FAPP, the integration it has with the SAF and indirectly with FEWS, and the main data flow.

The main data flow starts with FEWS, which runs the models and stores the results in a File Transfer Protocol (FTP) server. The FTP is accessible to the SAF, which downloads the data for further processing.

Within the SAF, work is divided between 3 components:

1 AppServer – an application server that provides the API for applications like FAPP to get spatial-temporal data and analytics at the pixel level, plot level and regional levels.
ProcServer – the server responsible for executing processing chains, such as the ones described in section **Error! Reference source not found.**.
2 GWTF data collector – a component developed specifically for this project, which is responsible for downloading the data generated by FEWS and storing it in the SAF database.

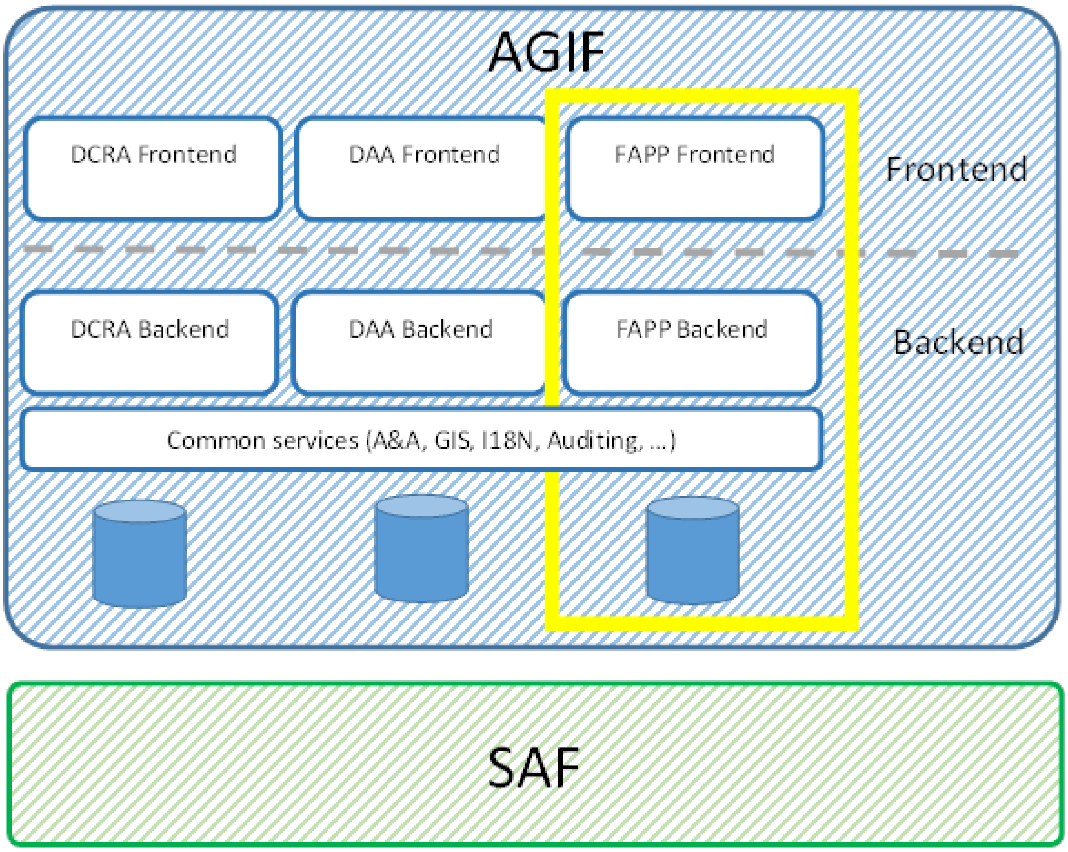


Figure 6.3 High-level architecture of Achmea's Agro Geodata Insurance Framework (AGIF)

The FAPP requests specific data about plots and pixel levels from the SAF, by accessing the SAF AppServer. Such requests may either fetch data from the database, or trigger requests to the ProcServer in order to perform additional processing. The FAPP was redesigned in order to be able to integrate the GWTF features in it.

One issue with this integration was that the AGIF project is proprietary and its code is closed. This includes the code of the existing FAPP, not including the GWTF component. However, the GWTF project is developed as open-source (as part of the project's requirements). The FAPP-architecture had to be redesigned in order to protect the code of AGIF unrelated to GWTF and keep that code closed-source, while keeping everything developed for GWTF open-source.
In order to do that, the components or mini-apps in FAPP were redesigned to be decoupled so they can be pluggable within the FAPP. This way, mini-apps can be developed in their own source code repository, then can be built, packaged and deployed to the FAPP itself. The FAPP Mini-app API is the interface in which the mini-apps interact with the FAPP.

7 Evaluation Farmers use of crop growth information

7.1 Initial User requirements

In a workshop setting, 5 farmers were visited and interviewed on location. Target of these workshops was to obtain insight in the information needs of farmers and to find a relation with parameters that could be provided by the GWTF project (model outputs). This resulted in an inventory of needs and expectations with regard to the parameters, apps, portals to be developed. From this inventory the most promising and feasible features were selected for the first stage of the project. Selection criteria are:

- Available time and budget and the need to gain experience in the use and accuracy of the models
- Contribution to base infrastructure for providing model data (from models)
- Most promising farmer needs.

7.1.1 Observations from interviews with farmers

There are many ‘point solutions’ for specific parameters like soil moisture or dry-matter production, but not many integrate the results and turn it into actionable items. Availability of GPS and other features for detailed field observations, facilitates precision farming and active data feedback.

There is a need for an integrated solution, completed with market and pricing information. Information is useful for daily support during the season but also for long term planning and financial decisions (investments). Several of the interviewed farmers explained that apart for information about the regular arable crops, useful parameters about grass as a crop are very relevant for them. Many of them have a mixed farm (mix of dairy and grass/arable crop). Challenge for these farmers is to be self-supporting with their protein production.

The acidity level (pH) of the soil is becoming increasingly important for the crop rotation planning. Information about current status and prediction and simulation is very useful. Planning and optimising fertilization is important from environmental, but also from cost point of view. Forecasting effectiveness and simulation could help. More information for farmers is useful but should not only serve crop protection and yield optimization. Many interventions have great impact for life in the soil and insects. Insight in impact is very useful. More general: increasingly farmers are held accountable for environmental aspects of their business.

7.1.2 Requirements for presentation of data

There is a need for core operational information quickly available in an app. Especially information that influences daily management decisions. To be completed with relevant market info like price developments of products, production rights etc. Preferably in graphical or image presentation.

Detailed (numerical) information about plots preferably presented in the portal on larger screen and with options to share (download) these figures and use them in other (personal) applications for further processing.

7.1.3 Requirements – conclusion

Based on the above we explored several domains where information can add value.

Sprinkling/managing available water

Effectively applying additional water requires good timing and estimation of the right quantity. Purpose is to avoid water stress but also (like last season) to cool the surface. Irrigation/sprinkling has impact on salt levels (EC value). Water is a scarce resource, but the operation of sprinklers is also costly.

Potentially interesting parameters are:

- Water stress in plant
- Precipitation deficit
- Soil temperature
- Growth stage of the crop
- Radiation (UV)
- Ground water table
- Available water in root zone (pF value)
- Salt level (EC value)
- Groundwater flow (seepage).

Manage the Use of pesticides

Pesticides are necessary, but the use of pesticides is under pressure. Responsible use requires the right moment, right place, and right quantity.

Potentially interesting parameters are:

- ‘Black soil’. Right moisture content in top layer
- Dew point
- Wind speed and direction
- Specific information about development of diseases in the crop or on plot (anomalies).

The app ‘Gewis’ is currently giving information about this (payed service).

Timing of harvest and post processing

After harvest the products are stored and processed (cooling, packaging etc.). It is becoming increasingly important to link harvest and storage conditions to a particular batch of the product. This allows for a good control in the chain from farmer to processor (or consumer). Some parameters have impact on the price (sugar, starch content).

Potentially interesting parameters:

- For harvesting (timing): condition of the soil, weather forecast
- Crop attributes (see above)
- For sales: market prices.

Data sources already used:

- Development of market prices for agriculture products (DCA), future market
- Export figures (VTA)
- Growth and cop information (qualitative) (BoerenBusiness), harvest predictions.

These are all payed services.

Some farmers already make use of what-if scenarios in a spreadsheet (simulation).

Managing more than one season ahead
Running a good business requires long-term planning and forecasting. There is a lot of financial pressure and risks. The bank highly appreciates long term crop-plans (income) and cost estimates.

Potentially interesting parameters are:

- Historical data on crop, yield and trends
- Business model, 5 or 10 year forecast of costs and benefits (financial model).

Required: good features for simulation of best and worst-case scenario's.

Dealing with accountability farmers
Increasingly farmers are held accountable for the use of the land, pesticides, fertilizer etc.
It triggers questions like:

- Was it necessary to use product X?
- What were the circumstances?
- How much was used?
- Is that in line with the outbreak of a disease (the incident)?

Defining the right (soil) conditions and circumstances, capture and store these data might give the farmer the evidence that his management practice is safe and compliant with regulations and a permit to operate.

Potentially interesting parameters:

- Circumstances of incident (e.g. outbreak of disease)
- Conditions for intervention
- Triggers to check whether conditions are met.

7.1.4 Selected requirements for this stage of the project

The above shows a wide range of opportunities, all output of the workshops with farmers. Ambition level of this pilot project is to first develop the basics. Following requirements and/or parameters are selected for the pilot in this project:

In the first phase only available model outputs and some basic data will be presented to the user of the FAPP. These include:

- Basic meteo data, actuals and forecast
- Basic plot and crop data
- Information about use of water and available water
- Crop development and yield production expressed in produced dry matter

The ultimate goal for farmers will be met when actuals and forecasts are available on a pixel size detailed enough to show relevant information on plot level. For that purpose location and some basic plot attributes need to be made available. Within the scope of this project pilot farmers can provide that information. Plot location can be obtained from digital crop plan (source DCRA or RVO).

Information can be made available in pixel format (image), as a single value on plot level or as a graph. Time series will be made available as graphs or tables.

7.2 Participants workshop

Customers of Achmea that have their address in the Raam Area have been approached to participate in the project. In total 14 companies have been contacted of which 5 joined the first workshop. Pilot farmers have been:

Melkveebedrijf Nabuurs	Kwekerijweg	15	5454 PK	Sint Hubert
Van den Oever-Agro	Lactariaweg	22	5844 AJ	Stevensbeek
VOF van de Mortel	Hoogveld	3	5841 CV	Oploo
Evers Melkveehouderij	Maarsven	8	5821 EG	Vierlingsbeek

7.3 Recommendations for future developments on the FAPP

During workshops and evaluation sessions the following recommendations for future development were mentioned:

- Add functionality for harvest prediction for several widely used crops. Currently the models are capable to calculate dry matter production. From there it should be possible with season forecast to arrive at the season dry matter production at harvest. Research is required to transform the dry weight (net harvest) into the gross (wet) harvest as measured under field circumstances.
- Add functionality to use plot level observations and (machine-) data to improve accuracy of model outputs. More and more data are available on plot or machine level. Feeding the models with these data could help to improve accuracy or to calibrate the model parameters. For some parameter settings the following sequence could be considered: start with default setting, next: model output for region or pixel lever, next: local (uploaded) observation, next: manual override (manual input). This will increase the value of the model outputs and motivate farmers (or other stakeholders) to participate.
- Create features for simulation by adding what if scenario’s for different weather and crop data. This will support management decisions and could help to decide about specific local circumstances or conditions.
- Make the FAPP more actionable by adding advice and link with farm planning and forecast tooling and machinery. Many of the model outputs are used to decide about extra costs or time spend. The data can be used as input for farm machine planning, planning of water suppletion in combination with optimizing resource use (machine, time, fertilizer etc.)
- Add financial data (futures pricing) and facilitate financial decision making. In combination with resource planning and harvest forecast supporting the farm economics.
  - Give insight in overall averages, share data where possible (peer to peer). Even with a small participation of farmers extrapolation to non-participating farmers and plots a better view of the current status of the crop and the regional forecast can be achieved.
  - Create features to share data with the water boards (required water levels) and visualize these. One of the farmer feedbacks was the requirement from farmers to improve feedback to water boards about water levels and water use. The app can facilitate two-way communication.

8 Conclusions and recommendations

The goal of this project was to demonstrate the possibility to develop a real-time forecasting system for crop production, enabling water boards, farmers and the insurance broker to improve their services and possibly reduce costs. The setup of both the Aa & Maas and Vechtstromen models within the “Grow with the Flow” operational system has shown promising initial results. The real value of the system can only be demonstrated in a real time setting. Although the initial goal was to test the system live in the field during the growing season we have been successful in finalizing the system and demonstration of the possibilities for a wet (2016), “normal’ year (2017) and dry (2018) season.

8.1 Conclusions

Despite large data, input, and output requirements, a connection made between the coupled iMODFLOW-MetaSWAP-WOFOST models and Delft-FEWS enables a realistic historical simulation of daily output based on observed meteorological data, as well as the forecasting of a number of hydrological and crop growth parameters.

Overall, the model results for both soil moisture and groundwater levels for the Aa & Maas pilot area provide a good indication of trends at most of the locations. For the Vechtstromen model only groundwater heads have been analysed. For the Vechtstromen the analysed locations provide a good indication not only of the trend but also of the groundwater levels themselves. For both pilot areas improvements could be made to the model with local measurements (e.g. meteo, pumping from wells) these areas to better represent local conditions (e.g. pumping from wells) could improve these results.

Although a lot of data-services (both as open data and via paid services) are already available for farmers in their operational businesses, not many integrate the results and turn it into accurate forecast and actionable items. Farmers indicate a need for multiple information sources to be able to choose the most accurate for their business and location, because current predictions of meteorological conditions are not accurate to take decision.

Several domains have been identified where information can add value for farmers in taking business decisions now and in the future:

- Sprinkling/managing available water to avoid water stress but also (like last season) to cool the surface
- Responsible use of pesticides which requires the right moment, right place and right quantity.
- Optimal harvest timing and storage conditions for a good control in the chain from farmer to processor (or consumer).
- Managing the future more than one season ahead for long-term planning and investments.

8.2 Recommendations

8.2.1 Model improvements

Model results could be improved by using data assimilation and use of combination of different meteorological data sources on the short time scale of days. Also forecast until end-of-growing-season is useful for optimisation yield in dry periods to minimize risk and possible losses.

In a future stage, the models could be downscaled and run at a finer resolution (e.g. 25 m x 25 m) to provide more detailed information at a plot scale. Parallel computing is recommended to be used in order to achieve this in an efficient manner.
Not all data require the same resolution; it is worthwhile to distinguish between for instance meteo data and crop data (with very distinct boundary at plot level).
The input files for both pilot areas should be updated so that they are consistent with the most recent versions in use. Also the extension of the models into the future is an aspect which would be further investigated. Attention should be given to updating the following model inputs on a periodic basis:

- Extractions from wells (WEL package): could be updated periodically by the model owners;
- Water levels in rivers (ISG and RIV packages): could be updated periodically by the model owners or automatically using real-time data (additional developments needed);
- Water levels in drains (DRN package): could be updated periodically by the model owners or automatically using real-time data (additional developments needed);
- Land use (CAP package): could be updated periodically by the model owners or by the farmers directly in the “Grow with the Flow” app (additional developments needed); and
- Crop information (e.g. sowing date, harvest date) (CAP package): could be updated periodically by the model owners or by the farmers directly in the “Grow with the Flow” app (additional developments needed).

A protocol should be established stating who is responsible for the updates and any troubleshooting regarding parameter updates and the frequency at which these files should be updated (e.g. automatically, weekly, monthly, yearly).

Several suggestions were done during the project, for inputting of farmer information in the model runs on a daily basis for WOFOST (see also overview in 4.5.1).
Lastly, a comparison should be made between results that include the coupling to WOFOST and without the coupling to WOFOST. This will likely be further explored as part of the Lumbricus consortium.

8.2.2 Improvements of the WOFOST model

The following suggestions were done during the project, for inputting of farmer information in the model runs on a daily basis about:

- Time of sprinkling, and how much;
- Time of emergence; this should be accurately specified what is meant by that in terms of LAI and how to recognise that moment in the field
- Time of reaching anthesis (dvs=1.0)
- Actual time of harvest; this has consequences for yield and also the moisture situation at the start of next year
- Management factor per location
- Add/make use of seasonal forecast and simulation features.

For operational use it would be useful to update the input for actual crop plan not only through existing file at the start of a year (restart at Jan 1.) Finally, it has been suggested to add more checks to the model code, avoiding core dumps and being more informative for the user.

A Used Acronyms

Acronym	Definition
AGIF	Achmea’s Agro Geodata Insurance Framework
API	Application Programming Interface
DAA	Damage Assessment Application
DCRA	Digital Crop Registration Application
DVS	Development Stage
FAPP	Farmers APP of Achmea
FEWS	Flood Early Warning System
GWTF	Grow with the Flow
LAI	Leaf Area Index
METASWAP	Groundwater model for Unsaturated Zone
MODFLOW	Groundwater model for Saturated Zone
SAF	Spatiotemporal Agribusiness Framework
SAAS	Software as a Service
WOFOST	WOrld FOod STudies

B Overview Parameters

METASWAP

Key	Item	Unit	Sign	Save as model output	In FEWS	In App	Pixel or plot value	Remarks
Pm	Measured precipitation	mm or m*	≥0	N	Y	Y	plot	only available as input for the model
Ebs	Evaporation bare soil	mm or m*	≤0	Y	N	Y	pixel	wish to be implemented in FEWS?
Tact	Actual transpiration vegetation	mm or m*	≤0	Y	N	Y	pixel	wish to be implemented in FEWS?
lai	Leaf area index	m2/ m2	≥0	Y	Y	Y	pixel	FROM WOFOST
ETact	Total actual evapotranspiration	mm or m*	≤0	N	Y	Y	pixel	

Key	Item	Unit	Sign	Save as model output	In FEWS	In App	Pixel or plot value	Remarks
S01	Soil water storage in rootzone	mm or m*	≥0	N	Y	Y	pixel	
Ssdtot	Total soil water saturation deficit	mm or m*	≥0	Y	Y	Y	pixel	
Hgwmodf	MODFLOW groundwater head	m+MSL	+/-	Y	Y	Y	pixel	FROM MODFLOW
TempCmnday	Minimum temperature during 24 hours	°C	+/-	N	Y	Y	plot	only available as input for the model
TempCmxday	Maximum temperature during 24 hours	°C	+/-	N	Y	Y	plot	only available as input for the model
TempC	Mean temperature	°C	+/-	N	Y	Y	plot	only available as input for the model

Key	**Item**	**Unit**	**Sign**	**Save as model output**	**In FEWS**	**In App**	**Pixel or plot value**	**Remarks**
Rad	Mean shortwave radiation	kJ/m2/d	≥0	N	Y	Y	plot	only available as input for the model
Hum	Mean humidity	kPa	≥0	N	Y	Y	plot	only available as input for the model
wind	Mean windspeed	m/s	≥0	N	Y	Y	plot	only available as input for the model
Rnt	Mean net radiation, discounting reflection (albedo effect) and long wave emission	kJ/m2/d	+/-	N	N	Y	plot	wish to be implemented in FEWS?

WOFOST

Symbol	Item	Unit	Sign	Saved as model output	In FEWS	In App	Pixel or plot value	File location	Remarks
dvs	Development stage	-	≥0	Y	Y	Y	pixel	wof_dvs	can be input from farmer
jdaygerm	Calendar day of germination	d	≥0	Y	N	Y	pixel	wof_jdaygerm	can be input from farmer; wish to be implemented in FEWS?
htvg_pot	Crop height, potential value	m	≥0	N	N	Y	pixel		wish to be implemented in FEWS?
htvg_act	Crop height, actual value	m	≥0	Y	Y	Y	pixel	wof_htvg_act	can be input from farmer
lai_pot	Leaf area index, potential value	m2/m2	≥0	Y	Y	Y	pixel	wof_lai_pot	

Symbol	**Item**	**Unit**	**Sign**	**Saved as model output**	**In FEWS**	**In App**	**Pixel or plot value**	**File location**	**Remarks**
lai_act	Leaf area index, actual value	m2/m2	≥0	Y	Y	Y	pixel	wof_lai_act	
Wstems_leaves_pot	Dry weight of stems & leaves, potential value	kg/ha	≥0	Y	Y	Y	pixel	wof_Wstems_leaves_pot	
Wstems_leaves_act	Dry weight of stems & leaves, actual value	kg/ha	≥0	Y	Y	Y	pixel	wof_Wstems_leaves_act	
Wstems_leaves_yld	Yield of stems&leaves	kg/ha	≥0	Y	Y	Y	pixel	wof_Wstems_leaves_yld	
Wstems_leaves_yldrel	Relative yield of stems&leaves	-	≥0	Y	Y	Y	pixel	wof_Wstems_leaves_yldrel	

Symbol	**Item**	**Unit**	**Sign**	**Saved as model output**	**In FEWS**	**In App**	**Pixel or plot value**	**File location**	**Remarks**
Wstorg_organs_pot	Dry weight of storage organs, potential value	kg/ha	≥0	Y	Y	Y	pixel	wof_Wstorg_organs_pot	
Wstorg_organs_act	Dry weight of storage organs, actual value	kg/ha	≥0	Y	Y	Y	pixel	wof_Wstorg_organs_act	
Wstorg_organs_yld	Yield of storage organs	kg/ha	≥0	Y	Y	Y	pixel	wof_Wstorg_organs_yld	
Wstorg_organs_yldrel	Relative yield of storage organs	-	≥0	Y	Y	Y	pixel	wof_Wstorg_organs_yldrel	

C Requirements Farmers App

C.1 First phase MVP

The first phase will not include all the topics marked N in the backlog below.

C.1.1 API Documentation

An API specification document will be created which will define the API endpoints (response & requests) that are needed in the front-end (between App and SAF). Back end development will use this document as reference to develop the actual API.

C.1.2 Front-end Development

The front-end of the application will be developed in Vue.js; an open source front-end JavaScript framework similar to React. As the timespan of the project is quite short, the MVP will have the following scope (besides the points described in chapter 2):

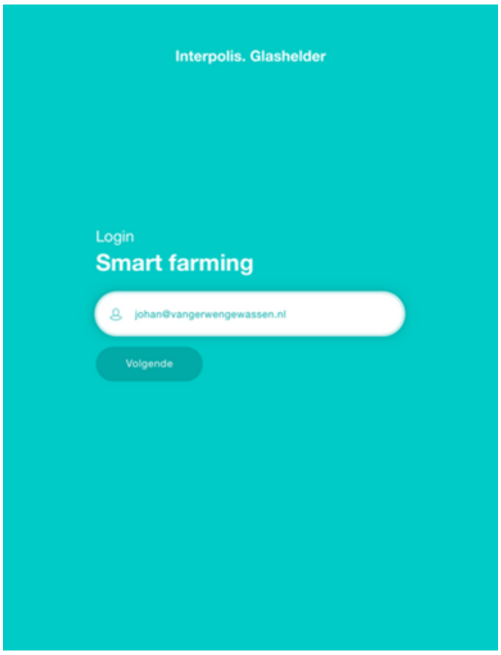
- Will be optimized to work on iPad portrait-mode.
- Has limited responsiveness (will not work on mobile).
- Will work on the latest two versions of all popular browsers (Chrome, Firefox, Safari, and Edge). IE 11 will not be supported.
- The graph will not be interactive and will only display data.
- The map will be scrollable within a restricted area.
- Deliverable will be a compiled HTML, CSS, JS package.
- The google maps API will be used to show the map and add
- interaction layers.

<u>The MVP will work with mock-data that is provided via the API from SAF.</u>
<u>SAF will retrieve data from Delft Fews using ftp.</u>

C.2 User requirements Farmers App

C.2.1 Login

Authorization and authentication of the farmer.



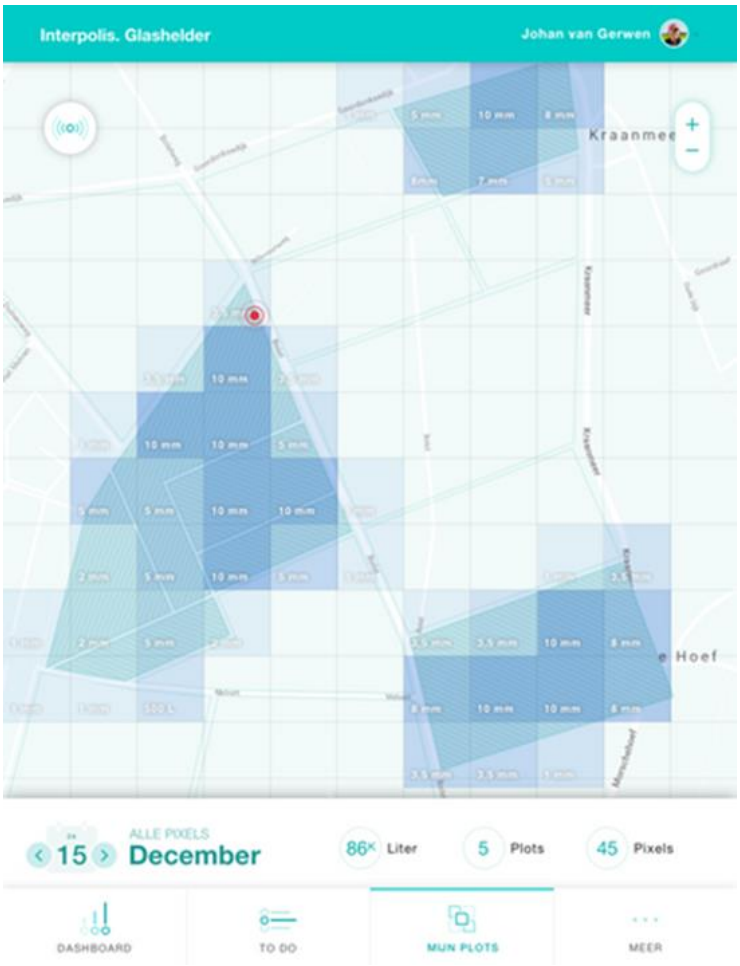
Interpolis. Glashelder

Login

Smart farming

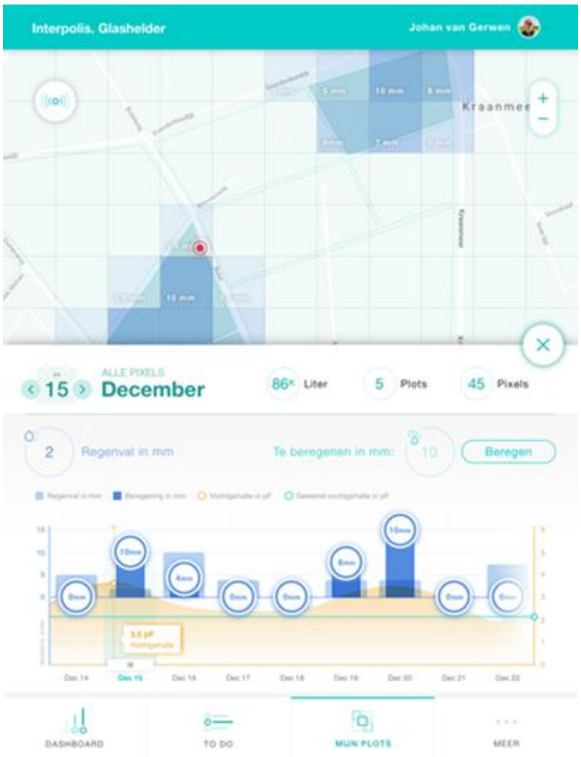
Epic	**Workflow**	**User**	**Story**	**First phase MVP**
1	Authorization and authentication	Farmer		N
1.1			Can identify himself with e-mail and password (key cloak data)	N
1.2			Will stay logged on until logoff (cross session)	N
1.3			Can logoff with logoff button	N
1.4			Will have access to own digital crop plan (plots and crops)	N
1.5			Will have access to data related to own digital crop plan (crops and plots) only	N
1.6			Can install the app from Apple and/or Android app store	N

C.2.2 Select plots or pixels from crop plan



Epic	**Workflow**	**User**	**Story**	**First phase MVP**
2	Select plots or pixels from crop plan	Farmer		Y
2.1			Can view the plots of the digital crop plan projected on a map (google maps layer)	Y
2.2			Can view the pixels that have been used to estimate or calculate plot and/or crop values (grid size 100x100 metres)	Y
2.3			Can select plots to view specific plot data (see plot details for list of data)	Y
2.4			Can select pixels to view specific pixel data (see pixel details of list of data)	Y
2.5			Can switch between plot and pixel view	Y
2.6			Can view the plot from the crop plan in a list	Y
2.7			Can select a plot from a list for viewing specific plot data (see 2.3)	Y
2.8			Can add to-do list	N
2.9			Can use the location data of the device to position on the map	N

C.2.3 View plot/pixel data



Epic	**Workflow**	**User**	**Story**	**First phase MVP**
3	View Plot/Pixel details	Farmer		
3.1			Can view the following data for the selected plot or pixel for the past 3 days (actuals), the current day (actual) and the next 5 days (forecast): - Rainfall (mm/day) - Water deficit (mm) - Evapotranspiration (mm/day) - Adviced/actual water suppletion (mm/day) In graphic and numeric representation	Y (only with fixed data, simulations in a later stage)
3.2			Can view the following data for the selected plot or pixel - Predicted dry matter production (ton/ha) (potential versus actual and predicted) - Predicted harvest (ton/ha) (potential versus actual and predicted). <optional: actual as percentage of potential>	N
3.3			Can enter actual water suppletion (mm/day) for the selected plot	Y
3.4			Can view static plot/pixel data - Soil type - Crop	N
3.5			Can look back status 3.1 t/m 3.4 for previous forecasts	N

C.2.4 Update Data

Epic	**Workflow**	**User**	**Story**	**First phase MVP**
4	View Plot/Pixel details	Farmer		
4.1			Show to farmer whether new information is available	N
4.2			Update information from ftp, update frequency tbd	Y

D Verbetering hydrologisch instrumentarium met koppeling WOFOST en zuurstofstress-simulatie

Notitie
Paul van Walsum
5 oktober 2018

D.1 Inleiding

Binnen het kader van onderzoeksprogramma Lumbricus is in 2017 en 2018 gewerkt aan het voorbereiden van het rekeninstrumentarium, om binnen het onderzoeksprogramma Lumbricus maatregelen door te kunnen rekenen. Binnen het project Wellend Water ligt daarbij het accent op het vertalen van de effecten van de lokale maatregelen, die op perceelschaal of schaal van een beek zijn onderzocht binnen Bewuste Bodem en Boeiende Beekdalen, naar het regionale stroomgebiedsniveau. De rekeninstrumenten worden in Wellend Water ingezet om maatregelen te positioneren, te combineren en te integreren binnen stroomgebieden. Afzonderlijke tests en proeven op percelen of andere locaties, bijvoorbeeld uitgevoerd binnen Bewuste Bodem, kunnen zo op gebiedsniveau beoordeeld worden op werking en doelbereik.

Binnen Lumbricus zullen onder meer maatregelen worden beoordeeld voor adaptatie aan drogere omstandigheden. Gedacht kan worden aan mogelijkheden voor waterconservering via peilgestuurde drainage en stuwbeheer. Bij het selecteren en optimaliseren van de maatregelen binnen Wellend Water zal de grens worden opgezocht welk beheer en maatregelen kunnen worden toegepast, zonder dat de gewasopbrengsten (te veel) zullen dalen door natschade als gevolg van zuurstofstress. Bij dergelijke afwegingen zal gebruik worden gemaakt van een combinatie van regionale hydrologische modellen en effectmodellen (de Waterwijzers). De effectmodellen van Waterwijzer-Landbouw zijn gebaseerd op de koppeling van:

- Bodemvocht- en verdampingsmodel SWAP (Kroes et al.,2018);
- Gewasgroeimodel WOFOST (Boogaard et al., 1998), uitgebreid met effecten van indirecte schade als gevolg van ongunstige omstandigheden voor landvoorbereiding, zaaien, kieming, en oogst;
- Zuurstofstressmodel (Bartholomeus et al. 2008).

WOFOST is een dynamisch gewasgroeimodel waarmee de interactie tussen vochtvoorraad, verdamping en plantengroei in beeld kan worden gebracht. Het zuurstofstressmodel rekent uit of de beschikbaarheid van zuurstof limiterend is voor de wateropname onder natte condities. Kenmerkend voor de gebruikte koppelingen is dat de interactie in twee richtingen is, waardoor er een model met complexe terugkoppelingen ontstaat. Met de combinatie SWAP-WOFOST-zuurstofstress kunnen de schades in beeld worden gebracht op perceelsschaal, en de effecten op het bovenste deel van het hydrologische systeem worden beschouwd.

Binnen Wellend Water worden echter ook de effecten op het regionale systeem beschouwd. Voor analyseren van ingrepen in het regionale systeem en effecten van klimaatscenario’s moet ook rekening worden gehouden met een gewijzigde terugkoppeling tussen het bovenste deel van het hydrologische systeem en het regionale hydrologische systeem. Hiervoor worden doorgaans regionale hydrologische modellen toegepast, zoals MIPWA (gekoppelde modellen van MetaSWAP en MODFLOW, eventueel uitgebreid met een oppervlaktewatermodule of model zoals Sobek).

Door in de regionale hydrologische modeltoepassingen, zoals MIPWA, ook een koppeling te maken met het gewasgroeimodel WOFOST worden de hydrologische processen beter gesimuleerd en wordt optimaal gebruik gemaakt van de actuele kennis over gewasgroei die is ontwikkeld in het kader van de Waterwijzers. Met deze koppeling wordt bovendien de benodigde consistentie gerealiseerd tussen de regionale hydrologische toepassingen en de Waterwijzers, en andersom.

Dit project is gericht op de technische implementatie van de koppeling tussen NHI (MetaSWAP) en WOFOST in combinatie met zuurstofstress zoals gemodelleerd in SWAP-WOFOST. Technische verificatie geschiedt aan de hand van SWAP-WOFOST. Een inhoudelijke validatie valt buiten het kader van dit project.

D.2 Koppeling van WOFOST en zuurstofstress aan MetaSWAP

Als uitgangspunt voor de code-aanpassing van MetaSWAP is gebruikt SWAP 4.0.16, de versie waarmee (op een kleine aanpassing in het opstarten van grasland na) Waterwijzer-Landbouw (“WWL”) is opgeleverd. De aanpassingen vallen onder drie hoofdactiviteiten:

- Toevoegen van de in WWL gebruikte Penman-Monteith rekenmethode voor de verdamping;
- Aanpassen van de bestaande WOFOST koppeling uit 2012, inclusief ‘indirecte schade’;
- Koppelen van de zuurstofstressmodule.

Penman-Monteith methode voor verdamping

In WWL is een nieuwe rekenwijze voor Penman-Monteith geïntroduceerd (Van Dam & Van Walsum, 2018). Het innovatieve daarvan betreft de wijze waarop de partitionering tussen de verdampingstermen tot stand wordt gebracht, gebaseerd op weerstanden. Het opnemen van deze rekenwijze in MetaSWAP was niet opgenomen in het projectplan. Desondanks is de rekenwijze toch geïmplementeerd, omdat anders het toetsen van de MetaSWAP-WOFOST uitkomsten aan die van SWAP-WOFOST niet mogelijk zou zijn geweest zonder de parameters van de NHI-gewasfactormethode te actualiseren voor de nieuwe WOFOST koppeling. Die actualisatie zou veel tijd hebben gekost. Het opnemen van de Penman-Monteith rekenwijze in MetaSWAP vereiste wel dat het mogelijk moest blijven om twee soorten rekenwijzen naast elkaar te gebruiken. Het is namelijk de verwachting dat het omzetten van de niet-landbouw gewassen naar Penman-Monteith in het NHI op een later moment gaat plaatsvinden dan de landbouwgewassen.

Actualiseren van de koppeling met WOFOST

WOFOST is een ‘mechanistisch’ gewasgroeimodel. Het is met SWAP gekoppeld via meervoudige verbindingen in twee richtingen (Fig. 1). Deze verbindingen zijn in MetaSWAP-WOFOST geactualiseerd. Ook de effecten van indirecte schade zijn in het model opgenomen.

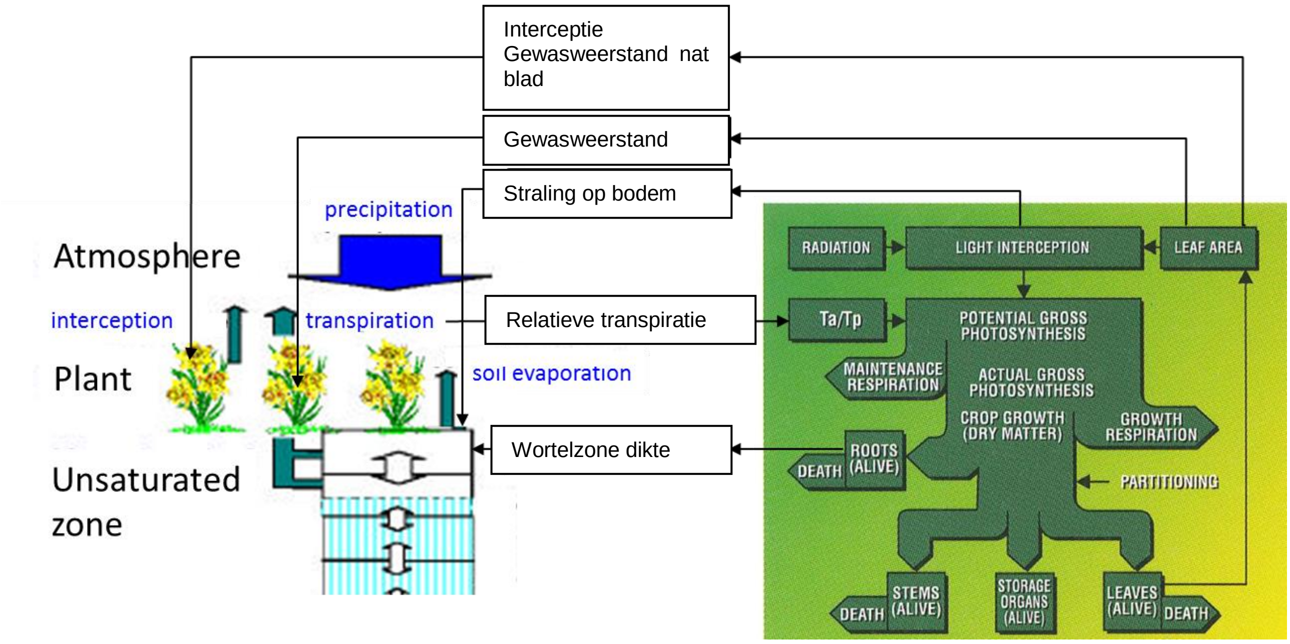


Fig. 1 Gekoppelde modellen (Meta-)SWAP en WOFOST

Koppelen van de zuurstofstress module

De zuurstofstressmodule is conceptueel onveranderd overgenomen van SWAP-WOFOST, zonder te vereenvoudigen. Het is dus niet een ‘repro’- versie die in MetaSWAP terecht is gekomen.

Voor de zuurstofstressmodule is het nodig om te kunnen beschikken over gedetailleerde vochtprofielen. Daartoe is gebruik gemaakt van de PostMetaSWAP module die de rekenresultaten neerschaalt van het niveau van de aggregatieboxen (waarvan de bovenste de wortelzone is) naar het niveau van SWAP compartimenten. Die neerschaling maakt gebruik van informatie die aanwezig is in de database van MetaSWAP.

De zuurstofstress module maakt gebruik van bodemfysische informatie in een vorm die alleen beschikbaar was in het PreMetaSWAP programma dat de database aanmaakt. Deze functionaliteit is nu ook in MetaSWAP zelf beschikbaar gemaakt. Maar de manier waarop in SWAP met die bodemfysische informatie wordt omgegaan bleek in MetaSWAP tot zeer grote rekentijden te leiden. Daarom is de ontsluiting van de informatie in MetaSWAP anders georganiseerd.

In NHI-toepassingen wordt de bodemfysische basisinformatie gebruikt in de vorm van tabellen. Dat is meer flexibel en generiek dan de in Waterwijzer gebruikte Van Genuchten methode met analytische formules. In Waterwijzer was eerst ook gebruik gemaakt van tabellen. Toen bleek dat die keuze tot grote rekentijden zou leiden is toch gekozen voor Van Genuchten. In MetaSWAP is dit probleem gedeeltelijk opgelost. Maar nog steeds is de rekentijd zeer hoog: zuurstofstress neemt bijna evenveel tijd als MODFLOW, MetaSWAP, en WOFOST tezamen.

D.3 Resultaten

Inleiding

De gekoppelde rekenmodellen hebben een complexe interactie met elkaar via de verschillende verbindingen en terugkoppelingen. Dat maakt het testen en verifiëren van afzonderlijke functionaliteiten nogal lastig en tijdrovend. Uiteindelijk gaat het om het totale effect. Daarom, en vanwege beperkingen in het beschikbare budget, is gekozen om alleen tests te doen waarin de complete functionaliteit wordt gebruikt. Er zijn twee soorten tests gedaan:

- met de meteorologische gegevens van Arcen voor 2015 en 2016 voor een zandgrond met lichte kwel van 0.5 mm/d. Deze test is vooral gebruikt om de koppeling met WOFOST in combinatie met zuurstofstress te testen;
- met de meteorologische gegevens van De Bilt voor 1971-2008, voor een zandgrond met zware kwel en een grond met wegzijging van 0.5 mm/d. Deze tests zijn vooral bedoeld voor het etsten van het langjarig gemiddelde en voor situaties met extreme droogte zoals in 1976.

Deze tests zijn gedaan voor 1-koloms modellen. Behalve deze tests zijn ook rekenruns gemaakt met een regionaal model van een deelgebied van het Waterschap Vechtstromen.
De rekenresultaten zijn gevoelig voor de gebruikte parameters van compartimentdikte en tijdstap. Wat betreft SWAP wordt in deze tests gebruik gemaakt van een compartimentdikte van 1 cm en een maximale tijdstap van 1 uur zoals ook is toegepast in Waterwijzer-Landbouw (wat overigens meer gedetailleerd is dan de tot nu toe in de praktijk gangbare parameters). Wat betreft MetaSWAP wordt gebruik gemaakt van de compartimentindeling zoals die nu aanwezig is in landelijke en regionale toepassingen. De compartimentdikte van neergeschaalde profielen is 1 cm voor de eerste 15 cm en 5 cm voor de rest van het profiel. Voor de tijdstap wordt de gebruikelijke 1 dag gebruikt.

De tests voor locatie Arcen zijn gedaan inclusief het CO2-effect en die voor De Bilt zonder.

Tests met 1-kolomsmodellen voor meteorologische gegevens van Arcen 2015-2016

De rekenresultaten voor de 1-koloms modellen zijn opgenomen in Tabel 1. Daaruit blijkt dat er beperkte verschillen zijn tussen de jaartotalen voor de verschillende modellen. De grens voor significante afwijkingen wordt hier gelegd bij 5% van de potentiële verdamping. Voor de transpiratie van maïs lijkt die te worden overschreden als daarvoor 5% van de potentiële transpiratie uit de tabel wordt genomen. Maar het interpretatieprobleem ontstaat doordat de “potentiële” transpiratie sterk wordt bepaald door de geremde gewasontwikkeling zoals voor maïs is uitgebeeld in Fig. 2 in termen van de *Leaf Area Index* LAI (zie figuuronderschrift). De werkelijke potentiële verdamping voor de potentiele LAI (blauwe lijn) zou zeker twee maal zo hoog zijn als wat voor de “actuele” LAI is gesimuleerd. In werkelijkheid is de interpretatie nog een slag ingewikkelder, omdat ook effecten als gevolg van ‘indirecte’ schade een rol kunnen spelen. Om die effecten zichtbaar te maken moet een extra run worden gemaakt met diepe grondwaterstanden.

De geremde gewasontwikkeling voor maïs ontstaat in deze test uitsluitend als gevolg van zuurstofstress. De gesimuleerde stress is uitgebeeld in Fig. 3, in de vorm van de relatieve transpiratie. Bij een waarde van 1 is er geen stress, bij 0 maximale stress. Uit het verloop blijkt dat MetaSWAP goed het verloop van SWAP volgt. Het verdampingsverschil met SWAP ontstaat door het LAI-verschil van 10% in de zomer.

Tabel 1. *Resultaten voor geselecteerde waterbalanstermen (mm) van MetaSWAP en SWAP voor het jaar 2016, locatie Arcen met kwel van of 0.5 mm/d*

Term	gras_maaien	gras_weide	snijmais	aardappel	suikerbiet	zomergerst
Tpot_M_SWAP	312.3	295.8	128.6	212.8	95.0	107.3
Tpot_SWAP	314.8	292.2	138.2	200.8	93.7	101.9
Tact_M_SWAP	293.4	278.4	121.5	197.7	89.7	83.7
Tact_SWAP	296.8	278.4	132.9	188.1	90.3	79.7
ΔTact	-3.4	-0.1	-11.4	9.6	-0.7	4.0
ETact_M_SWAP	524.6	513.2	393.7	421.1	372.0	346.7
ETact_SWAP	530.1	516.7	408.0	416.4	376.0	346.0
ΔETact (mm)	-5.5	-3.5	-14.3	4.7	-3.9	0.7

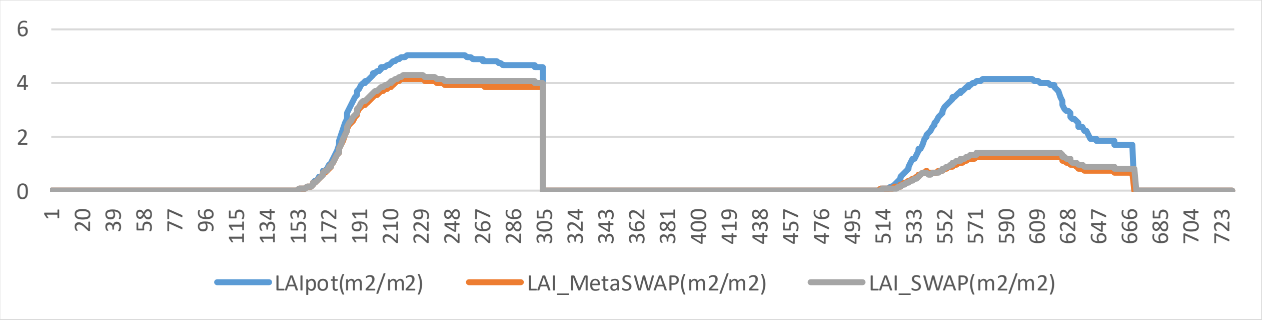


Fig. 2 Gesimuleerde bladontwikkeling (LAI) van maïs, voor locatie Arcen. De LAI is de verhouding tussen het totale bladoppervlak en het grondoppervlak. LAIpot – LAI voor potentiële gewasontwikkeling

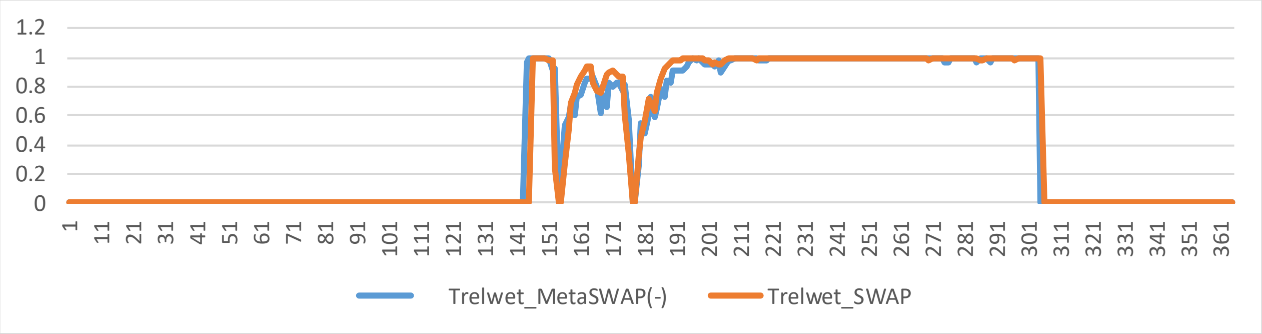


Fig. 3 Simulatie van maïs, voor locatie Arcen 2016: verloop zuurstofstress (1 - geen stress, 0 - maximale stress.)

Tests met 1-kolomsmodellen voor meteorologische gegevens van De Bilt 1971-2008

De rekenresultaten voor 1-kolomsmodellen met wegzijging van 0.5 mm/d zijn opgenomen in Tabel 2. Uit de tabel blijkt dat er acceptabele verschillen zijn tussen MetaSWAP en SWAP, zowel wat betreft het langjarig jaartotaal-gemiddelde als wat betreft het jaartotaal voor 1976. Voor grasland met beweiding zijn van enkele gewasvariabelen het verloop weergegeven voor het extreem droge jaar 1976 (Fig. 4 en 5). Als gevolg van een verschuiving in het begrazingsregime (Fig. 4) loopt MetaSWAP uit de pas bij SWAP. Maar voor de totale verdamping blijkt dat niet tot een onacceptabel verschil te leiden.

Tabel 2 Vergelijking van geselecteerde verdampingstermen (mm/jaar) van grasland (met beweiding) en aardappelen voor De Bilt 1971-2008 en De Bilt 1976, bij een wegzijging van 0.5 mm/d

	1971-2008		1976	
Gewas	gras_weide	aardappel	gras_weide	aardappel
Tpot_M_SWAP	293.0	275.1	292.5	335.9
Tpot_SWAP	294.2	274.2	307.2	334.5
Tact_M_SWAP	285.0	258.8	220.8	214.1
Tact_SWAP	283.8	256.6	234.5	217.4
ΔTact (mm)	1.2	2.3	-13.7	-3.3
ETact_M_SWAP	511.1	472.7	414.8	400.8
ETact_SWAP	510.0	470.6	426.4	404.2
ΔETact (mm)	1.1	2.2	-11.6	-3.4

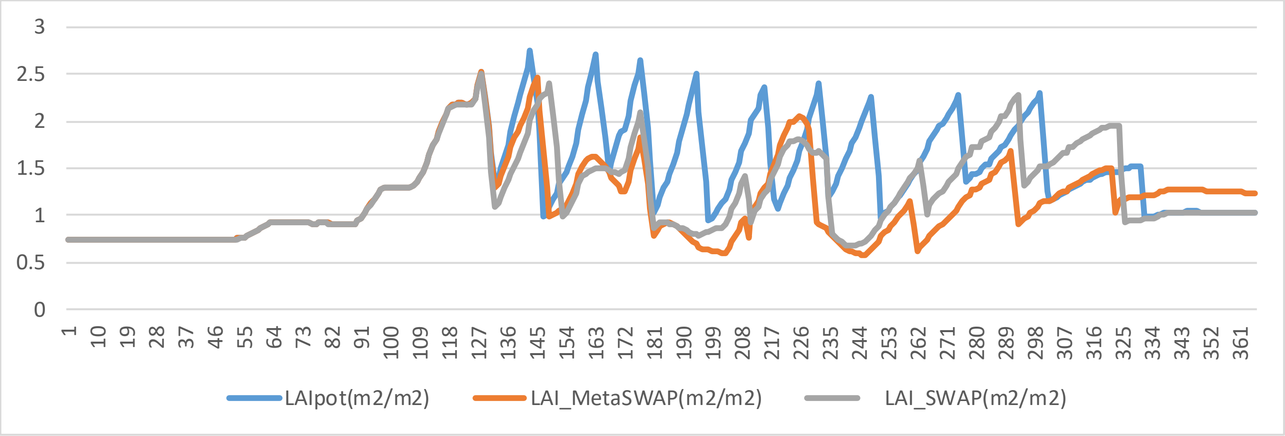


Fig. 4 Simulatie van grasland met beweiding, locatie De Bilt met wegzijging van 0.5 mm/d: verloop van de bladontwikkeling LAI (verhouding bladoppervlak en grondoppervlak) voor het extreem droge jaar 1976

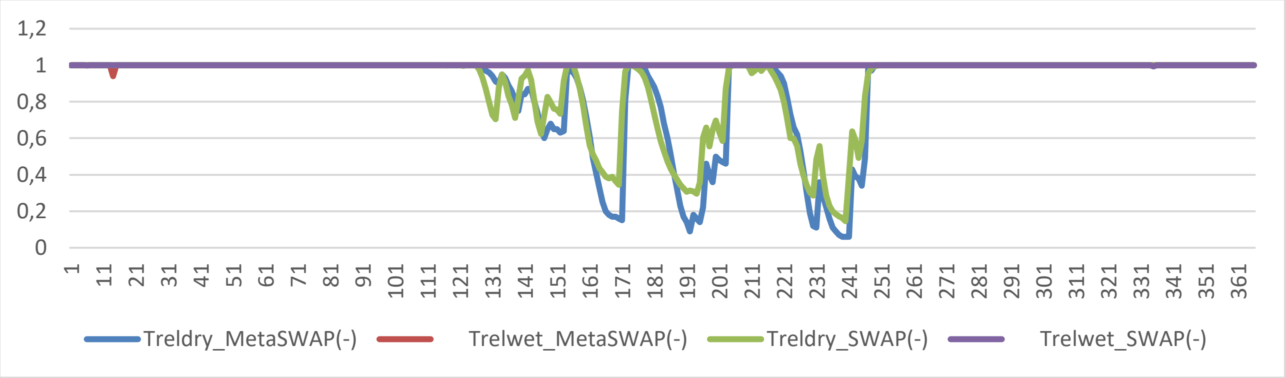


Fig. 5 Simulatie van grasland met beweiding, locatie De Bilt met wegzijging van 0.5 mm/d : verloop van droogte- en zuurstofstress Trel (1 = geen stress, 0= maximale stress), voor het extreem droge jaar 1976

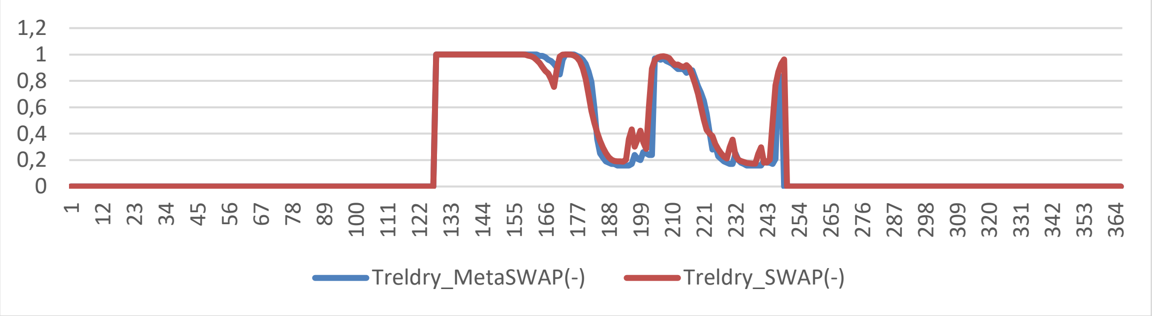


Fig. 6 Simulatie van aardappelen, locatie De Bilt met wegzijging van 0.5 mm/d : verloop van droogtestress (1 = geen stress, 0= maximale stress), voor het extreem droge jaar 1976

Voor aardappelen is de gesimuleerde droogtestress in simulatiejaar 1976 uitgebeeld in Fig. 6, wat een zeer goede overeenkomst laat zien tussen MetaSWAP en SWAP.
De tests voor locatie De Bilt met een kwel van 2 mm/d zijn vooral interessant wat betreft het langjarig gemiddelde van de zuurstofstress. Ook hier blijkt het langjarig gemiddelde van MetaSWAP-WOFOST uitstekend te sporen met dat van SWAP-WOFOST.

Tabel 3 Vergelijking van geselecteerde verdampingstermen (mm/jaar) van grasland (met beweiding) en aardappelen voor De Bilt 1971-2008 en De Bilt 1976, bij een kwel van 2 mm/d

	1971-2008		1976	
Gewas	gras_weide	aardappel	gras_weide	aardappel
Tpot_M_SWAP	289.6	243.9	352.1	313.8
Tpot_SWAP	290.3	243.6	353.4	314.8
Tact_M_SWAP	279.0	231.3	351.0	309.5
Tact_SWAP	281.2	234.5	352.6	312.6
ΔTact (mm)	-2.1	-3.2	-1.5	-3.2
ETact_M_SWAP	503.3	455.3	540.4	496.3
ETact_SWAP	509.1	460.5	543.9	499.7
ΔETact (mm)	-5.8	-5.1	-3.4	-3.4

Tests voor deelgebied van waterschap Vechtstromen

Het landgebruik in de gebruikte uitsnede van het Vechtstromen is weergegeven in Fig. 7. Voor dit gebied zijn de volgende rekenruns gemaakt voor de periode 2000-2014:

1. NHI-gewasfactormethode gebaseerd op SWAP-WOFOST versie 3.2.26 (2012) (SWAP versie nr.)
2. NHI-gewasfactormethode gebaseerd op SWAP-WOFOST versie 4.0.16 (2018)
3. Penman-Monteith in combinatie met MetaSWAP-WOFOST 4.0.16, 3 gewassen
4. Penman-Monteith in combinatie met MetaSWAP-WOFOST 4.0.16, 5 gewassen
5. Penman-Monteith in combinatie met MetaSWAP-WOFOST 4.0.16, 5 gewassen, met CO2-effect

De genoemde 5 gewassen zijn:

- grasland met maaibeheer;
- snijmaïs;
- aardappelen;
- suikerbieten;
- granen.

Voor grasland en snijmaïs zijn aan de hand van voorbeeldlocaties de rekenuitkomsten van jaartotalen opgenomen in respectievelijk Tabel 4 voor grasland met maaibeheer en Tabel 5 voor snijmaïs. De locaties zijn niet gekozen vanwege representativiteit.

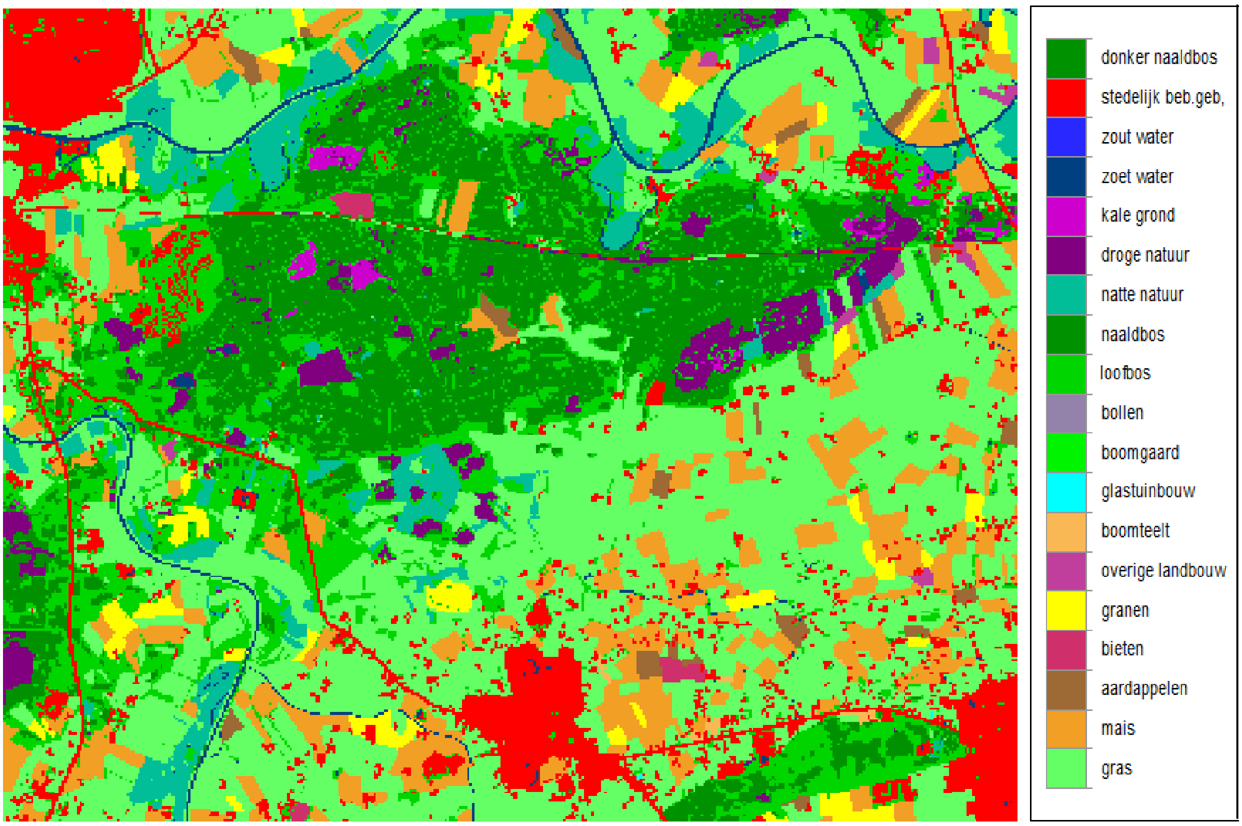


Fig. 7 Overzicht van landgebruik in de gebruikte uitsnede van het Vechtstromen model

Tabel 4. Jaartotalen van verdamping voor een voorbeeldlocatie met ***grasland*** *(maaibeheer). Verklaring van runs: 1 – NHI-gewasfactormethode 2012; 2 – idem 2018; 4 – WOFOST 5 gewassen (voor grasland gelijk aan run 3); 5 – idem met CO2-effect*

Jaar	run 1	run 2	run 4	run5	run 2-1	run 4-2	run 5-4	run 5-2
2000	557	563	560	556	7	-3	-4	-7
2001	543	539	513	511	-4	-27	-1	-28
2002	568	563	528	526	-5	-34	-3	-37
2003	485	479	464	463	-6	-16	-1	-17
2004	572	562	552	548	-10	-11	-3	-14
2005	575	575	528	525	0	-47	-4	-50
2006	481	478	455	453	-3	-23	-2	-25
2007	551	542	547	544	-9	5	-3	2
2008	508	507	493	491	-1	-14	-2	-15
2009	539	535	497	495	-4	-38	-2	-40
2010	500	499	488	487	-1	-11	-1	-12
2011	498	497	481	480	-2	-16	-1	-17
2012	567	563	533	530	-4	-30	-2	-32
2013	502	500	498	497	-2	-2	0	-3
2014	595	591	524	520	-4	-67	-3	-71
Gem.	536	533	511	508	-3	-22	-2	-24

In het graslandvoorbeeld (Tabel 4, locatie niet gekozen vanwege representativiteit) is het langjarig gemiddelde van de totale verdamping voor de NHI-gewasfactoren uit 2018 (run 2) vrijwel gelijk aan die met gewasfactoren uit 2012, zoals ook het geval was bij de herkalibratie van de gewasfactoren (Van Walsum, 2018). Het langjarig gemiddelde van de run 4, waarin WOFOST dynamisch is gekoppeld aan MetaSWAP, komt 4% lager uit dan 2, terwijl bij de herkalibratie van de gewasfactoren de gemiddeldes vrijwel exact spoorden met die van SWAP-WOFOST (Tabel 1 in het herkalibratierapport). Het verschil komt doordat bij de kalibratieruns de verdamping potentieel was en in dit voorbeeld er behoorlijk wat droogtestress is (met een gemiddelde relatieve verdamping van 0.93, en vrijwel geen zuurstofstress). Dat leidt ertoe dat de gewasontwikkeling achterblijft bij de potentiële ontwikkeling, wat een versterkend effect heeft op de verdampingsreductie, via het mechanisme van ‘positieve’ terugkoppeling.

Illustratief voor de werking van het gekoppelde model is dat de relatieve verdamping van de run met WOFOST *hoger* is (0.96) dan die zonder (0.93), terwijl de uiteindelijke verdamping toch *lager* is. Dat komt doordat het belangrijkste mechanisme voor reductie hier bestaat uit het achterblijven van de gewasontwikkeling en de invloed daarvan op de ‘potentiële’ transpiratie.

Aan de hand van de lijst van jaarverschillen voor de verschillende jaren (Tabel 4) is te zien dat als gevolg van de invloed van dynamische gewasgroei er in dit voorbeeld verschillen kunnen zijn tot bijna 70 mm ten opzichte van de gewasfactor methode (run 4-2). Het CO2-effect van run 5 voegt daar nog iets aan toe.

In het voorbeeld van een locatie met snijmais (Tabel 5, locatie niet gekozen vanwege representativiteit, met weinig tot geen droogte- en zuurstofstress) is het langjarig gemiddelde van de run 2 met de nieuwe gewasfactoren uit 2018 circa 4% lager dan de run 1 met de factoren uit 2012. Het verschil spoort met de resultaten van de herkalibratie zelf (3% lager in Tabel 1 uit Van Walsum, 2018). Dat verschil heeft te maken met de opgelegde randvoorwaarde aan de kalibratiewijze, namelijk dat op dat moment niet overgestapt kon worden naar de interceptieverdamping-rekenwijze van SWAP (vanwege de gevraagde compatibiliteit met de bestaande code), terwijl die SWAP-rekenwijze bij het gebruik van dag-neerslagen overigens wel de meest geschikte is. Het langjarig gemiddelde van dynamisch gekoppeld WOFOST is in run 4 is vrijwel gelijk aan die van run 2, doordat er in dit geval weinig reductie is en er daarom nauwelijks sprake is van versterkende feedback zoals in het graslandvoorbeeld.

Net als bij grasland kunnen er in individuele jaren forse verschillen zijn ten opzichte van de gewasfactormethode, met uitschieters tot circa 70 mm plus of min. Dat hangt samen met de variatie in de gewasontwikkeling, zoals uitgebeeld in termen van de LAI in Fig. 8. Voor de runs 1 en 2 is de LAI-ontwikkeling in ieder jaar hetzelfde. Het grote verschil tussen de piekwaarde van de LAI tussen run 1 en 2 is een gevolg van gewijzigde parameters van het WOFOST model uit 2018 in vergelijking met die uit 2012.

Tabel 5. Jaartotalen van verdamping voor voorbeeldlocatie met ***snijmaïs****. Verklaring van runs: 1 – NHI-gewasfactormethode 2012; 2 – idem 2018; 4 – WOFOST 5 gewassen (voor snijmaïs gelijk aan run 3); 5 – idem met CO2-effect*

Jaar	run 1	run 2	run 4	run 5	run 2-1	run 4-2	run 5-4	run 5-2
2000	563	533	598	590	-30	66	-8	58
2001	586	553	547	538	-33	-6	-9	-15
2002	552	526	534	524	-26	7	-9	-2
2003	493	479	458	456	-14	-21	-2	-23
2004	554	528	559	549	-26	31	-10	22
2005	583	562	517	510	-21	-45	-8	-53
2006	524	514	464	457	-10	-50	-8	-57
2007	539	504	558	548	-34	54	-10	44
2008	542	524	520	512	-18	-4	-8	-12
2009	577	553	525	516	-24	-28	-9	-37
2010	540	523	576	567	-17	53	-9	44
2011	516	476	506	499	-40	30	-8	23
2012	567	547	557	548	-20	11	-9	2
2013	529	513	518	512	-16	6	-6	-1
2014	588	565	499	492	-22	-66	-7	-73
Gem.	550	527	529	521	-23	3	-8	-5

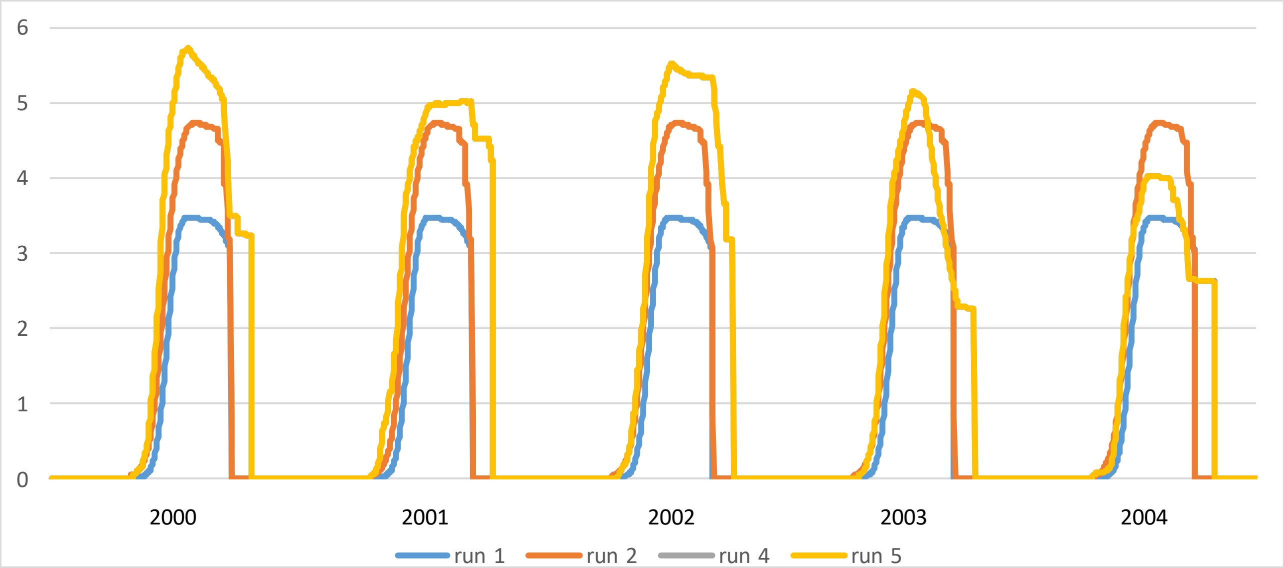


Fig. 8 LAI-ontwikkeling van snijmaïs op een voorbeeldlocatie, voor de drie runs van Tabel 5, voor 2000-2004.

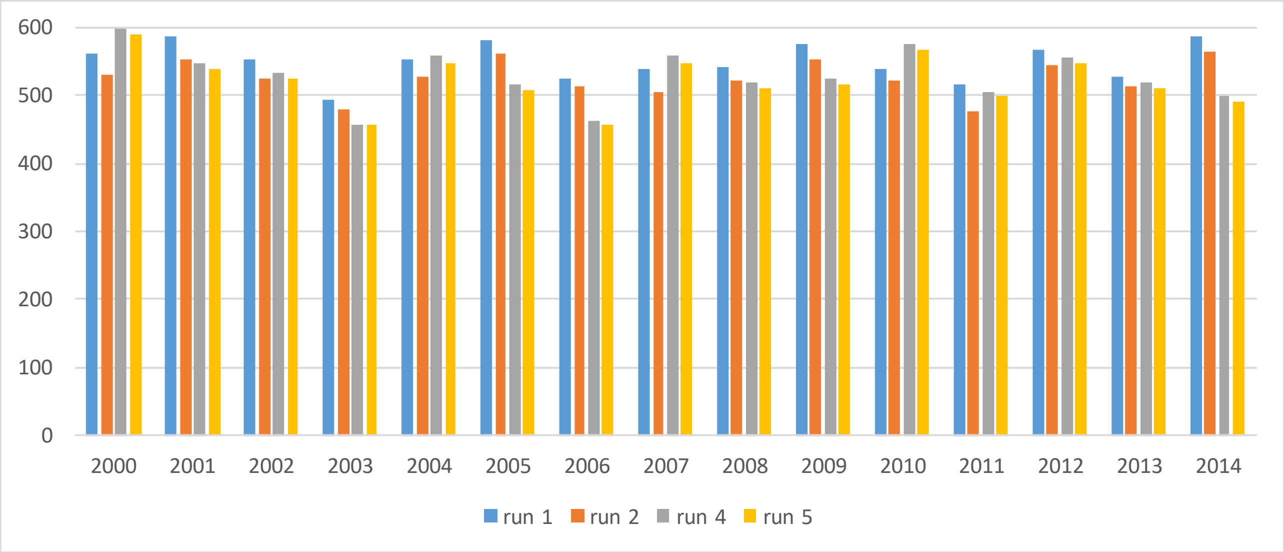


Fig. 9 Totale jaarverdamping (2000-2014) van snijmaïs op een voorbeeldlocatie, voor de vier runs van Tabel 5

Om de effecten van het koppelen van WOFOST en zuurstofstress te kunnen analyseren is een extra run $3^{\sim}$ ingelast waarbij WOFOST wel is gekoppeld maar de zuurstofstress niet.
Het ruimtelijk beeld van het verdampingsverschil in het jaar 2000 tussen run 3 (WOFOST en zuurstofstress) en run 2 (NHI-gewasfactoren) is weergegeven in Fig. 10, en in Fig. 11 idem voor run $3^{\sim}$ zonder zuurstofstress. In Fig. 12 en 13 is hetzelfde gedaan voor de verdamping in 2003, in Fig. 14 en 15 voor het GHG-verschil, en in Fig. 16 en 17 voor het GLG-verschil (voor periode 2005-2014).
De uitschieters naar de plus-kant in Fig. 10 hangen samen met de gewasontwikkeling die in dat jaar gunstig is voor snijmais. Dat was ook te zien in Tabel 5. De uitschieters naar de min-kant blijken hier vooral te worden veroorzaakt door zuurstofstress, wat te zien is in aan het feit dat in Fig.11 zonder koppeling met zuurstofstress de donkerblauwe vlekken zijn verdwenen.
In Fig. 12 en 13 voor 2003 (met en zonder zuurstofstress) zijn de positieve effecten verdwenen. Dat spoort de in Tabel 4 (grasland) en in Tabel 5 (snijmaïs) weergegeven effecten van de WOFOST koppeling op het verdampingstotaal van 2003, die allebei negatief waren. In Fig. 12 wordt dat extra versterkt door het op grote schaal optreden van zuurstofstress: de veroorzaakte verdampingsreductie maakt het model nog natter; dat is een zichzelf versterkend proces, via het mechanisme van ‘positieve’ terugkoppeling. Ook bij droogtestress is er een vorm van positieve feedback: als gevolg van achterblijvende gewasontwikkeling blijft de verdamping ook achter in periode na dat de droogtestress optrad, ook al is er geen droogtestress meer.
Deze twee mechanismes zien we in Fig. 18 aan het werk voor een voorbeeldlocatie met grasland aangegeven in Fig. 17 (5-punts gele ster linksonder):

- in droge jaren (2001 en 2003) zien we dat de NHI-gewasfactoren sterker verdampen en de grondwaterstanden verder naar beneden trekken doordat de gewasontwikkeling in de NHI-gewasfactor-methode niet te lijden hebben van de droogte; de factoren zijn voor ieder jaar hetzelfde;
- in alle jaren, maar vooral in de wat nattere zoals 2002 zien we de invloed van de zuurstofstress die voor reductie van de transpiratie zorgt waardoor de grondwaterstand minder ver naar beneden wordt getrokken tijdens de zomer.

Het beeld voor een locatie met aardappelen (6-punts ster in Fig. 17) ziet er verglijkbaar uit.

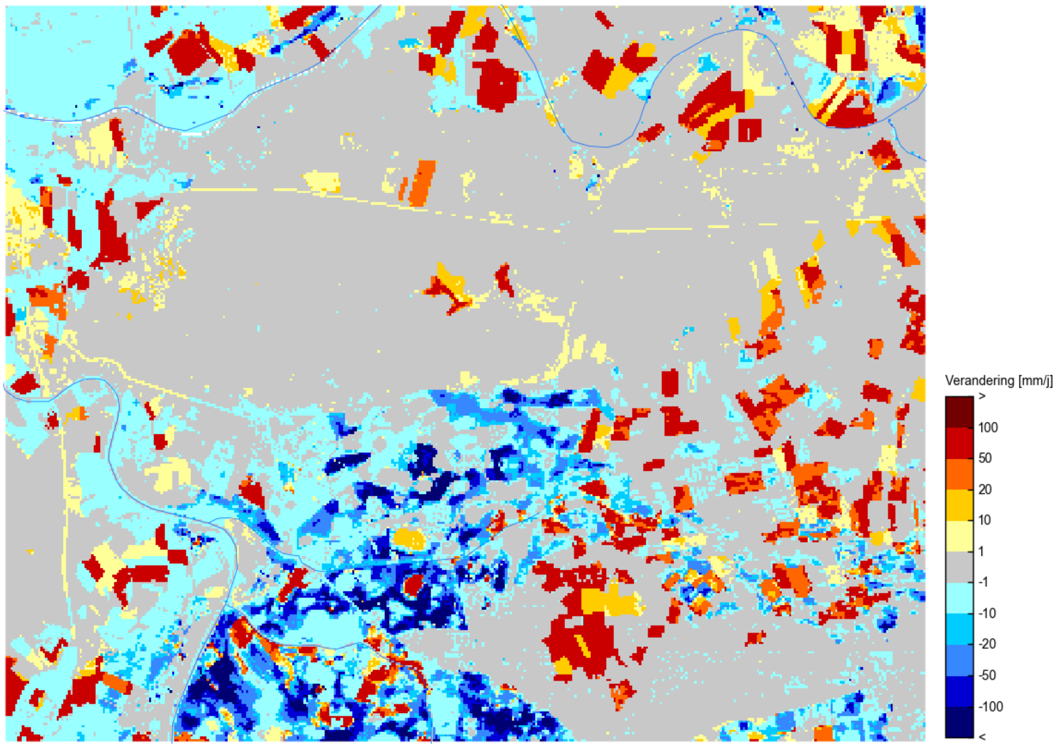


*Fig. 10 Verschil totale verdamping in 2000 tussen run 3 met dynamische WOFOST koppeling **plus** zuurstofstress en run 2 met NHI-gewasfactoren.*

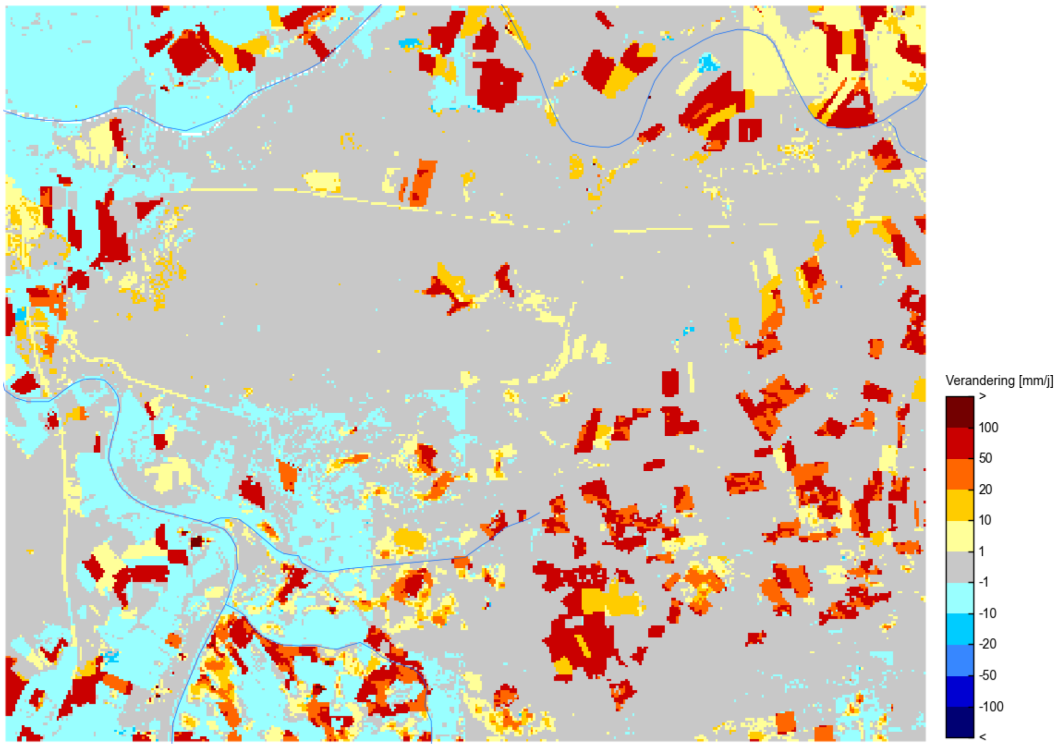


*Fig. 11 Verschil totale verdamping in 2000 tussen run 3 met dynamische WOFOST koppeling **zonder** zuurstofstress en run 2 met NHI-gewasfactoren.*

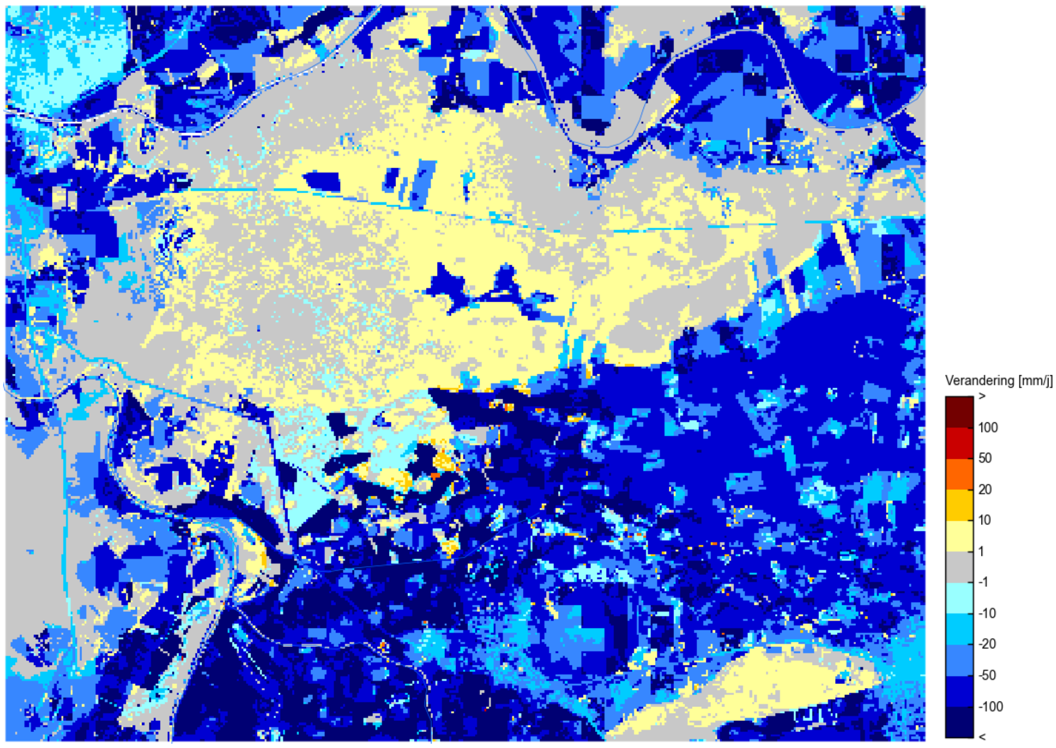


*Fig. 12 Verschil totale verdamping in 2003 tussen run 3 met dynamische WOFOST koppeling **plus** zuurstofstress en run 2 met NHI-gewasfactoren.*

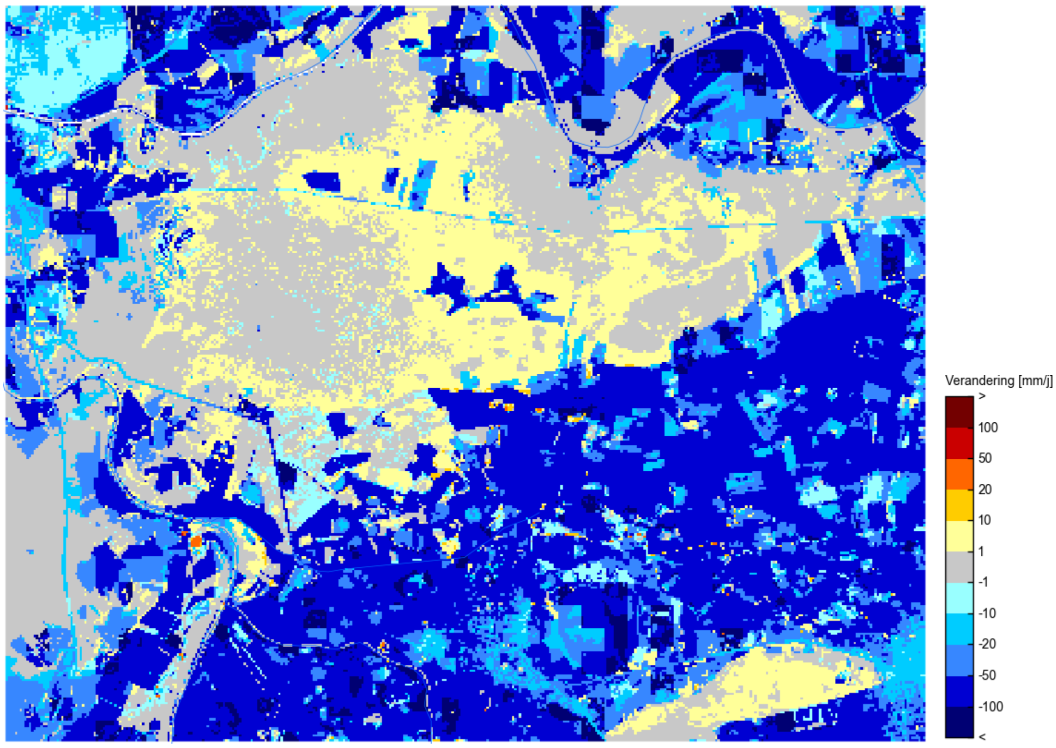


*Fig. 13 Verschil totale verdamping in 2003 tussen run 3 met dynamische WOFOST koppeling **zonder** zuurstofstress en run 2 met NHI-gewasfactoren.*

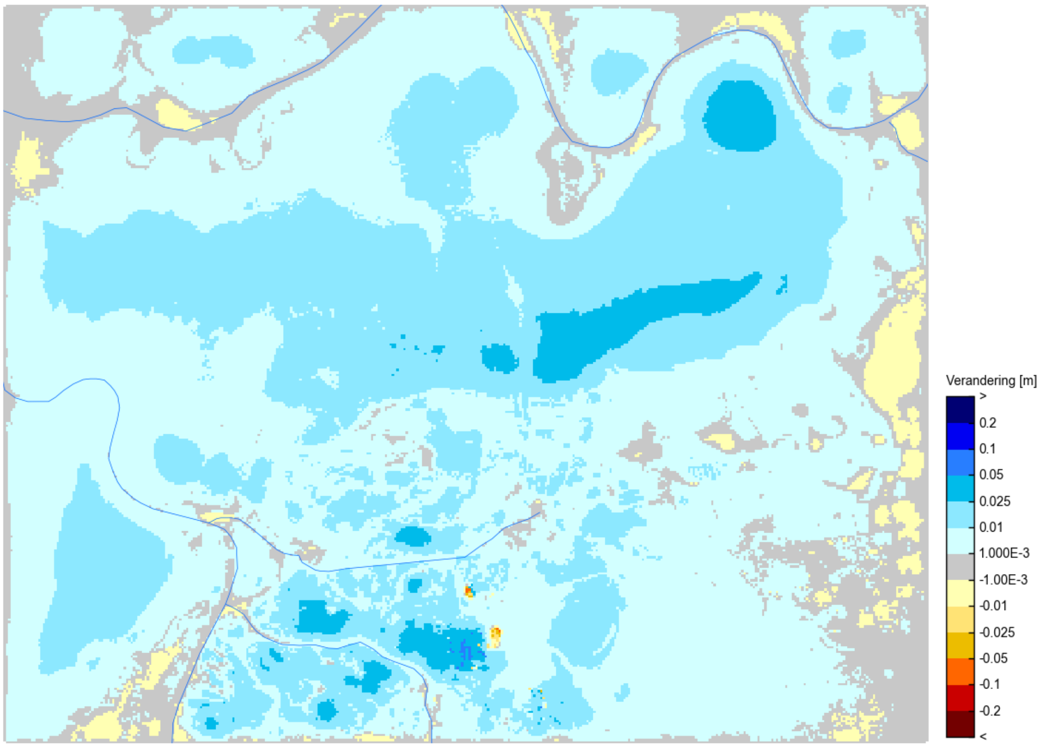


*Fig. 14 Verschil van de GHG (2005-2014) tussen run 3 met dynamische WOFOST koppeling **plus** zuurstofstress en run 2 met NHI-gewasfactoren.*

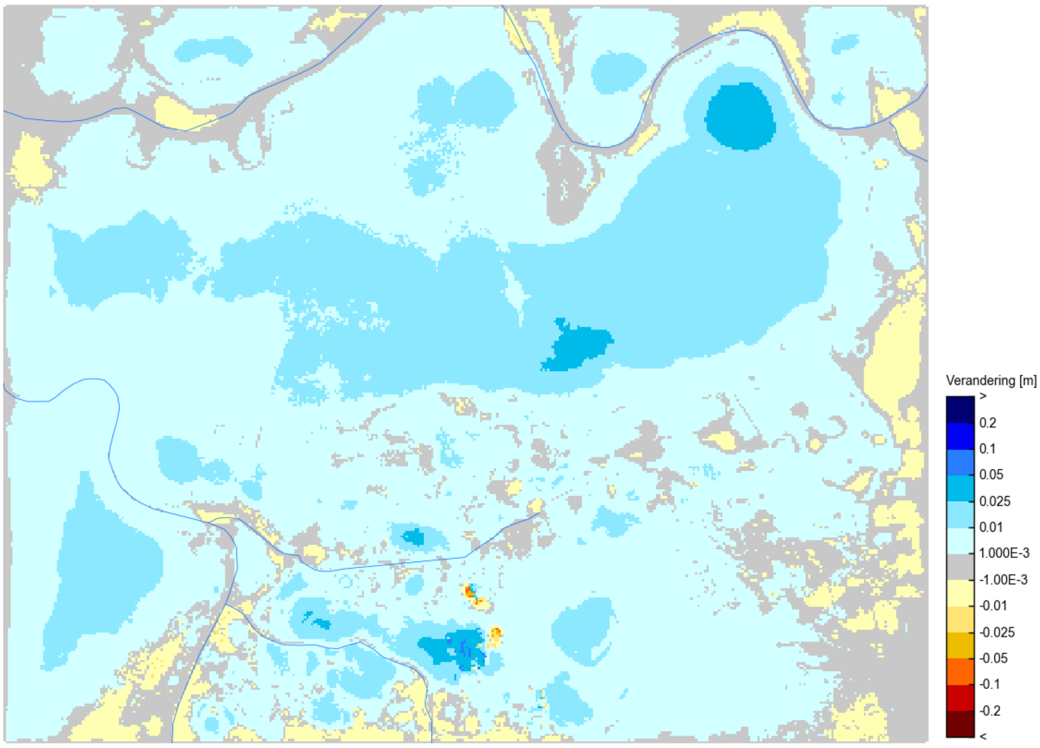


*Fig. 15 Verschil van de GHG (2005-2014) tussen run 3 met dynamische WOFOST koppeling **zonder** zuurstofstress en run 2 met NHI-gewasfactoren.*

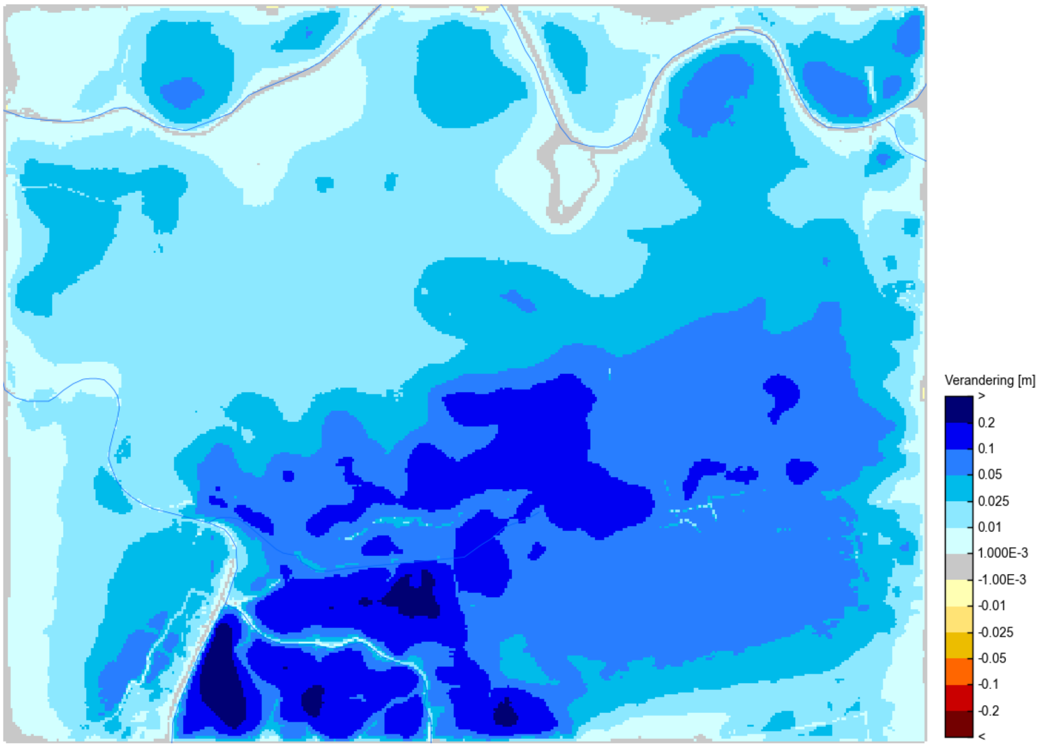


Fig. 16 Verschil van de GLG (2005-2014) tussen run 3 met dynamische WOFOST koppeling ***plus*** *zuurstofstress en run 2 met NHI-gewasfactoren.*

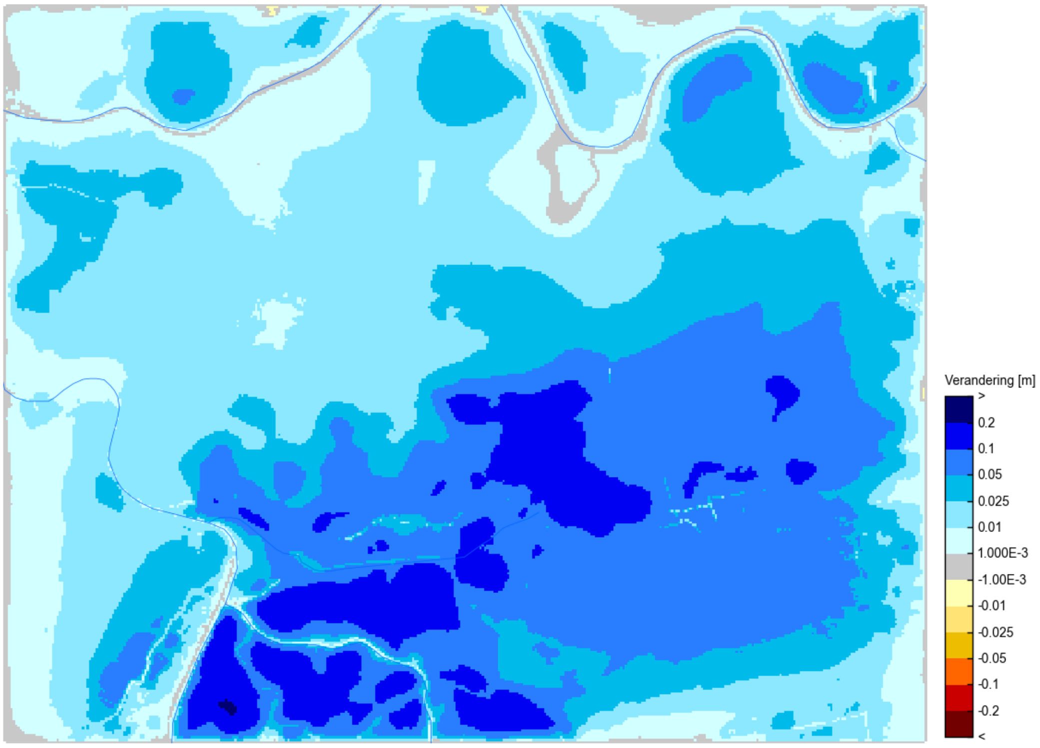


Fig. 17 Verschil van de GLG (2005-2014) tussen run 3 met dynamische WOFOST koppeling ***zonder*** *zuurstofstress en run 2 met NHI-gewasfactoren.*

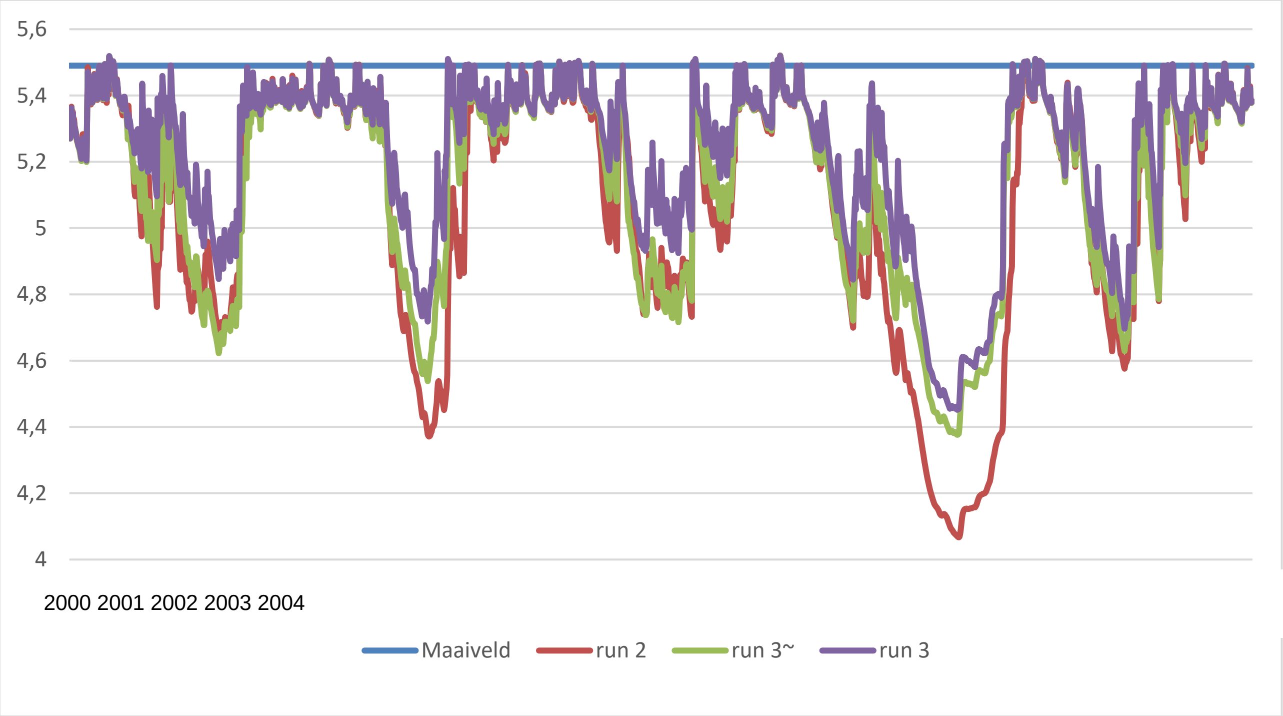


Fig. 18 Verloop van de gesimuleerde grondwaterstand voor drie verdampings-modelconcepten: run 2 – NHI-gewasfactoren; run 3⁻ - koppeling met WOFOST zonder zuurstofstress; run 3 – idem, met zuurstofstress

In Fig. 19 en 20, tenslotte, zijn verschillen weergegeven (voor 2000 en 2003) van de uitbreiding van het aantal ‘gidsgewassen’ van 3 naar 5, waarbij voor suikerbiet en granen aparte WOFOST files worden gebruikt in plaats van die voor aardappelen. De verschillen zijn in dit voorbeeldgebied beperkt van ruimtelijke omvang, maar de effecten zijn lokaal wel sterk: de vlekken met toename betreffen suikerbiet en die met afname granen.

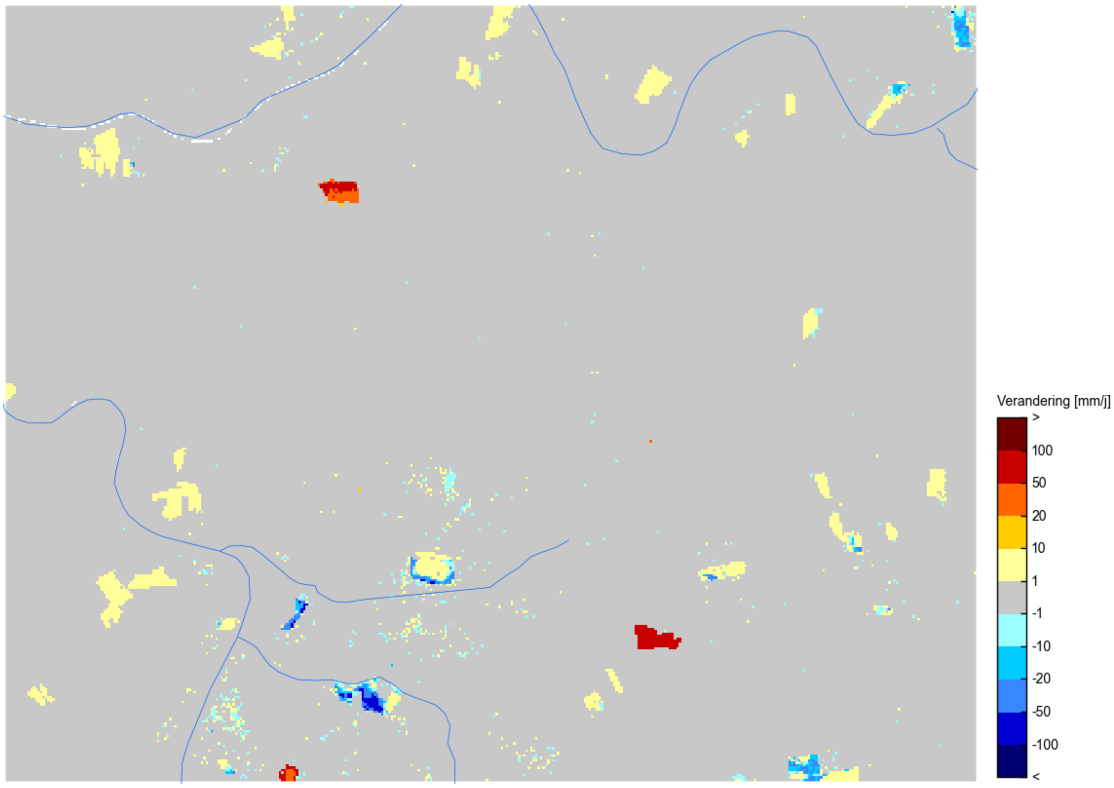


*Fig. 19 Verschil totale verdamping in 2000 tussen run 5 met dynamische WOFOST koppeling met **5** gewassen plus zuurstofstress en run 4 idem met **3** gewassen*

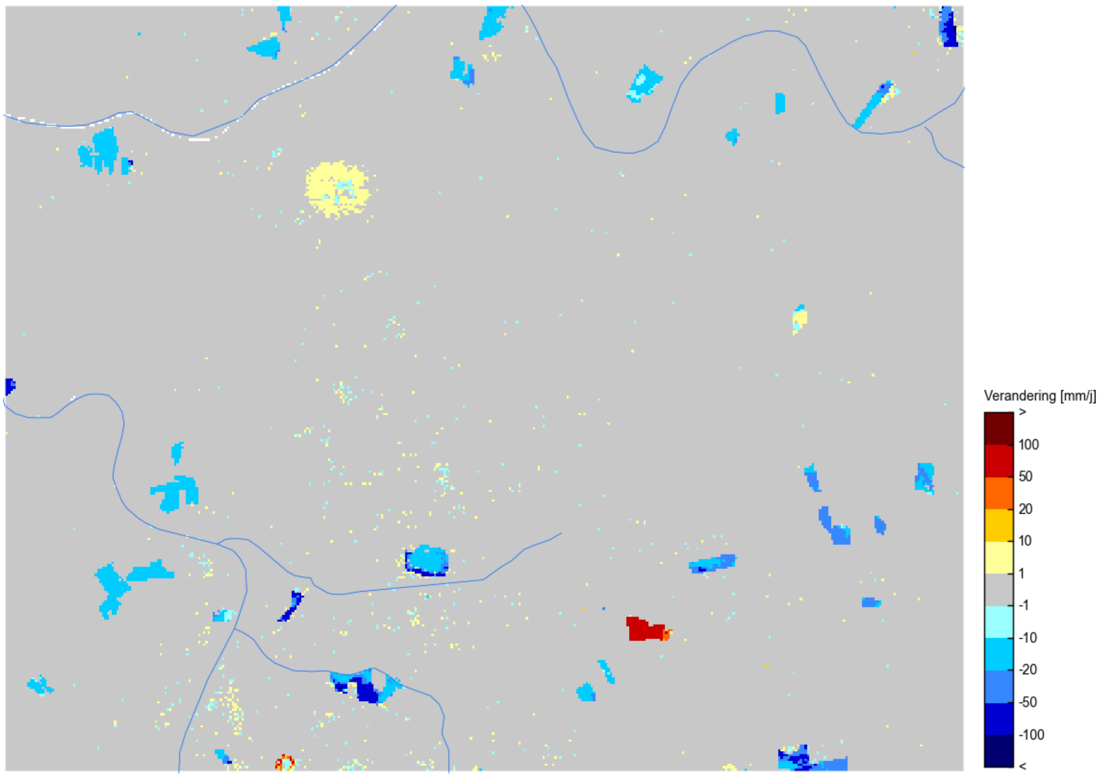


*Fig. 20 Verschil totale verdamping in 2003 tussen run 5 met dynamische WOFOST koppeling met **5** gewassen plus zuurstofstress en run 4 idem met **3** gewassen*

D.4 Conclusies en aanbevelingen

In deze notitie is verslag gedaan van de koppeling van WOFOST en zuurstofstress aan MetaSWAP op basis van SWAP-WOFOST versie 4.0.16. Technische verificatie van de resultaten aan die van SWAP-WOFOST geeft aan dat voor verschillende meteorologische condities (nat, droog) en hydrologische condities (kwel, wegzijging) de afwijkingen van MetaSWAP-WOFOST over het algemeen ruim binnen de 5% van de totale potentiële verdamping blijven, met in een enkel geval een waarde op de grens. Overigens wordt de ‘echte’ potentiële verdamping bepaald door de potentiële *gewas*ontwikkeling, en die wordt noch door SWAP en noch door MetaSWAP berekend, en moet worden ingeschat bij het beoordelen van de foutenmarge.

Van groter belang dan de afwijkingen tussen MetaSWAP en SWAP is dat het MetaSWAP-WOFOST model veel sterker reageert op verschillende meteorologische jaren dan het MetaSWAP model met NHI-gewasfactoren die van jaar tot jaar hetzelfde zijn.

Dat het dynamisch gekoppelde model sterker van jaar-tot-jaar reageert is een gevolg van het versterkende effect via de gewasontwikkeling: als er reductie is van de gewasverdamping door vochttekort dan heeft dat een achterblijvende gewasontwikkeling tot gevolg, met daardoor een *extra* reductie van de verdamping. Dit is een vorm van positieve terugkoppeling. Tegelijkertijd wordt het effect daarvan enigszins verzwakt door de ook optredende negatieve terugkoppeling vanuit het bodemvocht: als er reductie van de verdamping is door achterblijvende gewasontwikkeling, dan is er minder vraag naar bodemvocht, waardoor de reductie juist weer wat minder wordt.

Bij zuurstofstress is de zelfversterkende terugkoppeling via de gewasgroei het sterkst aanwezig doordat de effecten doorgaans aan het begin van het seizoen plaatsvinden en de effecten op het *hele* seizoen doorwerken. Bij zuurstofstress komt daar nog bij dat de wisselwerking met het bodemvocht ook zelfversterkend is: door reductie van de verdamping wordt de situatie nòg natter, wat weer extra zuurstofstress oplevert. Dat is een tweede vorm van positieve terugkoppeling. Daarmee onderscheidt zuurstofstress zich van droogtestress, want bij die vorm van stress werkt de wisselwerking met het bodemvocht juist dempend

Bij het testen van de modelaanpassingen op een uitsnede van het Vechtstromen model blijkt dat koppeling aan WOFOST zorgt voor een flinke variatie in de jaar-tot-jaar verdamping wanneer de uitkomsten worden vergeleken met een rekenrun zonder dynamische WOFOST koppeling. Het meest opvallende is echter het op grote schaal voorkomen van zuurstofstress met een sterk negatieve impact op de verdamping. Dit ligt zeker voor een deel aan het feit dat het grondwatermodel is gekalibreerd met het NHI-verdampingsconcept en niet met de MetaSWAP-WOFOST-zuurstofstress koppeling.

Uit de rekentests is verder gebleken dat het zuurstofstress-model bijna evenveel rekentijd neemt als de overige modellen bij elkaar. Dat wordt gezien als disproportioneel, maar niet onoverkomelijk. De oorzaken moeten nog verder onderzocht worden. Het vermoeden is dat de oorzaak ligt in het gebruik van bodemfysische tabellen in plaats van analytische van Genuchten functies zoals Waterwijzer-Landbouw.

D.5 Referenties

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