A new Watervision for HDSR

An evaluation of the usefulness of Watervision as a decision support system for regional groundwater governance: a case study in the Langbroekerwetering

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Abstract

In order to sustainably manage natural resources, policy makers and managers have to make a number of complex decisions. The difficulty lies in finding a balance between social and economic interest on one hand, while on the other hand avoiding overexploitation and long term mismanagement of resources. On top of that there are several uncertainties such as climate change and changes in socio-economic conditions that have to be taken into account. Environmental Decision Support Systems (EDSS) can help with these complex tasks in decision making.

This study is about a new EDSS called Watervision, released at the end of 2018. Watervision is a model that quantifies the effects of water level conditions and climate to vegetation (nature and crops). The model consists of two modules: Watervision Nature (WVN) and Watervision Agriculture (WVA). New climate data and updated (process based) models were integrated in the development of this new tool. However, since it just recently became available, a limited number of organisations has experience in using it. Therefore, this study aimed at analysing the usefulness of Watervision for regional groundwater governance. This was done by performing a case study for Hoogheemraadschap de Stichtse Rijnlanden (HDSR) in the Langbroekerwetering.

The potential of the Watervision tool was evaluated on the credibility of the model and the acceptability of the model for its users. The method of this research included two parts; first an extensive background study on the models, case study area and groundwater governance was performed. This provided the fundament for the quantitative analysis of the case study. In this part all possible model outputs of Watervision were analysed and the model was compared to the original model Waternood (from 2002). Lastly, a sensitivity analysis was performed.

The new model Watervision has a number of advantages compared to original Waternood. The model uses new climate data and uses process based models instead of expert judgement. Also, the outputs produced by Watervision provide useful insights in the location, severity and type of damage. It was found that these measures fit very well within the process of groundwater governance.
On the other hand some disadvantages were found. In the case of Watervision Nature the model provides two almost similar options to assess the water management conditions to the vegetation requirements. The fact that it is unclear which option is better while the results are different, increases uncertainty for managers and makes the model less acceptable. The credibility of Watervision can also be improved on some aspects. For instance the process based models overestimate some types of damage in some cases.

To conclude, Watervision is a useful instrument for groundwater governance. The model provides numerical calculation of damages and the ability to evaluate different scenarios. Besides that it is also useful to the policy debate in general because it helps understanding an area of interest and assist in understanding different stakeholders.

Contents

List of abbreviations

EDSS	Environmental decision support systems
WVN	Watervision Nature
WVA	Watervision Agriculture
HDSR	Hoogheemraadschap de Stichtse Rijnlanden (Water authority De Stichtse Rijnlanden)
PSS	Policy support systems
GIS	Geographic information system
STOWA	Stichting Toegepast Onderzoek Waterbeheer (Foundation for applied research in water management)
HCN	Hydrological constraints for Nature
GGOR	Gewenst Grond-en Oppervlaktewaterregime (Desired water level)
AGOR	Actuele Grond-en Oppervlaktewaterregime (Actual water level)
SWAP	Soil-Water-Atmosphere-Plant
WOFOST	World food studies
GLG	Gemiddeld laagste grondwaterstand (Average lowest groundwater level)
GVG	Gemiddelde voorjaars grondwaterstand (Average groundwater level in spring)
GHG	Gemiddeld hoogste grondwaterstand (Average highest groundwater level)
GG	Gemiddelde grondwaterstand (Average groundwater level)
BOFEK	Bodemfysische Eenhedenkaart (soilphysics map)
RS	Respiration stress, or oxygen stress
TS	Transpiration stress
DS	Drought stress

1. Introduction

1.1 Topic introduction

Uncertainties due to climate change, weather conditions and changing socio-economic conditions means that society faces major challenges in water, land and food management (Allouche, 2011). Therefore, sustainable management of natural resources has increasing societal and scientific interest (Matthies et al., 2007). Managing these challenges requires insight in the potential of land as a result of changes, such as crop variation, different management practices but also changes in water management (Hack-ten Broeke et al., 2018). In the field of land evaluation, soil scientists aim to predict the potential of land use on the basis of its attributes (Rossiter, 1996). However, the interactions between socio-cultural, economical and biophysical systems make that this relation has a high complexity. This complexity increases the need for so called environmental decision support systems (EDSS) or policy support systems (PSS) which enable people to manage complex choices and make strategic decisions (Matthies et al., 2007).

Before the ‘80s different empirical models have been used in the Netherlands to evaluate soil types and corresponding suitable land uses (Sonneveld at al., 2010). These models used qualitative assessments based on experiments and expert judgement (Hack-ten Broeke et al., 2018). While the models proved to be useful, they were limited in the sense that they often relied on specific soil scientists expertise and were bound to a certain area, which urged the need for a more systematic land evaluation approach (Haans, 1979). Over the following decades models were created that were more flexible, enabled simulation and included dynamic soil processes. Also over time more quantitative methods, GIS and simulation modelling were used to quantify the effects of land use change or climate change (Sonneveld et al., 2010).

Recently, at the end of 2018, a new land evaluation tool has been developed called Watervision (in Dutch: Waterwijzer) which was developed by KWR watercycle research institute and Wageningen UR together with STOWA (Stichting Toegepast Onderzoek Waterbeheer). Watervision is divided in two tools: Watervision Nature (WVN) and Watervision Agriculture (WVA). New developments in agricultural practices, weather conditions and climate change resulted in the need for this new tool in the field of land evaluation (Bartholomeus et al., 2018; Heinen et al., 2017). The tool allows for a spatial analysis of an area of interest and is therefore a GIS based tool. For this area outputs are produced that can be used to evaluate the suitability of present land use, vegetation and water management. This is done by calculating the optimal water level for the located land use, and the damage to the crops or vegetation due to the water level gap (too high, too low or too salt). To determine this, Watervision consists of process based models for groundwater transport and crop growth in combination with expert knowledge on vegetation characteristics. The application also provides the possibility to test the robustness of the current land use under climate change scenarios (Hack-ten Broeke et al., 2010; Hack-ten Broeke et al., 2015; Werkgroep Waterwijzer Landbouw, 2018).

Within water management, quantitative methods and decision support tools using GIS and simulation modelling are well-known techniques to evaluate different realistic options (Hack-ten Broeke et al., 2018). Examples are the HELP tables, the Hydrological constraints for Nature (HCN) framework and the Waternood tool. These tools all contain methods to evaluate a certain water level in relation to the vegetation/land use function that is present (Runhaar & Hennekens, 2014; Van Bakel et al., 2005). For groundwater governance it is especially useful to use these tools as water levels have to support the land use functions in the area and these functions are often related to the type of vegetation (HDSR, 2011). This means that the Watervision tool may also be of use for organisations as Provinces, drinking water companies and regional water authorities (Hack-ten Broeke et al., 2015). As the Watervision model provides both quantitative dynamic process simulation and qualitative expert judgements, and also enables the integration of climate change, this may be a good alternative to the HCN framework, HELP tables and Waternood.

However, the Watervision tool has not been used by organizations in this field yet, and herein lies the knowledge gap of the potential of this tool for groundwater governance. Research and feedback from current users of Watervision shows that there are also a number of uncertainties that have still to be addressed (Kros et al., 2017). One of these aspects is the credibility of the outcomes, which depends on their technical validity, whether the model is scientifically sound, uses high-quality data, and the quality of testing (Wassen et al., 2011). This includes the contents of the tool, sensitivity of underlying models and plausibility and reliability of the outcomes when compared to other models. As well as this, when developing a policy or decision support system not only the underlying knowledge such as socio-economic and physical factors, but also the usefulness and practicality of the tool for the intended users is important (van Delden et al., 2007). Furthermore tools should comply with the needs and capabilities of users, available information and the institutional context in which the decisions are made (Walker, 2002). These factors make up the acceptability of a model. Which is described by Wassen et al. (2011, p.340) as the extent to which "planners and stakeholders consider the results of these studies as (reasonably) valid and valuable" and whether "it is accepted that these results can be used in subsequent stages of the planning process".

To summarize, due to the fact that Watervision is relatively new, its credibility and acceptability in comparison with other models still has to be explored. Insights in the underlying assumptions, methods to describe and model processes, as well as insight in the practical use and potential for implementation are important knowledge for the added value of Watervision for groundwater governance.

In order to contribute to this knowledge gap, a case study will be performed to study whether Watervision can function as a decision support tool in the context of regional groundwater management, focusing on the application for regional water authorities in the Netherlands.

1.2 Problem description

This study aims to add knowledge to scientific literature on decision support systems in the field of groundwater management. The scientific problem entails the development of new decision support systems, in a field that is complex both in terms of the involved stakeholders and its biophysical processes, in combination with the need to take into account climate change.

The context in which decision support systems can play a role in regional groundwater governance, is the so called *peilbesluit*, which is a water level management plan for a specific bounded area which is valid for ten years. Every regional water authority in the Netherlands in obliged by law (the Water Act) to make a *water level plan* for the surface water that is present in their district. As mentioned earlier, this is a complex task due to fact that different land use functions are combined in the same area. This results in a societal problem because these different functions ask for different water levels and can therefore result in conflicting interests between different stakeholders.

Therefore, it is important for water level management to incorporate both the public and individual stakeholders interests as much as possible. Different factors are for example; preventing land subsidence, being able to both handle drought and peaks, take into account agriculture and creating positive circumstances for nature vegetation (Disco & van der Vleuten, 2007). On top of this, due to climate change, it is expected that extremes will become bigger and that the precipitation and evaporation regimes will change (Van den Hurk et al., 2014). Therefore, it also becomes increasingly more important for regional water authorities to incorporate such projections in their management plans.

The practical problem related to this is that water authorities have different tools and methods available in order to take all the different functions into account and come to an optimal water level. However, they do not yet have experience with the newest tool Watervision.

Bearing in mind the discussed complexities, this study will answer the following research question: *How useful is Watervision as a decision support tool for regional groundwater governance?*

To answer this question a case study will be performed for a specific organization; the regional water authority of the Stichtse Rijnlanden (further referred to as HDSR). HDSR has not yet used Watervision and is therefore interested in analysing the applicability of Watervision to the water level management. For this purpose the tool will be applied to a specific area which falls under HDSR responsibility to make a *peilbesluit.*

1.3 Aim and research questions

The objective of this research is to study the usefulness of the Watervision tool for regional groundwater governance in terms of credibility and acceptability. In order to make this research fit into the bigger context and provide useful results within the set timeframe, a case study will be performed for the Langbroekerwetering area. This results in practical experience with the Watervision tool and to research if and how the tool can contribute to the current establishment of the new water level plan for the Langbroekerwetering.

This aim is summarized in the earlier stated research question:

How useful is Watervision as a decision support tool for regional groundwater governance?

In order to answer this research question, several steps were taken. First it is studied what regional groundwater governance entails, with a focus on the governance context, choices that have to be made and data and instruments that are used to substantiate these choices.
Secondly, the background of Watervision was further explored. This focuses on three aspects. 1) The reasons for developing Watervision. 2) The (eco)hydrological processes that are included in Watervision. And 3) how climate change are scenarios included in Watervision.

To evaluate the usefulness of Watervision in regional groundwater governance, its application to a specific area was performed in a case study. For a thorough understanding of the case study area first insight was gained in the following aspects; (1) the land use functions that are present in the Langbroekerwetering and the differences in water management requirements for these functions, and (2) the (geo)hydrological processes that are present in the Langbroekerwetering.

Using this knowledge of the background of the Watervision tool, groundwater governance and the characteristics of the study area, the usefulness of the tool can be evaluated properly. In order to do so the results from the case study are used to answer the following sub research questions:

1. Plausibility study of the Watervision tool.
    1.1. How can the individual WVA and WVN outputs be used for water level management?
    1.2. What are differences in output in Waternood and the Watervision when the same inputs are used?
    1.3. How robust are the outcomes of the Watervision (sensitivity analysis)?
2. Added value of the option to use climate scenarios within Watervision.
    2.1. When running Watervision with climate scenarios in the study area, what does it tell us about the robustness of the water level management in the Langbroekerwetering?

The first question will analyse the plausibility and sensitivity of the Watervision model. The first part (1.1) will model all possible outputs of Watervision and will look at how they can contribute to the *peilbesluit* and which outputs are the most useful for the groundwater governance. Also, because there is a lot of expert knowledge available within HDSR about the study area we can study if the outputs that are calculated with Watervision meet expectations.
The next part (1.2) will go more into the plausibility of the Watervision tool by comparing the outputs from Watervision to original Waternood. It is relevant from the perspective of HDSR to look at the differences in outputs as they have used Waternood for the previous water level plan in the Langbroekerwetering. Looking at differences like outputs, spatial resolution, temporal resolution and robustness will provide relevant information on the usefulness of the tool. Both questions contribute to evaluating the acceptability.
Lastly (1.3), in order to get a better feeling of the credibility of the Watervision tool it is also important to know how sensitive it is. This will be done by step by step altering the inputs in the model and looking at the influence different parameters have on the outputs.

The second question is formulated because Watervision provides the possibility to work with climate change scenarios. Since climate scenarios are not yet used for water level plans in this way by HDSR, it will be analysed how these options can be used, and how they can potentially contribute to ground water management.

2. Background of regional groundwater governance

2.1. Regional groundwater governance plans and policies

In the Netherlands water management is assigned to regional water authorities who are responsible for the management of (most) surface water and sewage treatment. The main tasks of the regional water authorities evolve around: water safety, water provisioning and water quality (Mostert, 2010). Subsequently, regional groundwater governance is also one of their duties. Every water authority in the Netherlands in obliged by law (the Water Act) to make a *peilbesluit* for the surface water that is present in their district. A *peilbesluit* is a water level management plan for a specific bounded area which is valid for ten years, with the aim of creating an optimal water system that matches the land use functions of the area of interest. When making a water level management plan the water authority follows the procedure that is set in the *Beleidsnota Peilbeheer* (2011 for HDSR). By following a set procedure it is made sure that a water level plan complies with regional, national and international legislation like the Water Act, the National Administrative Water Agreement (NBW), the European Water framework Directive, National Ecological Network, Flora and Fauna Act and legislation that is made by the Provinces (HDSR, 2011). This research focuses on the water board Stichtse Rijnlanden (further referred to as HDSR).

The procedure that is followed in order to decide for and maintain a water level plan is the GGOR-methodology. The establishment of a GGOR (desired water level) is a cyclic process in which first bottlenecks are identified by comparing the optimal water level (OGOR) to the actual water level (AGOR). Secondly, different scenarios in water levels and type of management (e.g. flexible or fixed summer and winter level, see appendix I.a) are evaluated in order to decrease the bottlenecks. To decide for the best scenario a lot of different aspects have to be taken into account including: cost benefit analyses, effects on water quality, whether or not the system needs flushing, how to handle peaks. It is a complicated process that needs a lot of expertise for each aspect but also on the specific physical conditions of the area of interest. The best scenario will result in the GGOR which will be established in a new water level management plan (or in a *watergebiedsplan* if the scenario includes infrastructural adjustments). This plan will be enforced and monitored by the regional water authority (HDSR, 2008; HDSR, 2011).

One commonly used way to link the GGOR-methodology to land use, is by expressing it as goal attainment (*doelrealisatie)*. Goal attainment refers to the extent (%) to which the water level supports the realisation of the vegetation or crop. This relation can be visualized by means of an attainment-graph. In this trapezoid shaped graph it can be distinguished for which water levels the conditions are optimal, too wet or too dry, determining whether a plant realizes its potential (Figure 2.1).

Appendix I provides addition details about different methods and previously used EDSS that can help with water level optimization in regional groundwater governance.

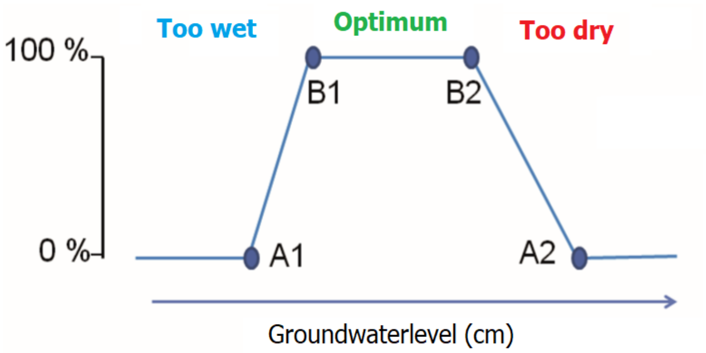

Figure 2.1 Goal attainment graphs (or "trapezoid graphs") that are used within the HCN instrument. A1 and A2 are upper limits that determine under what conditions the vegetation cannot be present. B1 and B2 are points that bound the area where the vegetation is in optimal condition.

3. Background of Watervision

3.1 Overview

The following Figure (3.1) provides an overview of the different components of Watervision. Watervision consists of two modules which are Watervision Agriculture (WVA) and Watervision Nature (WVN). In WVA the damages to crops are modelled with a process based model and in WVN this is partly process based. WVN includes two updated version of the original Waternood methodology, which are called WVN Waternood and WVN Waternood+. Subsequently, WVN consists of the process based model Probe. All of these modules will be further elaborated on in this chapter.

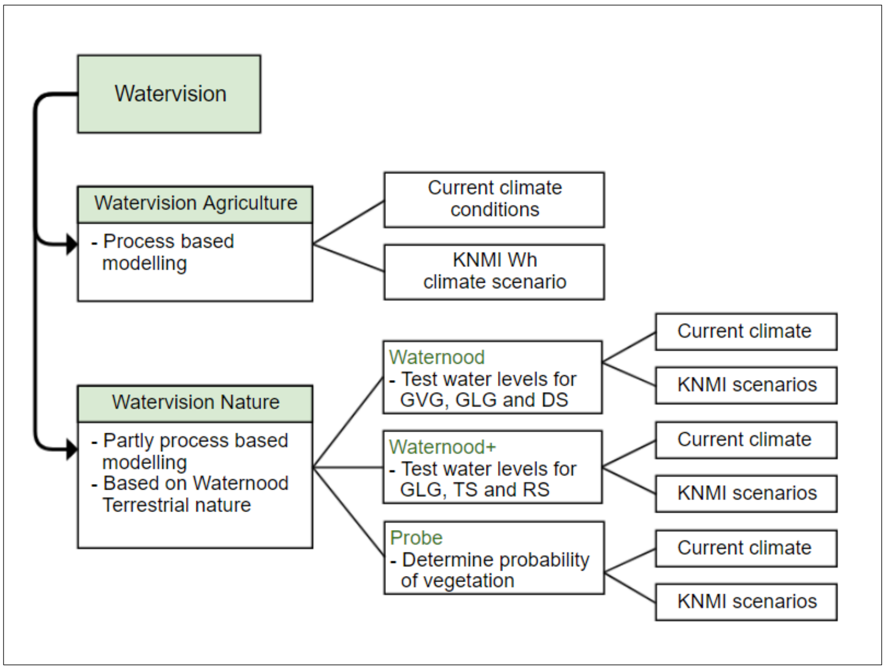

Figure 3.1 Overview of Watervision
GHG: average highest groundwater level, GLG: average lowest groundwater level, GVG: average groundwater level in spring, DS: drought stress, TS: transpiration stress, RS: oxygen stress (transpiration stress)

3.2 Why and for which purpose is Watervision developed?

In rural areas in the Netherlands, the land use functions agriculture and nature are most common and take up the majority of the space. These two functions require different conditions in terms of water management, groundwater level, and fluctuation of water levels. The Watervision tool is developed to answer questions related to these water level requirements such as: *What is optimal?* and *What is the damage to the vegetation and crops if we deviate from this optimal situation?* (Bartholomeus et al., 2018). There are different methods available to answer these questions. However, most of them are outdated in terms of the data they use and the assumptions that are incorporated. Examples are the HELP tables, Hydrological Constraints Nature and the Waternood module. These methods have in common that they are all based on empirical relations that have been established in the past, in combination with expert judgement (Bartholomeus et al., 2018). Watervision was released in response to those predecessors in 2018, with similar purposes.

In addition to this, due to recent developments like new agricultural legislation, technological innovations in agriculture, more flexible management in water levels and lastly, more extreme weather events, there was also a need for a new method to incorporate these developments (Hack-ten Broeke et al., 2010). Another major spark for this new tool is to create a method that is more robust to climate change and relies less on old climate data. Therefore, in Watervision it is possible to calculate outputs using different weather conditions and also for climate change scenarios. Lastly, there was also a need for more in depth insight in damage to vegetation in specific years (Hack-ten Broeke et al., 2015)

The main purpose for which Watervision is developed is to quantify the impacts on vegetation due to changes in the water system or climate. A lot of knowledge is bundled in one tool to enable users, such as water managers, easy access to information and expertise (Bartholomeus et al., 2018). This way the tool can function as a decision support system for organizations that regulate water levels, or have a responsibility over agricultural or nature areas.

Watervision Agriculture (WVA) is ‘an instrument that can determine crop yield effects and the effects on farm economy as a result of drought, too wet or too saline conditions for both current and future climate conditions based on simulation modelling’ (Hack-ten Broeke et al., 2018, p. 536). This can be used to determine damage to crops and optimising water management accordingly. The target users of the model are regional water managers and agricultural business holders. However, also drinking water companies, advisory organisations (such as ACSG, adviescommissie schade grondwater) and provinces have shown interests (Bartholomeus et al., 2018).
Watervision nature (WVN) serves a similar purpose, enabling insight in damage to vegetation in nature areas and finding measures to decrease this damage. However, for nature we are not interested in maximizing the production of vegetation and having water levels that support a high production. Regarding nature we are interested in having more extreme water condition that can support more rare species (Runhaar, 2013). This is interesting for similar organisations as mentioned before, with the additions of organizations that manage nature areas. The Netherlands is for instance obliged to maintain Nature-2000 areas in good conditions and if possible, improve them. In this light it is useful to be able to manage water levels in favour of natural vegetation (Bartholomeus et al., 2018).

3.3 Processes that are included in Watervision

3.3.1 General processes

In general we can say that to model the effects of a changing climate or changing water system to vegetation it is vital to incorporate the processes that interact between: soil, water, vegetation and atmosphere.
An increase of greenhouse gasses in the atmosphere will lead via an increase in temperature to changes in precipitation and transpiration which will both have an effect on soil moisture, groundwater and surface water. The amount of soil moisture is also influenced by the root uptake of the vegetation itself and vice versa. The amount of soil moisture translates to a number of chemical processes that happen in the soil like weathering of minerals and changes in nutrients and acidity. All these processes have therefore effects on the conditions in which vegetation grow and how optimal these are. Lastly, the concentration of CO_2 in the atmosphere also has a direct effect on plant growth. A higher CO_2 concentration will make plants grow faster and they will become more efficient in water use (Bartholomeus et al., 2018). These general processes are visualized in Figure 3.2

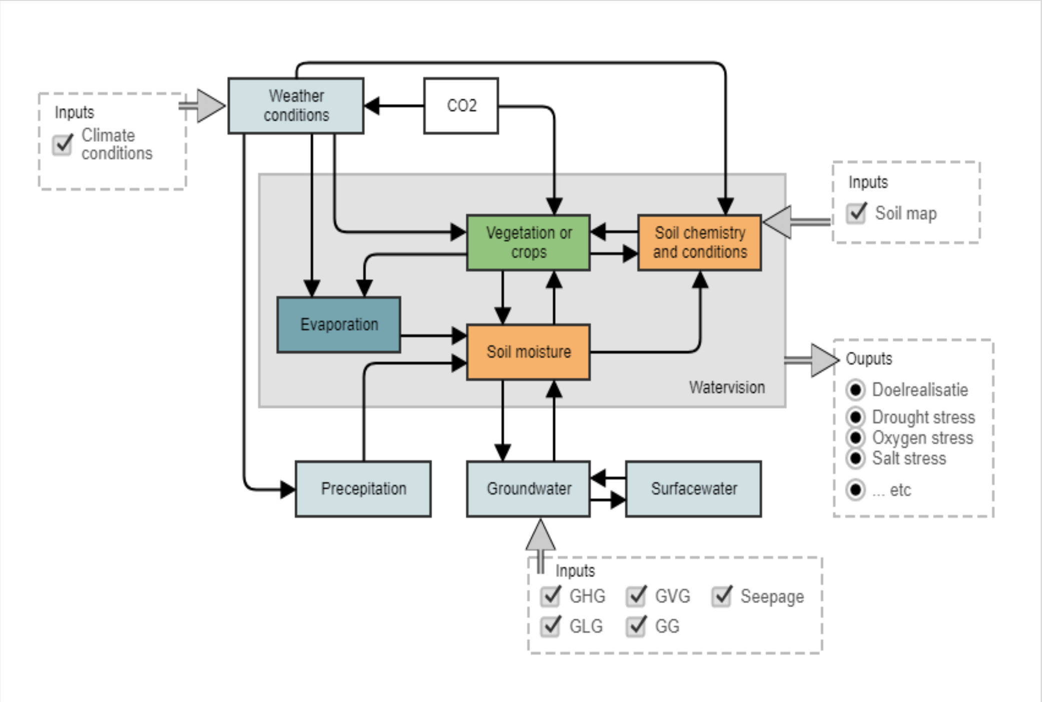

Figure 3.2 Overview of (general) processes that are part of Watervision. The dashed boxes represent the in- or output that are part of Watervision and to which process or variable they are related. Adapted from Bartholomeus et al. (2018)

All these processes are modelled within Watervision and the way they are incorporated is different for the two sub-models: WVA and WVN. In the following section the hydrological and ecological processes that are included in both sub-models is explained as well as how they are incorporated.

3.3.2 Processes in Watervision Agriculture

WVA uses two simulation models for the calculations of crop yield as a function of soil moisture. The first model is called SWAP (Soil-Water-Atmosphere-Plant) (developed by Kroes et al., 2017; van Dam et al., 2008) which is an (agro)hydrological model which forms the hydrological base of WVA. The second model is called WOFOST (by van Diepen et al., 1989) and models crop growth over time.

SWAP

SWAP is a widely used model which is developed by Wageningen University. It forms the hydrological base of WVA and its main purpose is to model the actual evaporation as a function of meteorological data, combined with vegetation and soil characteristics. It models different processes in the vadose zone, which is the unsaturated zone together with the upper part of the saturated zone. In this zone there is interaction between ground and surface water on a parcel scale. The following processes are included in order to come to the actual evaporation:

- The transport of water, solutes and heat in the vadose zone: The transport of solutes is calculated by the convection-dispersion equation, including adsorption and decomposition processes which means that the interaction between the dissolved substances and the solid matrix (soil) is included (van der Zee & Leijnse, 2013). The transport of heat is numerically simulated including heat capacity and thermal conductivity. Lastly, soil moisture transport is based on Richards equation which simulates movement using sinks and sources. In SWAP this sink term is root water extraction. The exchange between these three transport processes is calculated on daily time steps in order to account for the interaction between them. For example decomposition rates of solute is lower at a lower soil temperature.
- Crop growth is related to the daily soil moisture and salinity conditions by a generic crop growth model. In SWAP, the sink that is related to the soil moisture transport is root water extraction. Root water

extraction is related to the potential transpiration (which is calculated by atmospheric conditions) and plant characteristics (e.g. reflection, stomatal resistance and leaf area) and can be expressed in a potential root water extraction rate at a certain depth: Sp(z). The stresses that can occur to the vegetation due to wet, dry or saline conditions result in a reduction in Sp(z). The actual root water flux is calculated in SWAP by multiplying the separate stress factors.

- The stress factors are related to the following processes: <u>Oxygen stress</u> is related to physical relationships that are used to determine the oxygen demand and supply to plant roots. Root respiration is determined by calculating oxygen consuming and oxygen providing processes in the soil. For <u>Salinity stress</u>, SWAP uses a response function which means that if the salt concentration reaches a certain critical value, the root water uptake will linearly decline.
  To determine <u>drought stress</u> the root water uptake is related to the soil water pressure head. This function was proposed by Feddes (1978). In a certain pressure head range, root water uptake is optimal. Below this range the root water uptake declines linearly until a certain critical head which is called wilting point.
- The interaction between groundwater and surface water is included by analytical drainage formulas.

When looking at the vertical domain of SWAP, the inputs are atmospheric conditions at the top and soil water heads at the bottom. Figure 3.3 shows a schematic representation of the processes that are included in SWAP. Integration of all the mentioned processes results in the actual transpiration rate by in the end integrating the actual root water flux over the root zone.

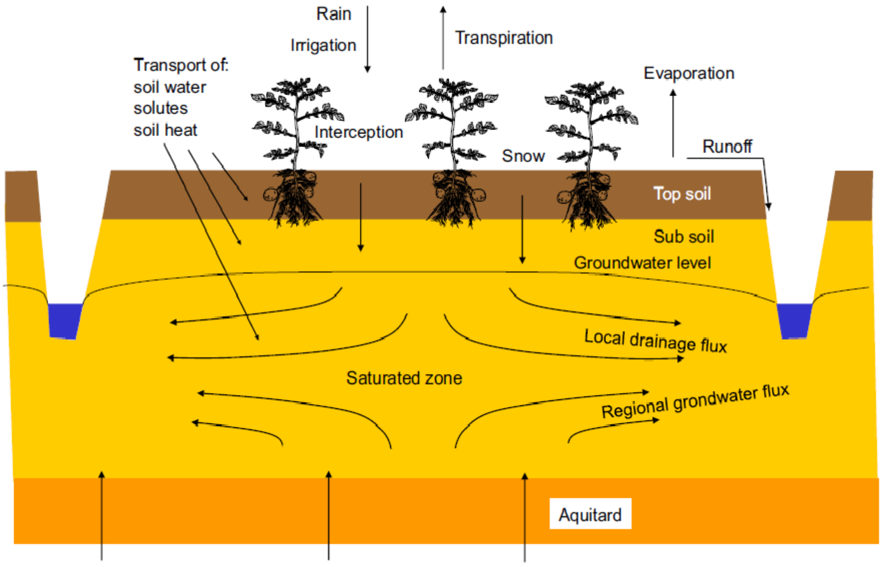

Figure 3.3 Domain of SWAP which consists of different processes in the vadose zone that have an effect on the actual evaporation. Taken from Kroes et al. 2017

<u>WOFOST</u>

The processes that are modelled within WOFOST (World food studies) are so called eco-physiological processes and they include: phenological development, assimilation and respiration, transpiration, partitioning over dry matter and the soil water balance.

- <u>Phenological development</u>: Phenological development is related to the development of a plant over time which is characterized by the rate of appearance. The order of appearance is crop related but the rate of appearance is strongly related to external conditions which are temperature and day-length. WOFOST accounts for these external effects by calculating a temperature sum and relating this to the thermal time that is required to go to a next development stage.

- Assimilation and respiration: Assimilation is related to the processes in plants that result in the supply of nutrients to the cells. An example of biological assimilation is photosynthesis. In WOFOST is CO_2-assimilation is determined from the total incoming radiation and leaf characteristics like leaf area and age.
  A part of the CO_2-assimilation is used by the species for maintenance respiration, the remaining part is converted into dry matter such as cellulose and proteins. Due to this conversion there is also some nett loss of carbohydrates, called growth respiration.
- Soil water balance: WOFOST distinguishes different ways to account for soil moisture depending on the implementations. In the case of Watervision the crop water requirements are determined from a simple water balance assuming a continuously moist soil. The crop water requirements are then quantified as the sum of the crop transpiration and soil evaporation with daily weather data and soil characteristics as external drivers. The amount of actual soil moisture determines the actual production (actual photosynthesis or actual assimilation rate)
- Partitioning of dry matter: The part of the energy that is transferred into dry material is divided over different plant organs: roots, stems, leaves and storage organs. This partitioning is modelled within WOFOST by partitioning tables which describe the fraction of assimilates partitioned to the various organs as a function of the crop development stage.
- Transpiration: Transpiration is the result of water movement through a plant and its evaporation from different part of the plant. Water is lost to the atmosphere due to opening of the stomata in order to exchange gasses with the atmosphere. To account for this loss, plants need to take up addition water from the soil. In WOFOST transpiration is modelled by using 'an optimal soil moisture range for plant growth as a function of the evaporative demand of the atmosphere, the crop type and soil water retention capacity. Outside this optimal range, the soil conditions can be either too wet or too dry. Due to these stresses the plant reacts in closing its stomata which results in a decrease of photosynthesis and therefore a decrease in assimilation rate. WOFOST models this reduction of the assimilation rate by using the ratio of the actual over potential transpiration as a reduction factor.

All these processes are modelled in WOFOST, following the order of steps that are presented in Figure 3.4. First it determines the potential production as a function of CO_2 concentration, solar radiation, temperature and crop characteristics which is related to the process of assimilation. Then, the reduction factor due to due to limiting soil moisture conditions is used to determine the actual production. From the actual photosynthesis, parts of energy are lost to respiration and the remaining energy is transformed into dry matter. After the partitioning of dry matter over the different organs, the resulting leave area will be used again for the next time step. The temporal scale on which this loop is calculated is daily. (Bartholomeus et al., 2018; de Wit, n.d.; Hack-ten Broeke et al., 2018; Hack-ten Broeke et al., 2015)

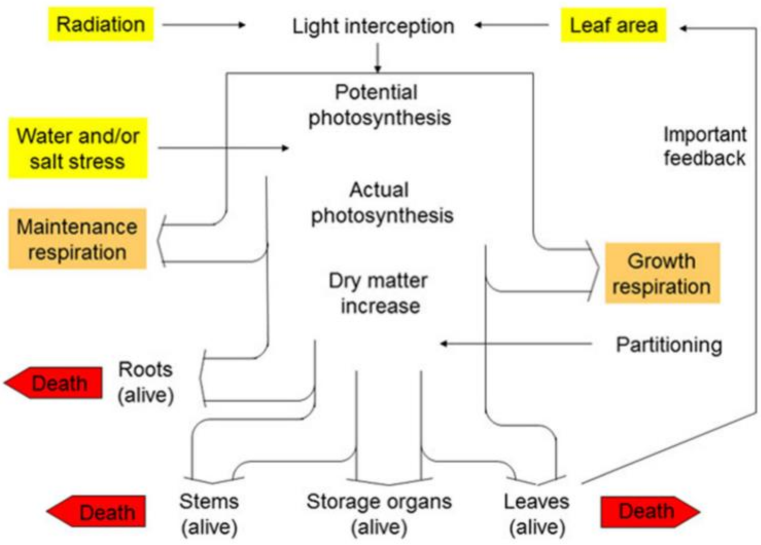

Figure 3.4 Processes and steps in WOFOST.
On a daily time step, first weather conditions (radiation) together with plant characteristics (leaf area) determine the amount of light interception with the crop which is then translated to the potential photosynthesis. The amount of potential photosynthesis is decreased due to stresses and result in the actual photosynthesis. Parts of the energy that forms from the photosynthesis is lost to respiration and the remaining energy is transformed into dry matter which is divided over the roots, stems, storage organs and leaves. The amount of dry matter increase to the leaves will form a new leave area which is used for the next time step again.
Taken from Hack-ten Broeke et al. (2015)

WVA combines SWAP and WOFOST in order to take into account both processes within the plant and external conditions. In this way limiting factors to goal attainment can be modelled. In SWAP, calculations are done using a static crop that develops over time with fixed characteristics for leave area, roots, etcetera. The integration of WOFOS into SWAP replaces this static crop and gives a more realistic representation of crop development over time (Hack-ten Broeke et al., 2015).

Diarywise

In addition to the simulation models, WVA uses the empirical model Dairywise (also BBPR) in order to include the on-farm practices. The processes that are modelled with Dairywise are technical and financial processes on a dairy farm. It models a range of aspects including: fertilizer use, energy use and financial budget. By integrating this model in Watervision both direct and indirect effects are modelled. Direct effects are related to the way the hydrological situation influences crop production directly, and indirect effects are related to how these hydrological conditions hold back farmers in their daily activities, reducing profits. Examples of indirect effects are those related to limited carrying capacity of the soil, limiting farmers to enter their land, delayed sowing and germination, and harvesting damage. Those effects, in combination with farm management, can be used in WVA to develop scenarios allowing for the quantification of farm economic results (Wageningen University, 2007; Werkgroep Waterwijzer Landbouw, 2018).

Table 1 provides an overview of the outputs that are calculated as a result of running WVA which consists of SWAP-WOFOST and Dairywise.

Table 1 – Outputs generated by WVA.

Output	Unit
Total damage	%
Damage due to drought stress	%
Damage due to oxygen stress	%
Damage due to salt stress	%
Direct damage	%
Indirect damage	%
Potential crop production in biomass	€/ha
Potential crop production in euro	kg/ha or pieces/ha

3.3.2 Processes in Watervision Nature

The Watervision Nature tool can be described as follows (based on Werkgroep Waterwijzer Natuur (n.d.)):

The specific aim for which the Watervision Nature (WVN) is designed is to calculate the effects of changes in water management or climate to the terrestrial vegetation. From this aim the WVN can be divided in two parts: (1) assessment of water levels to the requirements of the vegetation (with current or climate scenario conditions) and with Waternood or Waternood+ (2) Determining the occurrence probability *(kansrijkdom)* of vegetation types under given water levels with PROBE (using current conditions or climate scenarios). To summarize, WVN consists of two assessment modules: WVN Waternood and WVN Waternood+ and one predicting module called Probe (see also Figure 3.1).

The general processes that are described in section 3.3.1 are also relevant for modelling natural vegetation in relation to water management. However, it is more complex to model these processes predicting vegetation growth for nature areas, as compared to agricultural crops due to the presence of a lot of different plant species within nature areas. Additionally, in nature areas we are less interested in vegetation productivity, but also in biodiversity (Bartholomeus et al., 2018). Due to this heterogeneity the models that model nature vegetation are often based on empirical data. While this knowledge is very valuable, it is not appropriate to model climate scenarios, as the models are not process based. For this reason WVN includes a hybrid approach; where knowledge on processes is of acceptable quality it is incorporated, where this is not the case empirical data is used.

Assessment modules Waternood and Waternood+

In order to test water levels to the requirements of nature vegetation an updated version of the Waternood methodology is included in WVN. Within Waternood, the water level requirements of different vegetation types are determined using the GLG, GVG, seepage and the way these conditions influence other factors like acidity, drought stress, oxygen supply and availability of nutrients (Runhaar et al., 2011). The relations between these variables have been determined not by process based modelling but by empirical relations between the groundwater levels and presence of species. As explained by Venterink & Wassen (1997) a correlative method like this can be based on expert-knowledge or regression analyses based on field measurements. In the case of Waternood a combination of both methods was used.

In an earlier stage of Waternood, a database containing the abiotic constraints of 139 types of vegetation was constructed. This was done by combining different reports, databases, methodologies for categorization and characterization of vegetation types and consequently using expert judgement of vegetation types and their conditions to determine critical values (Runhaar et al., 2002). Besides that, regression analyses of the correlation between field observations of presence of vegetations types and hydrological conditions are used. Correlations between the presence of hydrophytes (species adapted to live in wet areas with oxygen stress) versus the GVG, and the presence of xerophytes (species adapted to live in drought) versus the drought stress determine whether an area is appropriate for certain types of vegetation (Runhaar et al., 2011). Furthermore additions were made, as some vegetation types were much alike and had to be differentiated in subcategories, others were left out as they were not likely to be included in Waternood procedures. Lastly, as soil type influences the earlier mentioned relations between different factors, a database containing soil types and characteristics was used.

This knowledge was used to construct the commonly used “trapezoid graphs” (as described in section 2.3) that show the relation between hydrological conditions and goal attainment for a specific type of vegetation. The graphs representing the data are visualized in the HRN application (Hydrologische Randvoorwaarden Natuur). In order to determine goal attainment of nature areas, a database was used which contains the composition of nature types in terms of vegetation types. By comparing the requirements of nature types, with the actual hydrological and meteorological conditions, the gap between optimal and actual goal attainment is determined.

For a detailed description of the way goal attainment of natural vegetation is determined in the Waternood application, including used methods and data sources see Runhaar et al. (2002).

In addition to this knowledge that is established in Waternood, WVN added some additional features which are:

- Improved consideration of ground level variation within nature areas by step by step altering the ground level while calculating the goal attainment. This is an addition to Waternood and results in the outputs: *Goal attainment maximum attainable* and *goal attainment scaled maximum attainable* (see Table 2). This output will be further discussed in the results section.
- The addition of more climate robust variables for the availability of oxygen and moisture. GVG is replaced by oxygen stress (RS) and drought stress is replaced by transpiration stress (TS). This makes it possible to connect Waternood to the model PROBE, which can be used for projections into the future. With these more climate robust variables, the user can test the water management conditions with what they call Waternood+. So instead of testing the vegetation and water conditions to the GVG, GLG and drought stress (DS) (which is the case for normal Waternood), they are now tested for RS, TS and GVG. For this purpose the trapezium graphs have been transferred by the developers of WVN in order to fit these new variables.

Thus to summarize, Waternood in WVA is very similar to Waternood in the Waternood Instrumentarium with the addition of consideration of ground level variation. The knowledge that is related to nature in Waternood comes originally from what is called HRN (Hydrological Constraints Nature). In Waternood in WVN the user tests the goal attainment of the vegetation using the variables: GVG, GLG and DS. In Waternood+ in WVN the user test the goal attainment with the variables: GVG, RS and TS and for this the user has to do a separate model run in Waternood+. In Table 2 an overview is presented of the different outputs that are produced by running Waternood and Waternood+ in WVN.

Table 2 Outputs generated by WVN for WVN Waternood and Waternood+

Waternood				Waternood+	
Gap to optimal for GLG	cm	Goal attainment for seepage	%	Oxygen stress (RS)	$grO_2/m^2/10$ days
Gap to optimal for GVG	cm	Goal attainment total	%	Transpiration stress (TS)	$mmH_2O/10$ days
Gap to optimal for drought stress	days	Goal attainment maximum attainable	%	Goal attainment for transpiration stress (TS)	%
Gap to optimal for seepage water	mm/d	Goal attainment scaled maximum attainable	%	Goal attainment for oxygen stress (RS)	%
Goal attainment for GLG	%	Drought stress	days	Goal attainment for GLG	%
Goal attainment for GVG	%			Goal attainment for seepage	%
Goal attainment for drought stress	%			Goal attainment total	%

Nature prediction module

Next to the assessment modules as described in the previous paragraph, WVN offers the nature prediction module which is called PROBE. PROBE is an ecohydrological model, which predicts the vegetation distribution under a changing climate (Witte et al., 2007). The model PROBE is used to incorporate the ability to predict with WVN under changing conditions. According to a study by PBL, climate change effects on nature vegetation will mostly manifest through changes in the water balance (Franken, van Minnen, & Ligtvoet, 2013). For example, rain peaks in summer can result in oxygen stress in combination with a relatively high soil temperature which are different conditions from what we see today. On the other hand, an increase of drought stress due to climate change will bring more drought resistant vegetation which generally evaporate less water. This also influences the water balance (Runhaar, 2013).

These changes in climate 'may hamper the preservation of nature targets, but may create new potential hotspots of biodiversity as well' (Witte et al., 2015, p. 835). It does however mean that empirical relations between habitat factors and plant characteristics will change. Therefore, it is key to model the processes that are influenced by climate conditions with a process-based model.

Processes that are involved in this, result in changes in soil temperature, soil moisture changes, oxygen supply to the roots, nutrients and acidity, which all have their effects on vegetation. PROBE models these processes and computes the suitability of a certain vegetation type under a certain climate scenario. The outputs that are produced are maps showing the occurrence probabilities of vegetation types, which can be calculated for current and projected climate conditions. The vegetation types that are used for Probe are ecotope groups which have quite broad classes, which allows for less uncertainty when using climate predictions. For a list of these ecotope groups see appendix IV (Witte et al., 2015).

3.4 Climate change scenarios

For both WVN and WVA there is the option to use climate change scenarios to predict goal attainment and damages due to a changing climate and different conditions. PROBE also provides the functionality to predict occurrence probability of ecotope groups under climate change scenarios.

Regarding the climate change scenarios, WVN can use all four KNMI scenarios (Wh, Wl, Gh,& Gl) and WVA only scenario Wh. The four climate scenarios are a representation of different IPCC scenarios on a local scale (the Netherlands). The Wh scenario stands for a scenario with high increases in temperature, sea level and winter precipitation (KNMI, 2015). For further details about the different KNMI scenarios see KNMI (2015).

4. Ecohydrological background of the Langbroekerwetering

4.1 General information and land use functions

The district of HDSR covers the southern part of the province of Utrecht and a small part of the province of South-Holland and its main tasks concern water safety, water provisioning and clean water (HDSR, 2016). Within the area of HDSR there are 47 water level ordinance districts of which 4 are currently being reviewed. One of the currently revised areas is the Langbroekerwetering (Figure 4.1) which is the focus area of this study. The Langbroekerwetering spans approximately 6800 ha and is a diverse region that is located on a transition area between the higher elevated area of the sandy Utrechtse Heuvelrug and lower clay grounds that have been deposited by the Kromme Rijn. The land use functions that are located in the Langbroekerwetering are: agriculture, nature and urban settings. The district also covers different soil types: peat area, clay and sand. So for the water level management in this region these land use functions and soil characteristics have to be incorporated.

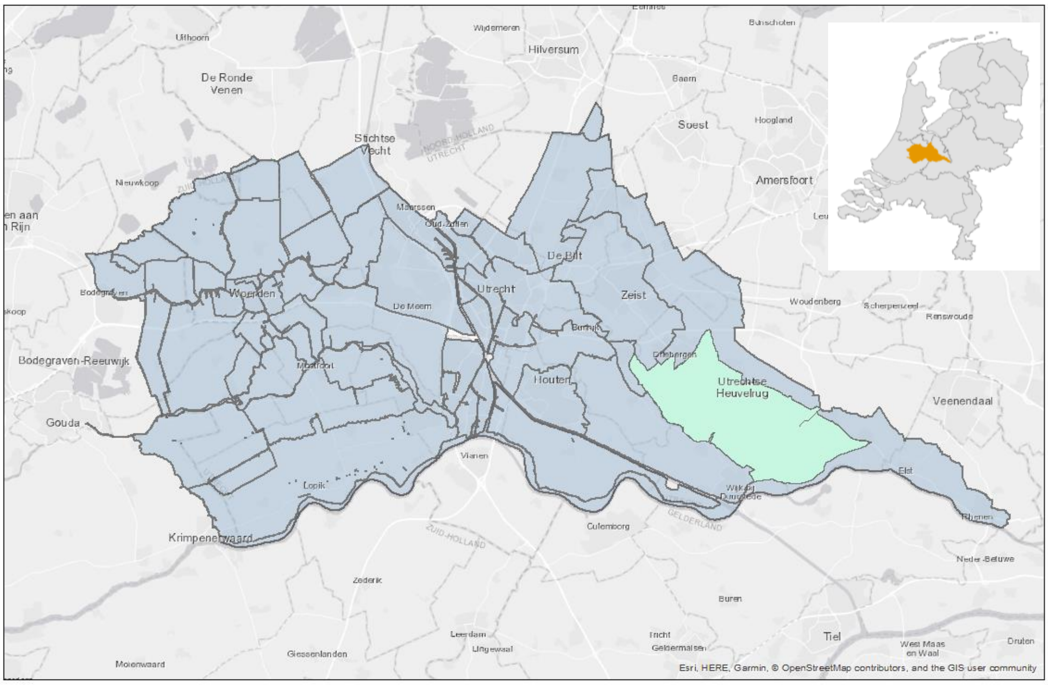

Figure 4.1. The water level management areas of HDSR with the Langbroekerwetering in green

Agriculture

As presented in figure 4.2, the following crops are produced in the Langbroekerwetering: grass, maize, potatoes and cereals. The most common agricultural land use in the Langbroekerwetering is grassland which is mostly used for dairy farming. In general agricultural land use prefers a lower groundwater level compared to nature land uses.

When looking at the different types of water level management, a summer and winter water level is preferred for most agricultural functions. For farmland this means that in summer a higher water level is preferred in order to be more robust against drought. In winter a lower water level is preferred for farmers so that they can enter their parcels earlier in spring (HDSR, 2011).

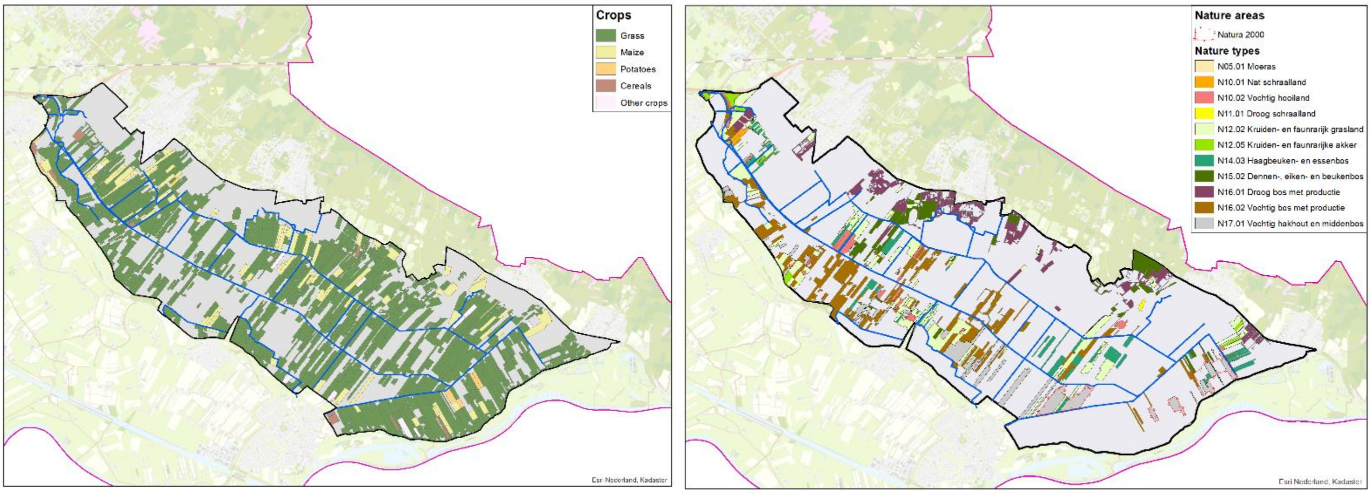

Figure 4.2 Agricultural (left) and nature (right) land use maps of the Langbroekerwetering

Nature

Figure 4.2 also shows the areas that have a nature function in the Langbroekerwetering. In general, it is common that a higher water level is preferred for nature areas as compared to agriculture. The province of Utrecht creates an annual maintenance plan for nature areas. In this plan nature areas are categorized in nature targets (N00.01 to N17.06). The areas that are presented in Figure 4.2, show the nature areas in this categorization. Due to the presence of good quality seepage water there is quite some nature vegetation present. The most common vegetation types that are present are forest complexes, chopping wood, (wet) grasslands and willows (grienden). Appendix II gives a short description of the different nature management types that are present in the study area and their water management requirements.

As explained in Appendix I.a, for nature areas there are different types of water level management that are possible. To benefit nature, the most optimal way of water level management is no management which is referred to as a natural water level. However, this type of water level management is currently not followed within Langbroekerwetering. the Langbroekerwetering. In order to simulate a natural water level a flexible water level can be introduced or a lower summer and higher winter level can be used (HDSR, 2011).

The optimal range for different types of nature areas is shown in figure 4.3, where the x axis represents the GVG water levels, on which the goal attainment of each nature type is plotted. Green is the optimum range (100% goal attainment) and white to blue is the range from 0 to 100%. It can be concluded that Dry Forest with timber production, Herbaceous and fauna-rich field, Pine, oak and beech forest, Dry forest with timber production and hornbeam and ash forest are the nature types that profit most from dryer conditions. Wet forest with timber production, Wet coppicing wood and Marshes profit most from wet conditions.

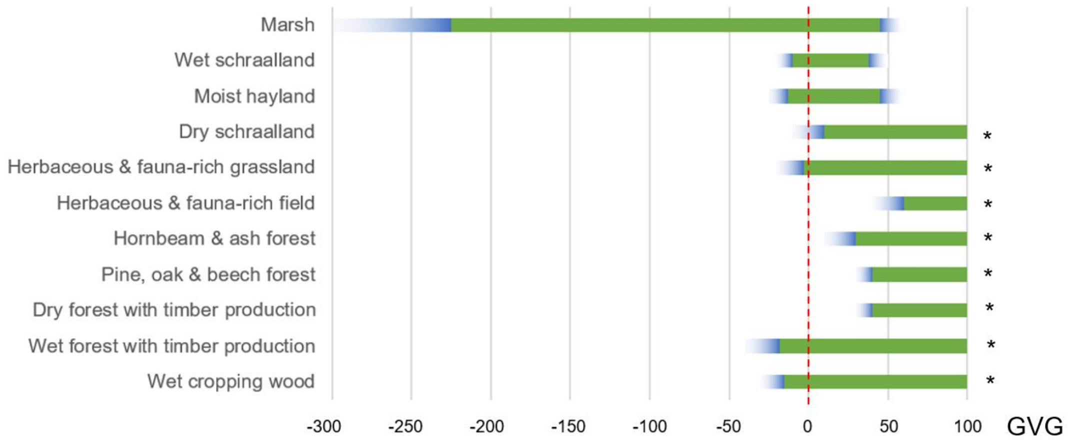

Figure 4.3 Goal attainment of different nature management types that are present in the Langbroekerwetering. A green bar refers to a goal attainment of 100% and blue means declining goal attainment.
** Are nature target types for which no deeper GVG limits are specified*

4.2 Soil composition and Geohydrology

Figure 4.4 shows the soil map of the Langbroekerwetering. On the northeast side of the study area, on the Utrechtse Heuvelrug the soil consists of mostly coarse sand. This area is higher in elevation and can reach up to +12 m. In the lower area at the west side of the study area there are clay soils. Due to the difference in elevation the lower areas have a more dense clay which becomes less dense moving towards the Heuvelrug. The clay was deposited here as a result of river flooding. Moving towards the Heuvelrug we find more sands that become increasingly coarse (HDSR, 2018).

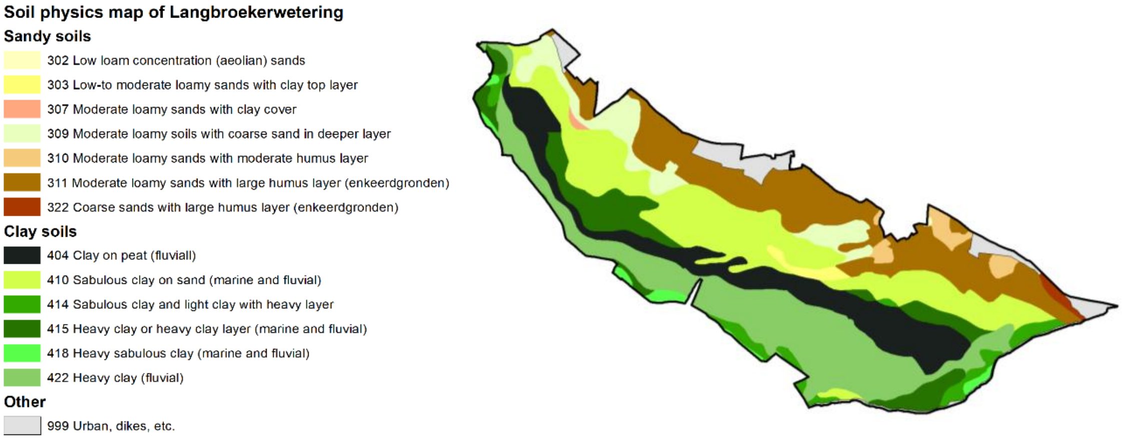

Figure 4.4. Soil physics (BOFEK) map of the Langbroekerwetering

Due to the difference in elevation in the Langbroekerwetering and the combination of different soils there are unique groundwater conditions. In the higher elevated sand area precipitation can easily infiltrate move downhill. At the boundary of the hill and the lower lying land this water comes up as seepage water (See figure 4.6). Some of the water moves through deeper soils and comes up further to the west. The quality of the seepage water is high and benefits some of the nature areas present in the study area. There is also seepage water coming from the Lek river.

The Langbroekerwetering is mainly drained by two channels: The Langbroekerwetering and the Gooyewetering. In the areas with larger seepage intensity and clay soils that have a low permeability the parcels can have trouble draining. Therefore, some parcels are modified by making them bulged at the top and digging extra ridges (HDSR, 2008). Figure 4.5 shows how the seepage intensity is spatially distributed in the study area and where there is infiltration present.

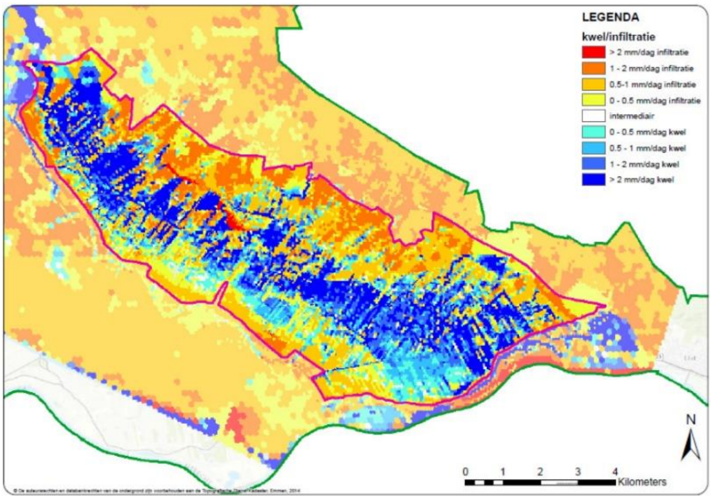

Figure 4.5 Map of seepage fluxes or infiltration fluxes in the Langbroekerwetering.

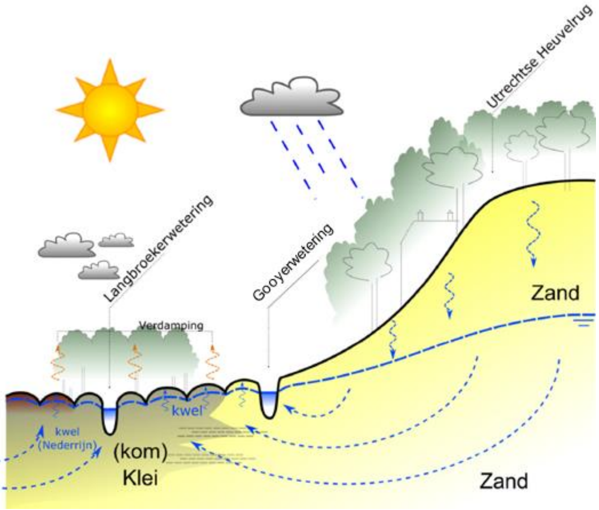

Figure 4.6 Schematic representation of different sources of seepage water in the Langbroekerwetering. Taken from HDSR (2018)

5. Methodology

5.1 General research approach

This study consisted of two parts which are a background study and a case study. The background study mainly consisted of an in-depth review of the Watervision model in which the different processes and concepts that are part of Watervision were studied. This was an important part of this research because it is crucial to have a good understanding of a model in order to give recommendations about the usefulness. The second part of the background study consisted of reviewing the details of groundwater governance. This was done in order to find out in which steps of the water level management process Watervision can be used. Lastly, the details of the study area were also reviewed in order to be able to test Watervision to the area.
In addition to the literature review also an interview was done with one of the developers of WVN, Flip Witte, and a meeting with developers and users of WVN was attended to gather more information about both models.

The aim of the case study was to test Watervision in terms of plausibility and to gain experience with the tool. This was mainly done by running the model together with a GIS analysis of the different outputs. In order to study the plausibility Watervision was also compared to original Waternood. This was done by comparing outputs but also by comparing it in terms of practical use. Additionally, a sensitivity analysis was also performed in order to study the robustness of the tool and to gain a better understanding of the model.

By relating the outcomes of the case study to the information found in the background study it was possible to conclude on the usefulness of Watervision for regional groundwater governance.

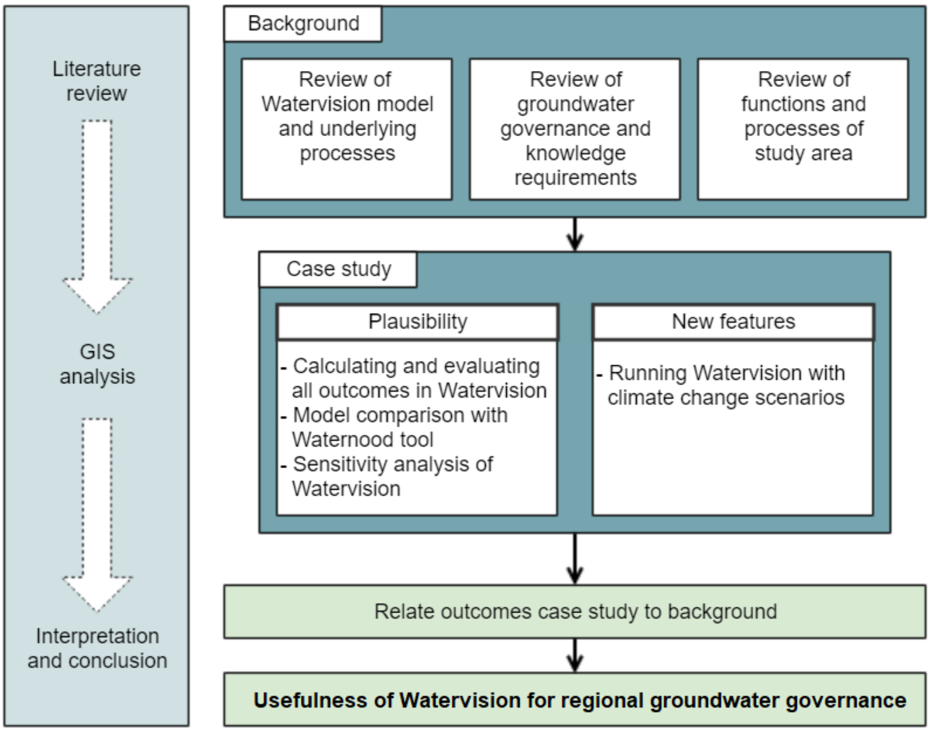

Figure 5.1 Schematization of the different steps that were taken in order to answer the main research question

5.2 Methods of data collection

The data and information used in this study can be roughly divided into two categories; 1) qualitative information which was used to provide insight into the background of the different models, the study area and the way that water level decision making works, and 2) quantitative data which was used as an input for the Watervision and Waternood tools and different analyses that have been performed.

Qualitative data collection

Different types of qualitative data were used in this study. Knowledge from scientific literature was used in order to provide insight in the complexity of natural resource management, Environmental Decision Support Systems (EDSS) and the field of land evaluation. Furthermore, literature was used to find a method to evaluate the value of models in policy making.
Additionally, knowledge on the development and background of Watervision was collected, both in scientific articles and other documents. These include the user manuals from: *Werkgroep Waterwijzer Landbouw* and *Werkgrope Waterwijzer Natuur.* Different scientific articles, such as those from Bartholomeus and Hack-ten-Broeke present how knowledge was developed and built up to create the Watervision tool.
In order to compare Watervision to previous models, documents on the background of the other models and look-up tables were collected: Waternood, HELP and Hydrological constraints nature. Most of these documents were published by STOWA.
Lastly, document on regional groundwater governance were collected. These include documents from the regional water authority HDSR such as: Knelpuntenrapport Langbroekerwetering 2018, Watergebiedsplan Langbroekerwetering 2008, Bedrijvenproef Langbroekerwetering 2018 and Beleidsnota peilbeheer 2011. Which provide insight in the process of regional groundwater governance and specific information about the study area.

Another form of qualitative data was gathered by interviews and attending a meeting (*gebruikersdag WWL*) for users of Watervision. This meeting provided more insight in the experience of other users. Interviews with developer Flip Witte and experts at HDSR could be used both for background information and interpretation and validation of results.

Quantitative data

The following quantitative data sets were used in this research. Most of them were collected from HDSR.

Table 3 Overview of quantitative data

Name	Description	Specifics	Source
1:50.000 Soil map	1:50.000 Soil map of the Netherlands	Vector data	WUR
BOFEK2012 Soil map	Soil physics unit map of the Netherlands	Vector data	WUR
LGN6 crops	Land use map of the Netherlands	Vector data	WUR
Index natuur en landschap	Map with nature management types from 2017	Vector data	HDSR (originally from province of Utrecht
UNATs	Nature target types from the Province of Utrecht from 2001	Vector data	HDSR (originally from province of Utrecht
GHG*	Average highest groundwater level (Average of the three highest groundwater levels over one hydrological year, again averaged over 8 consecutive hydrological years)	Unit: cm-mv 25 m raster	HDSR
GLG*	Average lowest groundwater level (Average of the three lowest groundwater levels over one	Unit: cm-mv 25 m raster	HDSR

	hydrological year, again averaged over 8 consecutive hydrological years)		
GVG*	Average water level in spring (Average of the groundwater levels on March 14th, March 28th and April 14th for one year, again averaged over 8 years)	Unit: cm-mv 25 m raster	HDSR
GG*	Average groundwater level	Unit: cm-mv 25 m raster	HDSR
Seepage*	Seepage water	Unit: mm/day 100m raster	HDSR

* Groundwater and seepage data is generated by the hydrological model cluster of HYDROMEDAH.

5.3 Data analysis

As mentioned in the beginning of this chapter this research was carried out by performing a background study using mostly qualitative data and a case study to test the plausibility and potential of Watervision. The case study consists of three parts which can be divided over the different sub questions of this research:

Analysis of all Watervision output

The first part consisted of running both WVA and WVN and analysing all the possible outputs that were created, using input data of the current climate (average of 1980 to 2010). In order to run both models, the spatial data was first prepared by making sure all data sets were in the correct data format which are raster files saved as .ascii. This was done using several spatial analyst tools in ArcMap like: vector to raster, resample and raster to ascii. After running Watervision the outputs were visualized using again ArcMap. The amount of outputs is different per sub model: 8 for WVA and 19 for WVN (see Table 1 and 2).

Comparison with Waternood

The second part of the case study consists of comparing the outputs of Watervision to the outputs of the original Waternood. In order to do this, input files for Waternood had to be prepared as well. The input data for Waternood needed to be in so called vector rasters, in which every cell is a shape.

In the case of agriculture, the same input could be used in original Waternood as used for the first part of the analysis, which is LGN6 data. However, for nature it was not possible to run original Waternood with the nature management types (from Index Natuur and Landschap) which are from 2017. Therefore, the old nature targets (UNATs) were used in order to make this comparison. This meant that Watervision nature also needed to be ran with the UNATs in order to make a better comparison.

Sensitivity analysis

In order to study the sensitivity of WVN the following sensitivity analysis was performed. The aim of a sensitivity analysis was to study how much different outputs will change as a result of a small change in the input variables. This way you can get a better grip on the operationalization of a model. In this study it was decided to analyze the sensitivity of Watervision by creating an artificial landscape in which a large amount of input combinations is created. For the following variables a raster landscape was created: soil type, crop type, GHG and GLG. Due to the large amount of soil types it was chosen to pick the most common ones from every main soil groups (sand, clay, peat, loam, organic) together with the most important soils in the study area of the Langbroekerwetering, which resulted in a total of 12 soils. For crops it was decided to choose the 4 crops that are present in the Langbroekerwetering: grass, maize, potatoes and cereals. For the GHG and GLG it was decided to use groundwater levels between -50 cm to 300 cm under ground level with steps of 10 cm.

With the 12 soils, 4 crops and different combinations of GHG and GLG, 4 different ascii files were created using Microsoft Excel as presented in Figure 5.2. Subsequently, they were used as inputs to run WVA.

The outputs from WVN were analyzed using R Studio for the following outputs: direct damage, indirect damage, drought stress and oxygen stress. For every output category 48 matrixes were created, with one matrix representing a combination of 1 crop with 1 soil type and all the useful groundwater combinations (from 0 to 200 cm). For every matrix the sensitivity was calculated for both the GHG and GLG by subsequently calculating the absolute difference in output for every step of 10 cm GHG or GLG while keeping the other constant. For the crop types, the sensitivity was determined by comparing the sensitivity of every matrix with the same soil type but with different crop types. And for the sensitivity of soil type this was done the other way around.

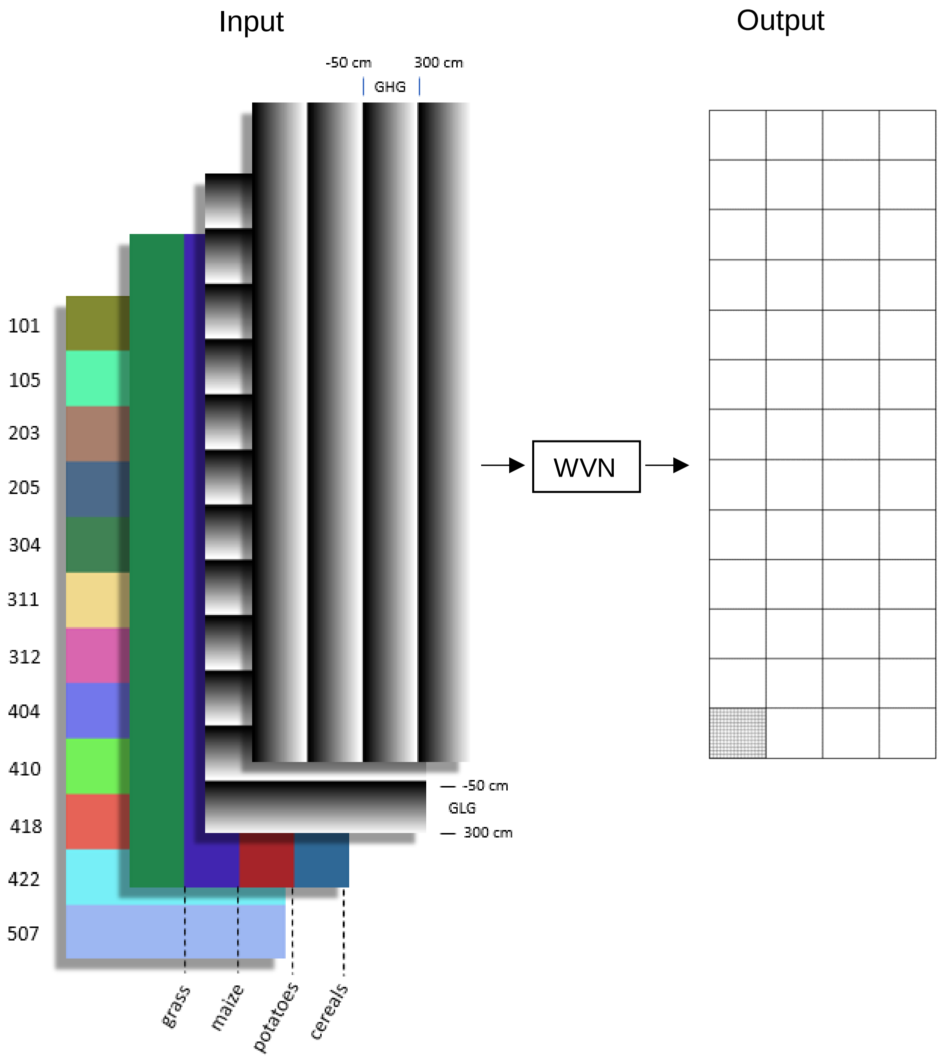

Figure 5.2 Schematic overview of methodology of the sensitivity analysis

The outputs that were produced by Watervision was not the end goal of this research. The aim was also to use these outputs to draw conclusions on a higher level, about the usefulness of Watervision in the process of regional groundwater management. A higher level comparison was provided amongst others by using zonal statistics in ArcMap and excel. Averages of damage and goal attainment were calculated for certain areas in order to compare them. Also spatial variation of the outputs, and zooming in on specific parcels and pixels was used to evaluate differences between the models.

6. Results

6.1 Results Watervision Agriculture

Using Watervision Agriculture, the agricultural productivity is presented in relation to the current hydrological conditions and climate or a climate scenario. After running WVA, the model writes the output files in a specified output folder as .asc files (when using raster data). These .asc files have been visualized and analysed in ArcMap and the results are presented in this chapter.

6.1.1 Running Watervision Agriculture for current conditions

Running WVA for the current situation results in 8 outputs. On average the model is finished running after only 2-3 minutes.

Figure 6.1: Total damage to agricultural crop in Langbroekerwetering, calculated with WVA

Damage outputs

Figure 6.1 shows a visualized map of the total damage to agricultural crops in the Langbroekerwetering under current conditions. This is a very relevant output for water managers because total damage sums up all the damage in the area of interest. The total damage to agricultural crops over the whole study varies between 15% and 50% and is on average 23.4%.

Total damage is a combination of indirect damage and direct damage. Direct damage is the combination of damage due to oxygen stress, salt stress and drought stress. In the case of salt stress, the user of WVA has to add the salt concentration. In the Langbroekerwetering salt is not an issue so this was not provided as an input. Direct damage is therefore in this case a combination of oxygen and drought stress. Indirect damage is caused when hydrological conditions hold back farmers in their daily activities, reducing profits, like limited carrying capacity of the soil.

Figure 6.2 shows the spatial variation in direct and indirect damage, and the oxygen and drought damage. The average direct damage equals 22.2% in the study area, which includes the average wet damage of 8.2% and the average damage due to drought of 14%. For most of the parcels there is no indirect damage calculated and takes up the remaining 1.2%. In the centre of the study area there are some parcels that have indirect damage which are all around 10 to 15%. The model does not specify what sort of indirect effects are calculated. Most of the damage is due to direct influence of hydrological conditions on crop growth. Both oxygen stress and drought stress play an important role, but they are concentrated in different areas. Oxygen stress is concentrated in the centre and drought stress in the south-west of the study area.

When looking at the different maps in figure 6.2, one thing that stands out is that the spatial variation in damage shows similarities with the spatial variation of soil types (see soil map Figure 4.4). When looking at the damage per soil type they either have a higher damage due to drought stress or a higher damage due to oxygen stress, not both. Drought damage mainly occurs in heavy clay soils (404, 414, 415 and 422), while damage due to oxygen stress mainly occurs in sandy clay soils (303, 410, 418).
It is of course not surprising that damages are related to the soil type. It is still the question whether this is due to soil composition, or other factors like seepage. Seepage is probably also an explanatory factor, as the spatial variation in damage shows similarities with the variation seepage and higher groundwater levels.

An expert of the area states that in the case of wet damage, the results show outputs that match the situation as she knows it in the area. For agriculture there are some cases known of farmers that have expressed limitations to their work due to too wet conditions in the centre of the study area. The drought stress however, differs from what she usually experiences at this magnitude. This raises questions, which will be further discussed in the discussion, Chapter 7.

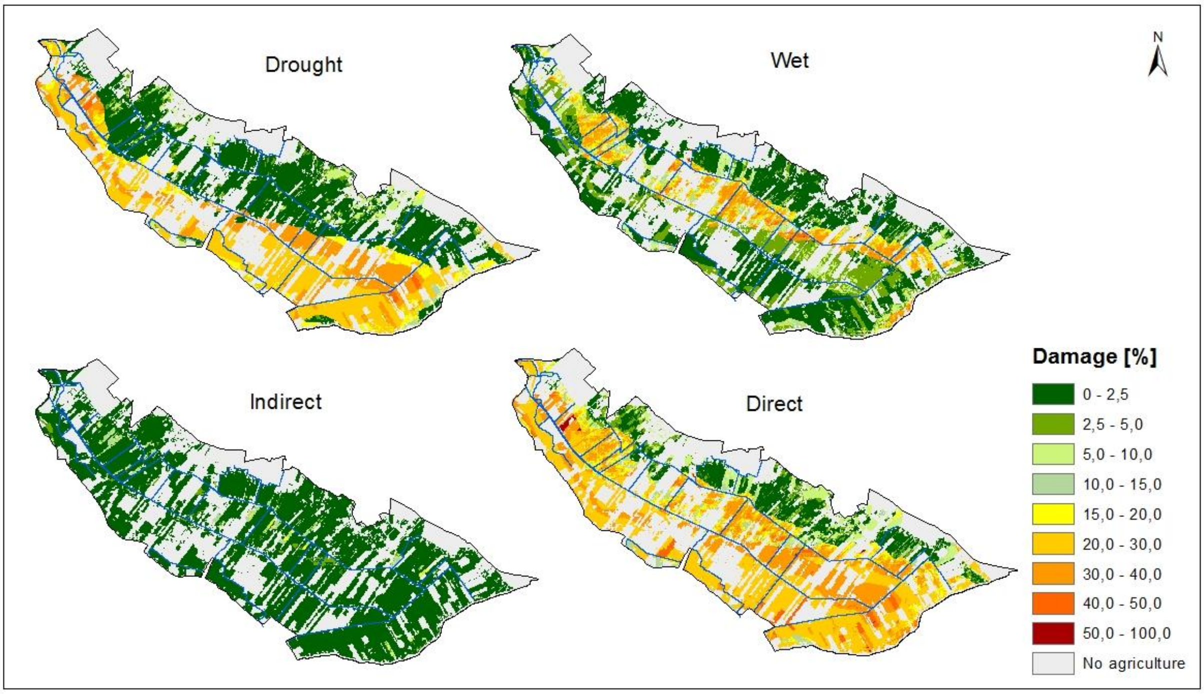

Figure 6.2: Drought, wet, indirect and direct damage to agricultural crops in Langbroekerwetering, calculated with WVA.

In the study area, there is also a variation between crops in terms of damage. The total damage for grass is on average 23%, for maize 25%, for cereals 31% and for potatoes 36% so some crops experience more damage on average than others. This consists for the largest part of drought damage, especially for potatoes (33%), followed by oxygen stress, and then indirect damage. What is remarkable is that the indirect damage for maize is 4.2%, while the other crops are lower than 1%. Because the crops are spread over the area, this can not only be attributed to the location at which they are produced.

The different output maps mentioned up until now can be used by water managers to gain insight in the severity, type of damage and where the damage is located. These insights can help to evaluate the most important cause of the damage. Also, when combining these maps with the water level areas an overview of the damage per area can be made, and the optimal water level for this area can be chosen. The maps also provide insight in how damage corresponds with soil types and types of crops.

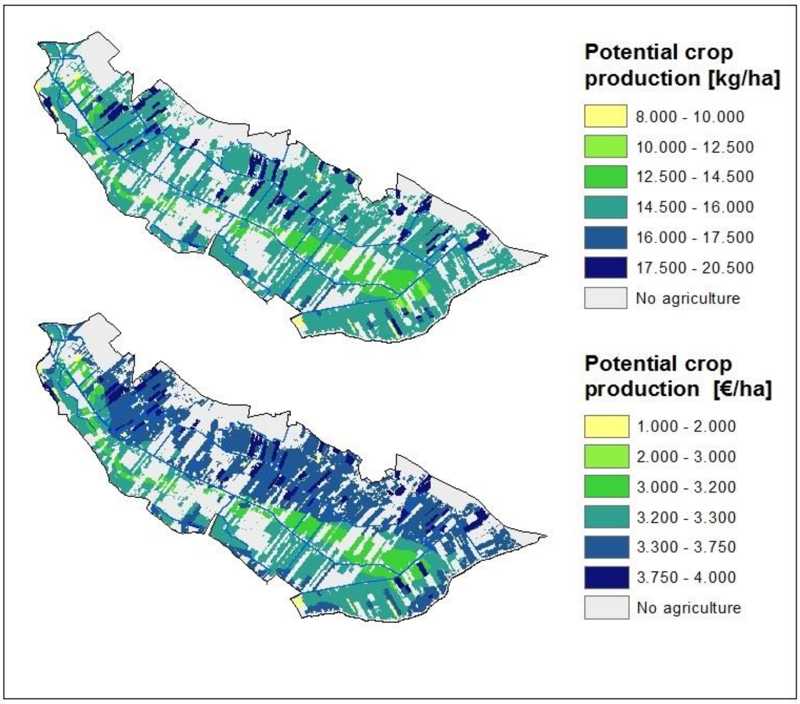

Figure 6.3 Potential crop production in Langbroekerwetering in kg/ha and €/ha, calculated with WVA

Potential production outputs

Figure 6.3 shows the outputs in potential production. The potential production provides a translation to the economic effect related to the production damage. For ruminant breeding crops (grass and maize silage), the potential production is calculated by using the nutritional value (kVEM/ha or kDVE/ha) and subsequently expressing it in kg dry matter/ ha (kg_{ds}/ha). Arable crops are also expressed in kg_{ds}/ha and vegetables are expressed in kg/ha or pieces. To express this in monetary values the potential production is multiplied by the crop price.

What we see in the study area is that the outputs are in different classes for different crops. Maize has the highest potential production, grass has a lower potential production and potatoes and cereals the lowest. Potatoes do however have a higher potential production when measured in euros per hectare compared with kilogram per hectare. It is of course not surprising that different crops have different amounts of yield, there are however differences in production in different locations for the same crop. The production is higher on the north-east side of the study area and lower in the south-west side of the area which matches the locations with high and low damage.

What is surprising is that some of the parcels (mostly maize) that are some of the highest in total damage, appear highest in potential production. This means that maize is more vulnerable to damage but does also generate more revenue per ha.

The potential production outputs can be used to evaluate which crop would be most profitable to produce under certain circumstances. Also, when comparing different scenarios or water levels the effect on potential production for a crop can be determined. This way the profits or damages to specific farmers can be taken into account. Lastly, outputs in € can also be used as part of a cost-benefit analysis.

6.1.2 Comparing Watervision Agriculture to original Waternood

As mentioned earlier, in the case of Watervision Agriculture, it is complicated to do a one on one comparison with WVA to Waternood. However, since HDSR has a lot of experience working with Waternood in the past it is useful for them to see how the new WVA compares to Waternood. Not only in outputs but also in the level of (spatial) quality, practicality and plausibility. The following paragraphs will explain the findings that are the result of running Waternood and WVA with the same inputs for crops and water levels.

Inputs

One thing to pay attention to as a user is that WVA uses different classification for crops than Waternood. HDSR is used to using LGN6 crop data for their analyses with Waternood. So, in order to make the LGN6 data fit WVA the user must translate these classes using GIS, which is not that much work. However, what does make it more complicated is the fact that WVA distinguishes five types of grasses (grass mowing, grass grazing, grass grazing and mowing, grass grazing and intensive mowing and lastly, grass grazing and extensive mowing[1]). This means that if a person is interested in using these different types of grass crops, the user must do additional research or find additional data on the types of grassland in the area of interest. The same applies to potatoes which have three different types in Watervision (consumption, starch and seed potatoes) and cereals for which WVA distinguishes between (winter)wheat and (summer)barley.

Another input difference is the soil data. For the soil map the user just simply uses the BOFEK soil map that comes with the WVA model files instead of the 1:50.000 soil map which is commonly used by HDSR. This means that the user had to be familiar with both soil maps.

Lastly, both models use the ‘current’ climate data. However, for Waternood this means that data from before 2005 is used while Watervision uses more recent data. For Watervision Agriculture it is also possible to calculate damage for a specific year, or a specific set of years while for Waternood it is only possible to use the average over a period of 30 years.

Outputs

What is quickly noticed when using WVA, is that it does not calculate goal attainment but only expresses the outputs in damage as a percentage. Goal attainment is a criterion that is commonly used by HDSR and a concept which they are used to communicate with. It is however easy to switch from goal attainment to using (total) damage or to determine goal attainment because they are the inverse. So, a goal attainment of 90% means that there is a 10% total damage to the vegetation.

Also, Waternood does not provide the distinction between direct and indirect damage in outputs. And Waternood does not calculate the damage in production and in monetary value. Furthermore, both models have similar outputs in terms of the types of damages they distinguish.

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[1] In this study it was decided to use grass mowing

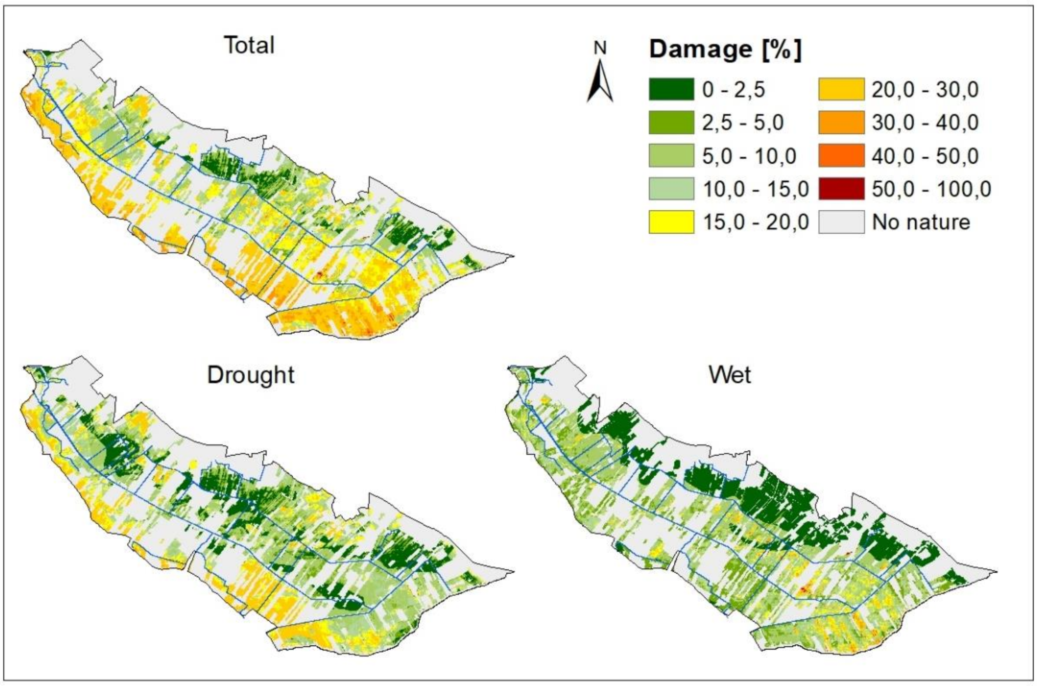


Figure 6.4: Drought, wet and total damage to agricultural crops in the Langbroekerwetering, calculated with the Waternood tool.

When comparing WVA and Waternood outputs one of the first things that stands out is that the total damage is higher all over the area for WVA. This can be seen in the overall average total damage too, in Waternood this is 17.3% while in WVA this is 23.4%, for further details see Table 4. It can be seen that damage due to both drought and wetness is higher for the WVA outputs in some areas. Damage due to wetness is also experienced by farmers in this area (C. Wijnen. pers. communication, 14-05-2019). Damage due to drought turned out higher in the outputs than is recognized by experts in the area. Therefore, this raises the question as to whether this is really experienced by farmers, or whether the model is overestimating drought in some areas.

From a meeting with the developers of WVA it was found that WVA does unfortunately overestimate the drought and oxygen stress in some cases. From feedback from other first-time users, it was found that drought stress can be overestimated by the model for some of the 72 BOFEK soil units: 105, 201, 404, 405, 415, 422, and 503. Some of these units are also present in the case study area, namely: 404, 415 and 422 which are all clay soils. For oxygen stress it was found that for clay soils the model also overestimates the outputs in some cases. The developers of WVA explain that this is due to the fact that WVA does not take into account macro pores in the soil, which are larger holes and cracks that can form in the soil which allow for better infiltration of water. Currently the developers of WVA are working on incorporating macro pores in a new update of the model (Stowa, 2019).

Table 4: comparison mean outputs of WVA and Waternood

	WVA	**Waternood**
Total damage	23.4 %	17.3 %
Drought damage	14.0 %	10.8 %
Wet damage	8.2 %	7.3 %

6.2 Results Watervision Nature

As explained in chapter 3.3.2, WVA offers three options: (1) assessing with Waternood, (2) assessing with Waternood+ and (3) predicting with Probe. All three options can be used with current climate conditions and current groundwater conditions. A difference is that the Probe model does not use the current nature vegetations. Probe uses the other inputs to determine for which ecotope groups, conditions are most favourable, and therefore if they have a high occurrence probability at a specific location. Due to this difference and the fact that Waternood and Waternood+ have similar purposes, this chapter will start by analysing the outputs made with Waternood and Waternood+ and how these two models compare in terms of usefulness. Chapter 6.2.3 will discuss the results of Probe.

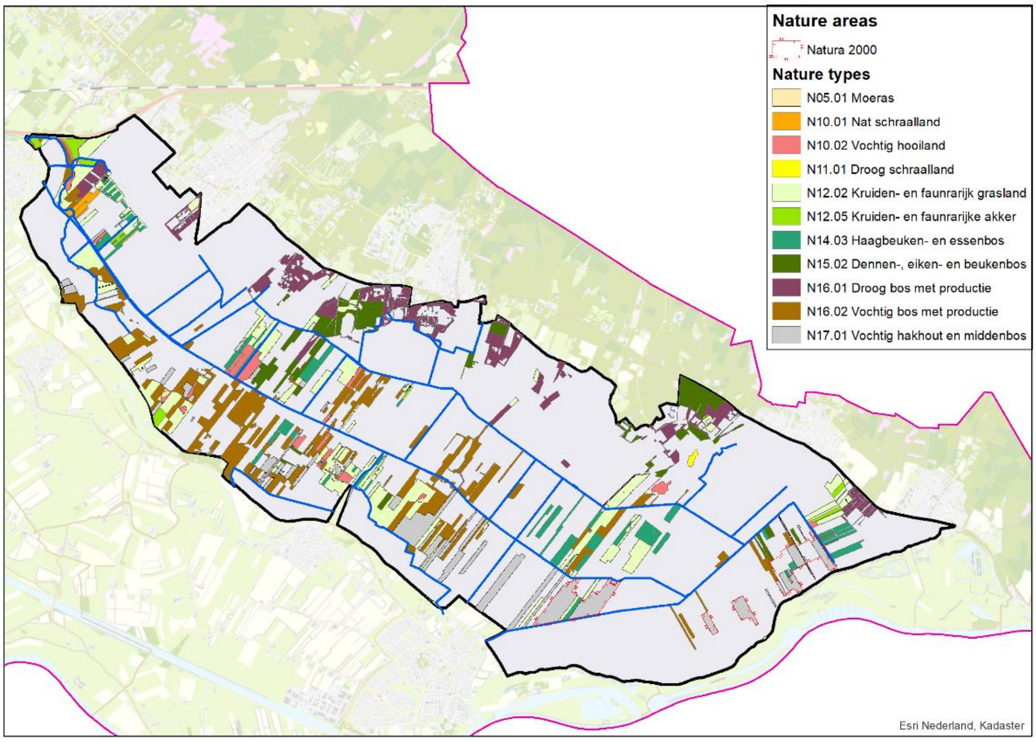


Figure 6.5 Nature areas in the Langbroekerwetering (case study area)

6.2.1 Running Watervision Nature for current conditions

As explained in Table 2, Running Waternood will result in 14 different outputs and running Waternood+ will results in 7 different outputs. Which means that for this part of the results 21 different maps will be analysed. Due to this high number of maps the full overview is presented in Appendix VII and this section will focus on the most important outputs and findings in terms of usefulness for regional groundwater governance.

6.2.1.a WVN Waternood

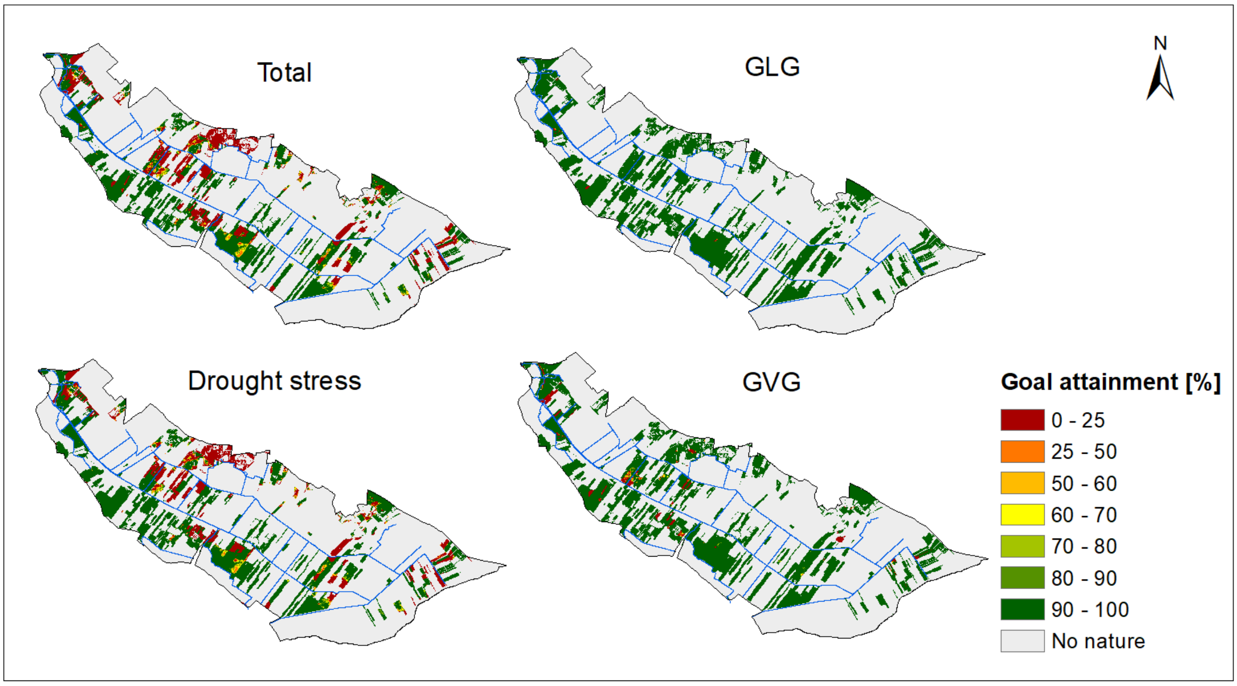


Figure 6.6: Goal attainment of GVG, GLG, drought stress and total goal attainment of nature areas, modelled with WVN.

Goal attainment outputs

Figure 6.6 shows an overview of four different goal attainment maps in the Langbroekerwetering for current conditions. As explained in section 2.1, goal attainment is determined by plotting the groundwater levels on the pre-defined trapezium graphs which have specific boundaries for GVG, GLG and drought stress (DS in days) per vegetation type or group. In the case of seepage, goal attainment is determined in a different way. For seepage, the user has to indicate which of the input vegetation types is seepage dependent, and what minimum flux is needed. For this part of the research seepage was not included which means that the goal attainment seepage is automatically 100% for all parcels.

The first thing that stands out when looking at Figure 6.6, is that with WVN a lot of the pixels either have 100% or 0% goal attainment, while not that many pixels have a medium score. This is due to two reasons. When zooming in on a pixel scale, we see that total goal attainment is a multiplication of the goal attainment for: GLG, GVG, drought stress and seepage. Therefore, if one of the goal attainments is 0%, the total goal attainment will automatically become 0%. Another reason for the low number of medium scores is due to the fact that the trapezium graphs that are used often have steep slopes between A1 and B1 or A2 and A2 (Figure 2.2) which means that there are not that many water levels that fall within those ranges.

On average the total goal attainment for nature areas is 70.8%. This is mostly related to goal attainment for drought stress, which is on average 74.5%. The GVG and GLG on average have lower limiting impact on goal attainment, with 95.8% and 99.8% goal attainment respectively. However, for some specific nature types and locations their impact is bigger. For nature type N05.01 - marshes - the GLG is a limiting factor and makes that these areas have a low goal attainment.

<u>Maximum attainable goal attainment</u>

The regional water authority, HDSR, often starts by looking if the total goal attainment is sufficient, and only looks further into other outputs when the total goal attainment is too low in a certain sub-water level area (A. de Boer, pers. communication, 2019). However, for this new version of Waternood, WVN provides two additional versions of goal attainment, which may be useful to evaluate the region in more detail. Those measures are: *maximum attainable goal attainment* -and *scaled maximum attainable goal attainment*.

The reason that these outputs are added is because vegetation classification maps often have quite large areas per class, which means that there can be quite some ground level variation within one class or parcel. This would mean that the vegetation in that area can only have a 100% goal attainment if the groundwater levels follow the ground level variation very precisely. This is however not a realistic requisite. Therefore, WVN takes into account the variation of ground level within nature areas by step by step altering the ground level with 1 cm while calculating the goal attainment. The water level which realizes the highest goal attainment of the defined area is the maximum attainable goal attainment. For the scaled max attainable, the current goal attainment is scaled to the max attainable goal attainment (J.P.M. Witte, pers. communication, 27-05-2019; Werkgroep Waterwijzer Natuur, 2018).

In the example parcel, see figure 6.7, we see a nature area for which the total goal attainment ranges from 0 on the north side to 100% on the south side, with a mean of 67%. Max attainable, this parcel can reach 89% and scaled max attainable the parcel is 77%. The scaled figure thus takes into account how much can still be improved.

This data can be useful for water managers because it tells more about how much room there is for improvement. If the scaled max attainable is <100% this means that there is room for improvement to make sure that a whole parcel has a better goal attainment. On the other hand, if the scaled attainment is 100% while in the total goal attainment there are some cells with a low score this means that water level changes will not improve the average goal attainment in the area.

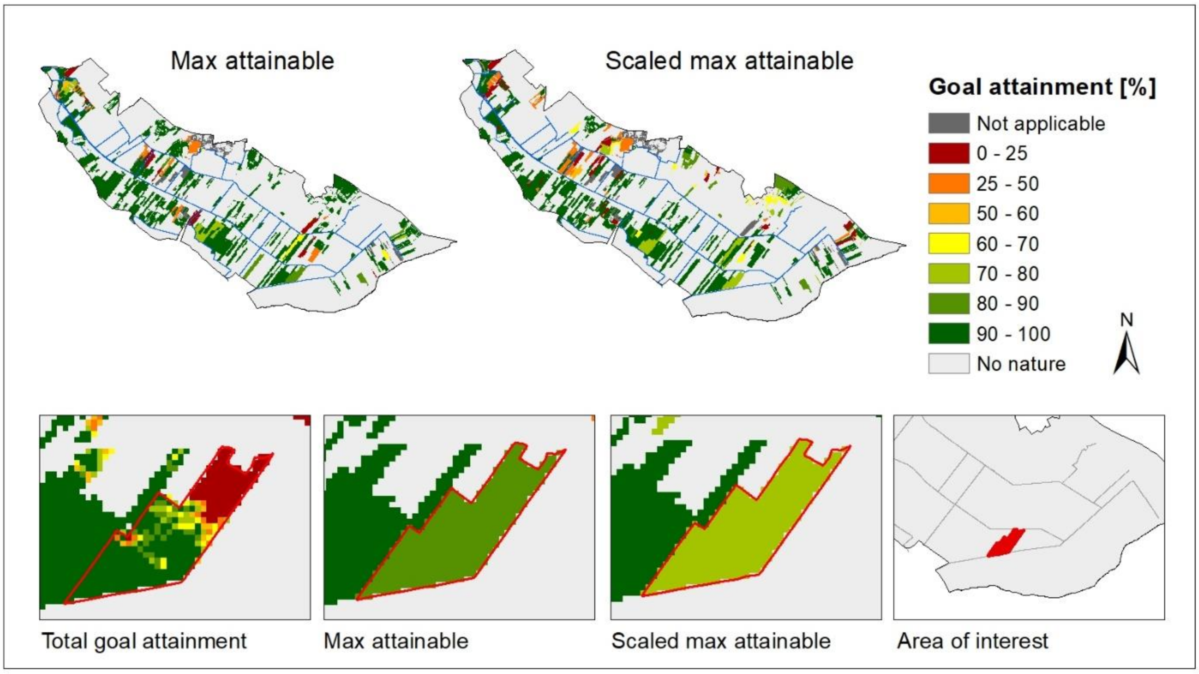


Figure 6.7. Maximum goal attainment and scaled maximum (top), zoomed in on a specific nature area (below).

Gap to optimal outputs

Nature areas can also be evaluated in terms of how much room there is to improve to the optimal situation. This is done by a so called *gap to optimal* measure. The outputs *gap to optimal* for drought stress, GVG, GLG and seepage present the increase or decrease of one of these variables in order to reach a 100% goal attainment. In terms of the trapezium graphs this corresponds to the distance to the b1 or b2 values. Since in this case study the total goal attainment is mainly due to lower attainments in drought stress, this is where the largest gaps to optimal are. Figure 6.8 shows the gap to optimal for drought stress in the Langbroekerwetering. On average the whole area has a drought stress of - 3 days which means that more drought stress is preferred and that the conditions are too wet at those locations. Some have a drought stress gap to optimal of 0, meaning that drought stress is not a limiting factor. The specific parcel has an average of - 4 days drought stress, however again a variation is seen between no drought stress at all up to -15 days.

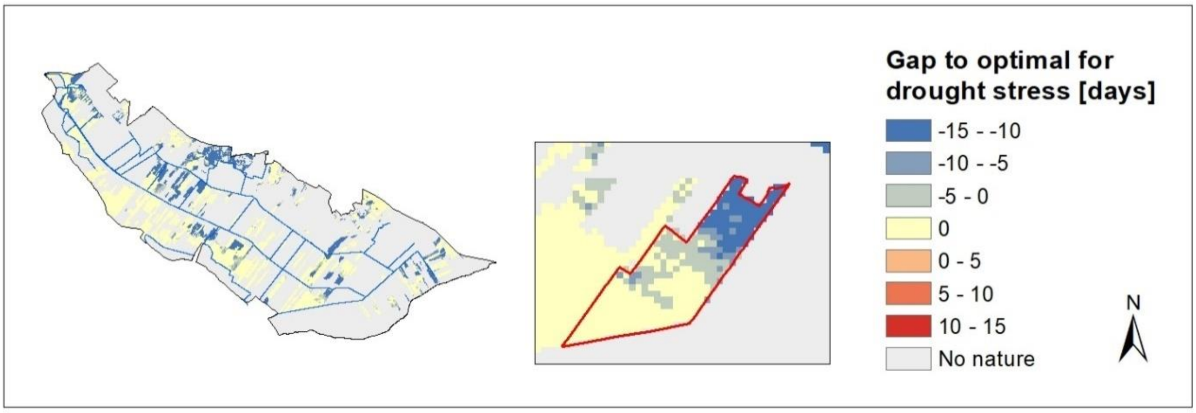


Figure 6.8: Gap to optimal for drought stress in days, calculated with WVN Waternood.

Drought stress is related to the minimum soil water pressure head for which plants can transpire. The fact that drought stress is expressed in days does make it more complicated for water managers to gain insight on what measures will contribute to improving the drought stress.

6.2.1.b WVN Waternood+

For WVN Waternood+, similar output maps are produced as WVN Waternood. However, the water management conditions are tested for different variables, namely: GLG, oxygen stress (RS) and transpiration stress (TS). In original- and WVN Waternood GVG is used as an indicator for oxygen stress. In Waternood+ this indicator is replaced by oxygen stress (RS). Oxygen stress is used because the decrease in root respiration is the first reaction of a plant when there is a deficiency of oxygen in the soil. When this is the case this means that the actual respiration is lower than the optimal respiration, limiting goal attainment. For Waternood+ drought stress (DS) is replaced by transpiration stress (TS). Both RS and TS can be used with the climate model PROBE, so that is why they were included in Waternood+. The outcomes for both factors are determined in the model PROBE, with current climate conditions (Werkgroep Waterwijzer Natuur, 2018). The specific trapezoid graphs for these new variables are not accessible for the user, meaning that it is not possible to find out how specific outputs are produced.

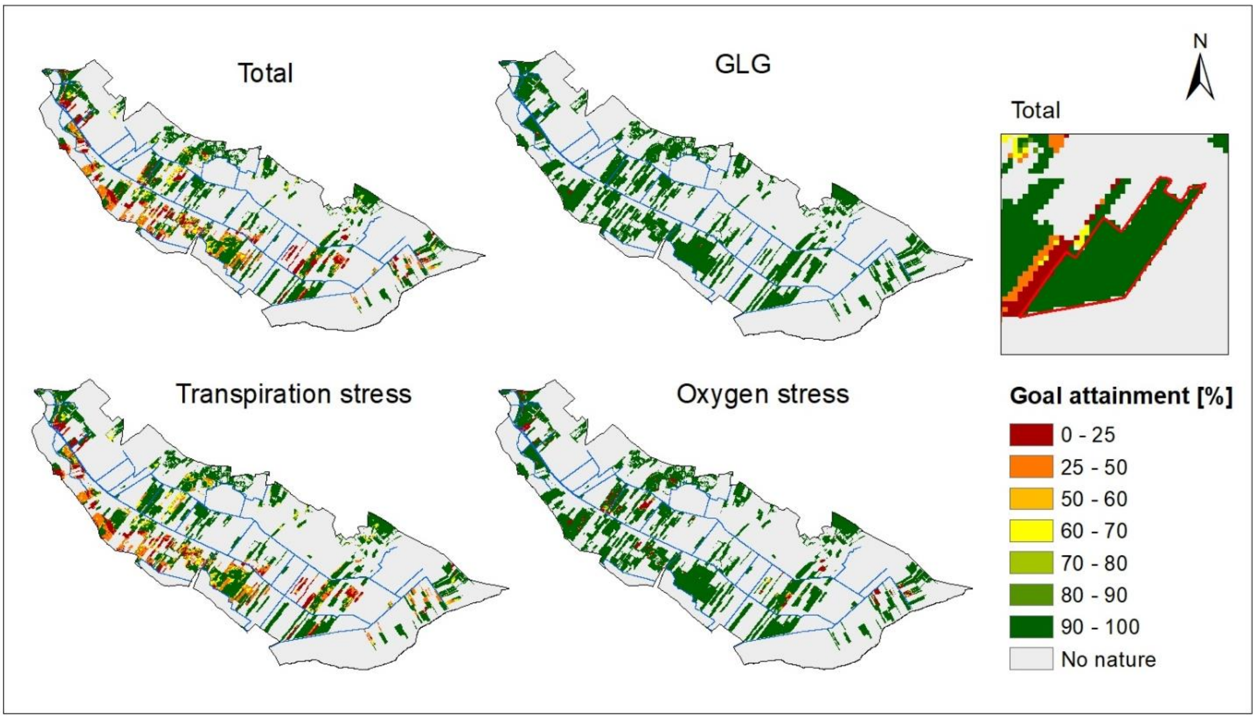


Figure 6.9 Goal attainment of GLG, transpirations stress (TS), oxygen stress (RS) and total goal attainment of nature areas, modelled with WVN Waternood+

After analysing some individual pixels in ArcMap, it is found that Waternood+ uses the same calculation to determine the total goal attainment. Waternood+ works similar in the sense that goal attainment factors are again multiplied to find the total goal attainment.

Figure 6.9, shows the a couple of the goal attainment output maps of Waternood+. It is found that a suboptimal goal attainment is in most cases caused by transpiration stress. The areas that have this low goal attainment are mostly located on clay soils along the west border of the study area (soils 404 and 422). The nature vegetations that score the low goal attainment in this area are mostly the more wet forests (like N16.02).
In a few areas there is also oxygen stress. In the area with seepage there is more oxygen stress. Most of this area is filled with nature types that prefer this. Some areas however, like the dryer forest nature types (N14.03), suffer from oxygen stress and have a lower goal attainment.
What is also noticeable is that the example parcel has a goal attainment of 100%, meaning that all conditions are favourable according to Waternood+.

6.2.1.c Comparing WVN Waternood and WVN Waternood+

When looking at the outcomes for the full study area it is found that different areas have a lower goal attainment in WVN Waternood than in Waternood+. According to the user manual the differences between WVN Waternood and Waternood+ can be expected and are caused by: transformations of trapezoid graphs, differences in soil maps; transpiration stress is based on the BOFEK soil map, drought stress is based on old soil classifications. And lastly, differences in reference periods for the meta relations. Which is 1971-1995 for drought stress and 1981-2010 for transpiration stress.

There are differences in the outcomes for goal attainment. In WVN Waternood there is more oxygen stress in the centre of the study area (see gap to optimal for drought stress) and less drought stress on the west border of the study area. In Waternood+ we see less of the oxygen stress in the centre of the study area and we see more drought stress at the west border of the study area.

6.2.2 Comparing Watervision Nature to original Waternood

To evaluate the added value of Watervision Nature, we are also interested in analysing the differences between WVN and the original version of original Waternood (Version 2005). Ideally, this comparison was done for the current classification of the nature areas. However, all attempts of running Waternood 2005 with the current classification of the nature areas have failed. The reason for this is that the new classification of nature areas is not part of Waternood 2005 and adding the new classification was not possible due to the need for old software. Therefore the most recent classification of the original Waternood was used, for both analyses in Watervision and original Waternood. For the classification that was used, see Appendix II.

Figure 6.10 shows the different outputs. On first glance, the outputs look similar, the variation in goal attainment is spread over the area in the same way. Zooming in on the area of interest we can see that there are some differences; the parcels in the southeast for instance have a lower goal attainment in the original Waternood. The reason for these differences has not been identified.

One of the developers of WVN pointed out that Waternood in WVN should have the same results as the original Waternood (F. Witte, pers. communication, 2019). The results for WVN and Waternood seem quite similar but do not have a 100% match. Original Waternood has a larger area with values between 0 and 100% vs. more values with 100% goal attainment in WVN. Updates in the trapezoid graphs in Watervision cannot explain the difference between the outputs because this was ruled out. Other reasons can be that the inputs files for both models are different, Waternood requires polygons which are turned into a raster grid afterwards by the model, which can slightly move the location of the inputs data. However, what exactly makes up the larger differences is unknown.

In terms of practical use of the tools, WVN is preferred over the original Waternood. The original Waternood does not enable adding new nature types. The software also allows the user less choice and control in what data and tables are used, this way original Waternood less transparent compared to WVN.

From this result, it can be concluded that the outcomes do not differ a lot. However, as new nature types cannot be added to the original Waternood, and WVN has been updated more recently, WVN would be more appropriate to use.

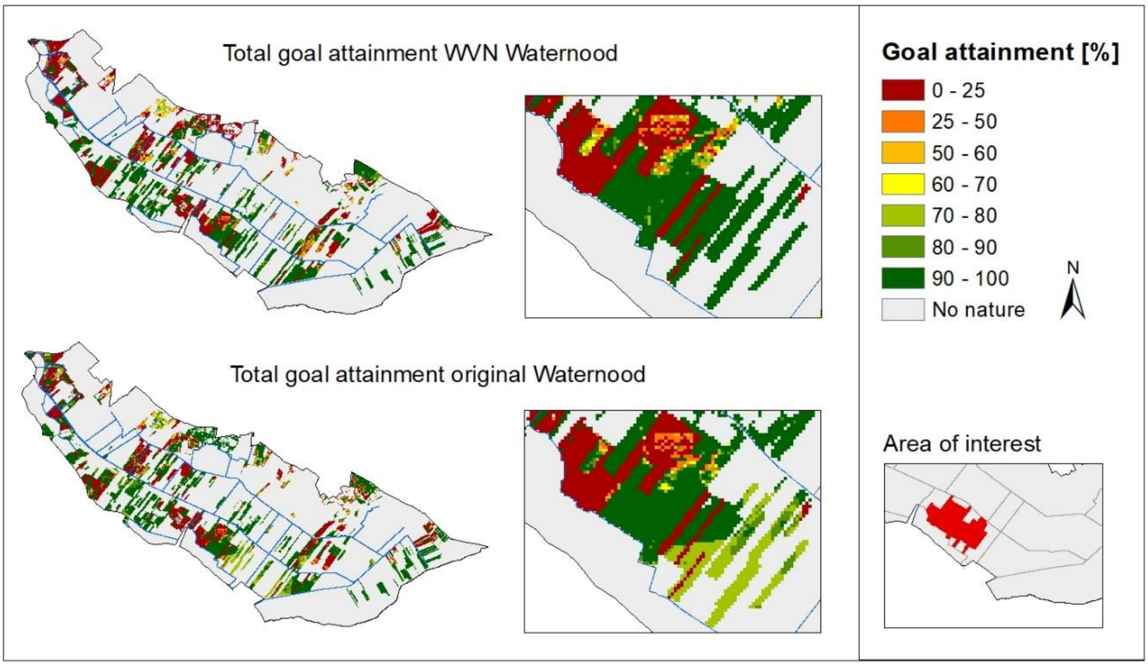


Figure 6.10 - Comparison WVA Waternood & (original) Waternood.

6.2.3 Results PROBE

As discussed earlier PROBE can be used for determining the occurrence probability of vegetation types under given water levels (using current conditions or climate scenarios). The model was first used with data on current climate and hydrological conditions.

This provided the following results. Figure 6.11 shows the maximum occurrence probability over the whole area, and 6.12 shows which specific ecotope groups have a high probability to occur under current conditions. It appears that in most of the area three different ecotope groups are most probable to occur; H61, H48 and K48. Furthermore, for most parcels, the ecotope group with the highest probability has a probability above 80%. This implicates that the current conditions of the whole area are favourable for nature. Reasons for areas with lower percentages may be due to elevation differences in parcels, or due to unfavourable conditions; too wet or too dry in some areas.

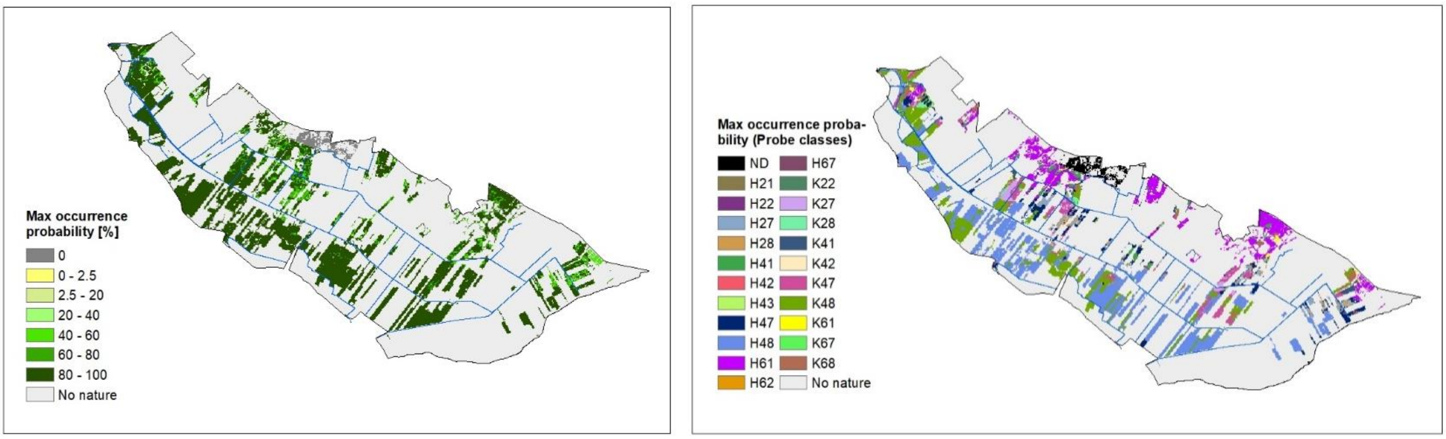


Figure 6.11 & 6.12 – Maximum occurrence probability (in percentage) of different ecotope groups under current conditions, using the model PROBE.

The three ecotope groups that have the highest probability are:

- K48 Pioneer vegetations and grasslands on humid, very nutritious soils (acres, banks, factory sites)
- H48 Forests and scrubs on moist, very nutritious soils (young planted forests on clay soils)
- H61 Forests and scrubs on dry, acidic soil low on nutrients (dry oak-, birch- and beech forests)

The occurrence probability of these specific ecotope types over the area is shown in figure 6.13.

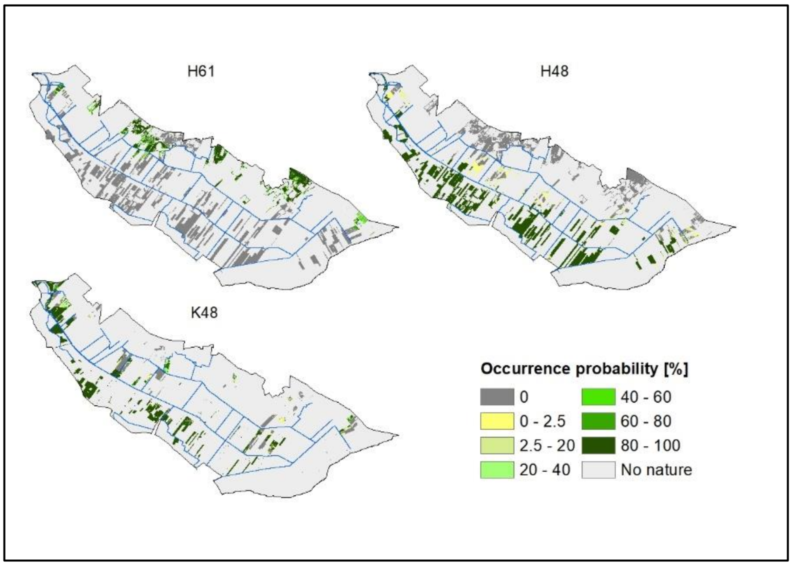


Figure 6.13 – Occurrence probability of the three highest ecotope types.

There may be different reasons why these types of vegetation are probable in the area. They may be in line with the current soil types and hydrological conditions that occurs there. The PROBE outputs provide insight in the type of vegetation that is most suitable when we look at the current conditions.

When we compare this to the earlier shown map (Figure 6.5) of the current nature types, this map looks different, showing a variation of 11 different nature types. However, the nature type classification describes the aim of this area in terms of what type of nature should be maintained there. This does not tell us whether or not specific vegetations grows there.

The results of PROBE can provide added value for managers in the following ways. By further exploring the actual ecotope groups in the area and the ecotope groups that PROBE presents, it could be argued whether the model is an accurate representation of reality, or whether there are reasons why the actual vegetation looks different. One of the outcomes may be that the nature types that are currently maintained are less suitable under current hydrological conditions.

The climate change scenario option of PROBE would be interesting to test in order to see what nature types are most probable to occur under a changed climate. However, for reasons that will be elaborated on in the next section, these functionalities could not be tested in this study.

6.3 Climate scenarios

Both WVA and WVN have the option to predict goal attainment with climate change scenarios up to 2050, and also Probe can be used to predict the occurrence probability of nature types in the future. In terms of practical use these options require the user to select future climate scenarios instead of the current climate.

A limitation lies in the inputs that are required. While the model can be used by providing current hydrological conditions (GxG) as an input, this would not result in an accurate prediction. In one of the interviews (F. Witte, pers. communication, 2019) it came to light that the models do not alter input groundwater levels to the selected climate change scenario. Instead the user is required to develop a model to predict groundwater levels according to climate change scenarios and use this as an input. Because such models and the required data were not yet available, these functionalities could not be tested for the Langbroekerwetering yet.

6.4 Robustness of Watervision

In order to test how robust the outputs of the models are, a sensitivity analysis was performed. As described in the methodology chapter, this was done for WVA by selecting a combination of 12 soil types and 4 crops was tested on variation in GLG and GHG inputs. With regard to WVN, analysing the robustness is not possible in the same way as for WVA due to the fact that WVN is not process-based.

6.4.1 Robustness of Watervision Agriculture

General remarks on WVA operationalization

Running WVA for the 12 soil types, 4 crops and variation of GLG and GHG resulted in 144 matrixes that needed to be analysed. This is divided over 48 matrices of total damage, 48 matrices of wet damage and lastly, 48 matrices of drought damage. An example of one of these matrices is presented in Appendix VII. Before further analysing the data in the matrices, there are already some interesting findings that can be concluded from just browsing through them and looking at them in total. The following things were found:

- Firstly, for combinations with a lower GHG than GLG (and vice versa), the model does not generate plausible results because they are all -3996. This is a very obvious finding, but it does show that the model will not provide results when mistakes or impossible combinations are present in the input files.
- Secondly, it seems that the model does not work for water levels that are above ground level (inundated). Contact with the help desk of WVA supported this finding. It was said that WVA does not determine wet damage due to a (long) period of inundation. Situations like this where there are water levels above ground level are also very uncommon for agricultural areas.
- Lastly, what does show a surprising result, is the fact that the outputs show limits. This becomes clear when opening the outputs in excel. Once the water levels pass a certain depth the outputs stay constant. This is found in both directions, so when GHG is kept constant the outputs will become constant at a depth of around 200 cm and when GLG is kept constant the outputs become constant at smaller depths around 120-150 cm.

According to the Watervision Agriculture helpdesk, these deeper groundwater levels are in fact still within the limits of the model. The limit of the model lies at 3m below ground level. If at some point, deeper groundwater levels do not generate more damage this means that at that point crops are not directly influenced by the groundwater but by capillary actions. The amount of capillary action depends on the soil type and the crop type (root length) and therefore shows variations in the matrices. It was found that on average the outputs stay constant beyond a GLG of 200 cm and a GHG of 150 cm.

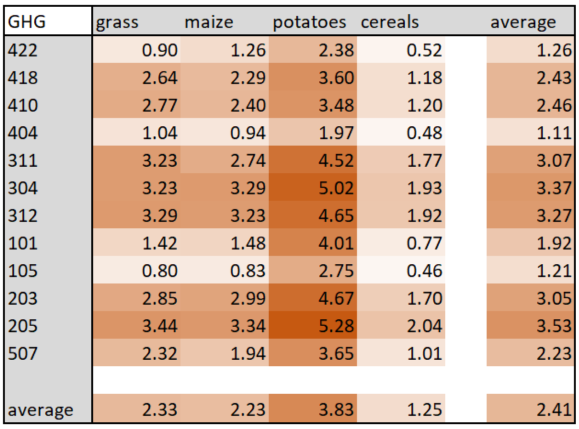
Robustness of WVA in total

When further analysing the matrices we can create statistics and graphs that tell more about the sensitivity of the model. Table 5 and 6 present the outcomes per soil type and per crop.

When analysing the effect of increasing the GLG on total damage, over all combinations of the other variables, we find that the sensitivity ranges from 0.17 to 2.11% with an average of 1.17%. Increasing the GLG has the largest effect on grass, with the highest effect on soil type 410. The smallest sensitivity for GLG is found for cereals. When looking at the soil types, the highest sensitivities for GLG are calculated for 312 and 304.

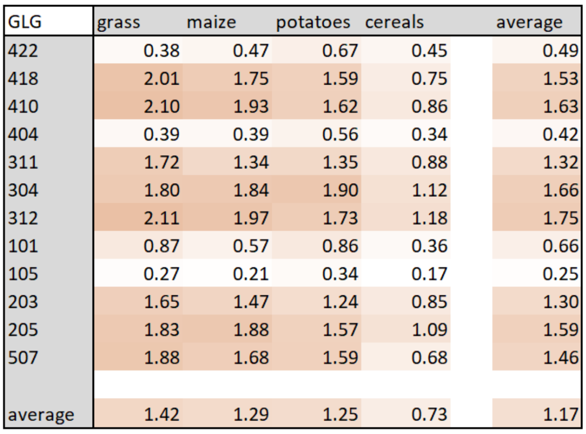
When analysing the effect of increasing the GHG on total damage, over all combinations of other variables we find that the sensitivity ranges from 0.46 to 5.28% when increasing the GHG with 10 cm, with an average of 2.41%. The largest sensitivities are calculated for potatoes, followed by grass, with the highest on soil type 205. The smallest sensitivity is found for cereals. When looking at soil types, the highest is found for 205, the lowest for 404.

Table 5 Average influence of the GHG variable on total damage per crop and soil type (in percentage)



GHG	grass	maize	potatoes	cereals		average
422	0.90	1.26	2.38	0.52		1.26
418	2.64	2.29	3.60	1.18		2.43
410	2.77	2.40	3.48	1.20		2.46
404	1.04	0.94	1.97	0.48		1.11
311	3.23	2.74	4.52	1.77		3.07
304	3.23	3.29	5.02	1.93		3.37
312	3.29	3.23	4.65	1.92		3.27
101	1.42	1.48	4.01	0.77		1.92
105	0.80	0.83	2.75	0.46		1.21
203	2.85	2.99	4.67	1.70		3.05
205	3.44	3.34	5.28	2.04		3.53
507	2.32	1.94	3.65	1.01		2.23
average	2.33	2.23	3.83	1.25		2.41

Table 6 Average influence of the GHG variable on total damage per crop and soil type (in percentage)



GLG	grass	maize	potatoes	cereals		average
422	0.38	0.47	0.67	0.45		0.49
418	2.01	1.75	1.59	0.75		1.53
410	2.10	1.93	1.62	0.86		1.63
404	0.39	0.39	0.56	0.34		0.42
311	1.72	1.34	1.35	0.88		1.32
304	1.80	1.84	1.90	1.12		1.66
312	2.11	1.97	1.73	1.18		1.75
101	0.87	0.57	0.86	0.36		0.66
105	0.27	0.21	0.34	0.17		0.25
203	1.65	1.47	1.24	0.85		1.30
205	1.83	1.88	1.57	1.09		1.59
507	1.88	1.68	1.59	0.68		1.46
average	1.42	1.29	1.25	0.73		1.17

When looking at the differences between soil types we find that 205 and 304 are most influenced by the GHG. For the GLG this is soil type 312 and then 304.

Looking at the differences between crops we find that GHG has a higher effect on total damage for all crops, and potatoes are influenced most by changing the GHG. GLG has the highest effect on grass. This difference can be explained by different growth periods throughout the year, making that different crops benefit more or less from changes in winter or summer.

The specific results on drought damage and damage due to too wet conditions is presented in appendix VII and VIII.

Robustness of WVA in the Langbroekerwetering

To further explore what these results mean for the Langbroekerwetering, specific outcomes have been further analysed. Therefore, the following Figure 6.14 present outcomes for 5 BOFEK soil types which have a large share in the study area, together with some groundwater levels which are common for the study area. Each graph shows how total damage of a crop (y axis) on different soils (different lines) is influenced by 10 cm increases in GLG or GHG (x axis). Looking at patterns in the data the following results can be found.

GLG and GHG

The slope of the graph indicates the sensitivity of the variable. In case of GHG, it can be seen that the steepest slopes lie between 0 and 50 cm. For the GLG this is between 30 and 100 cm. This indicates that within this range damages can be changed most by altering the water levels.

Comparing soils

When comparing different soil types it can be seen that GHG has less influence on soils 422 and 404, total damage is stable independent from variations in GHG or different crops. The fact that some GLG graphs show an initial increase of damage when GLG is increased indicates that in those soils, crops require a higher water level. For variation in GLG a similar pattern can be seen, however variations in GLG from 30 to 90 cm do have some negative impact on total damage. In the other three soil types included in the analysis; 418, 410 and 311, a decrease in damages can be seen when GLG and GHG increase.

Comparing crops

The patterns of increase or decrease in damage seem to be mostly related to GHG, GLG and the soil type. When looking at different types of crops, the patterns seem to be similar, although there is a variation in the severity of the damage. Some crops have a lower damage overall, such as maize. Furthermore, it can be seen that damages depend on soil type. For instance maize and grass have higher damages in soil type 418 and 410 than potatoes and cereals. This indicates that different crops have a different sensitivity to groundwater level changes. Also, different crops have different hydrological requirements.

Concluding remarks on sensitivity

The overall averages indicate that the sensitivity of different variables is not that high, also there are no extreme values. What can be seen is that within specific ranges sensitivity can be higher. These findings can be used in specific situations to provide insight in how much water levels have to be altered in order to change damages.

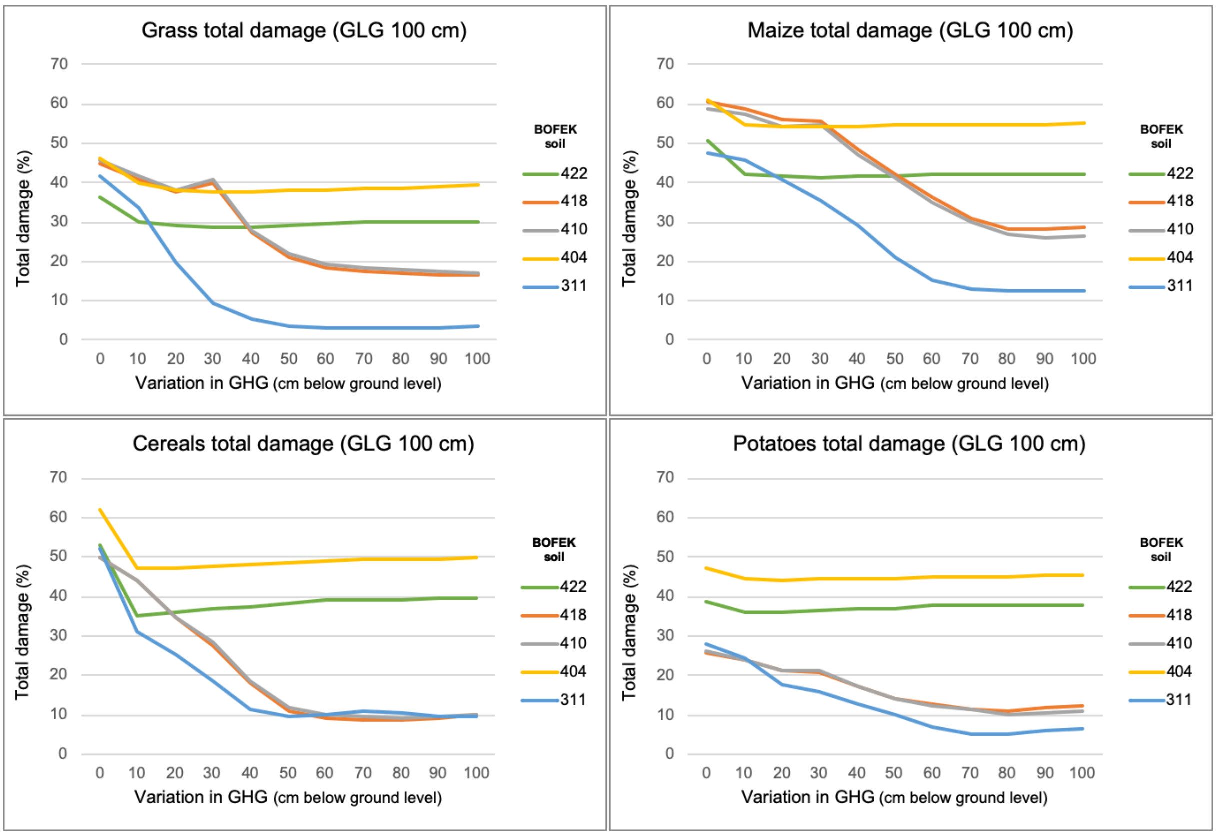


Figure 6.14 Sensitivity results showing how the total damage changes for a variation in GHG while keeping GLG constant at 100 cm below ground level for grass, maize, cereals and potatoes. 422: heavy clay, 418: Heavy sabulous clay, 410: Sabulous clay on sand, 404: clay on peat and 311: moderate loamy sands with large humus layer

6.4.2 Robustness of Watervision Nature

Robustness and sensitivity are different for the Watervision Nature model as this is not a process-based model. Within the Waternood model in Watervision Nature trapezoid graphs play an important role; they visualize between which range of water levels goal attainment is optimal and constant (100%) and in which range of water levels the goal attainment increases or decreases. Those parts of the graph directly illustrate the sensitivity of the of the GLG and GHG variables in relation to goal attainment.

A disadvantage is that in Waternood+ the trapezoid graphs cannot be shown, and therefore the user is not able to determine the sensitivity of this model directly. This also makes that Waternood+ has a lower transparency compared to WVN Waternood.

7. Discussion

7.1 Reliability of the results

This research described here aimed for evaluating the usefulness of the decision support system Watervision. Watervision was tested by applying it to a case area the Langbroekerwetering. Data mostly from HDSR was used as input for the model to run different options and produce results. These input data already include some uncertainty in the validity of the groundwater level data as these values were modelled (in a groundwater model). However, while it is important to acknowledge, this uncertainty did not affect the results that contributed to evaluating the usefulness of Watervision.
One of the aspects of Watervision that remains to be improved is the validation of the outputs. For this purpose the current study relied on the experience and knowledge of experts from the area. This could have been done more elaborately by in-depth interviews of nature managers, land owners or farmers in the area. Also field measurements could have provided more certainty for assessing the validity of the outputs.

While the reliability of the data or the model could be discussed, in this case the interpretation of the results in light of its value for regional groundwater governance seems to be more relevant. Hence, the reliability of the results does not primarily depend on the input data and the model itself but more importantly on the way results generated by the model are interpreted.

Furthermore, this study aimed to provide information enhancing the transparency of the model. This was done by performing thorough explorations of the background in terms of the contents of the models, characteristics of the study area and the context of regional groundwater governance. By exploring and describing these in detail it can be assured that the outputs of the model are interpreted in the right way. Also describing the methods of the analysis in detail, as was done in this study adds to the replicability of the analysis.

To conclude, the quality and availability of the data appear to be sufficient to produce results and answer most of the research questions. Unfortunately, for exploring the option of using climate change scenarios there was not sufficient input data to run the model. However qualitative results were obtained about the aspect that can be used to assess its added value.

7.2 Discussion of the results in relation to the research question

As described in the introduction chapter, the potential of the Watervision tool depends on the credibility of the model and the acceptability of the model for its users. *Credibility* entails the technical validity of outcomes, whether the model is scientifically sound and uses high quality data and testing methods. *Acceptability* refers to whether stakeholders and managers find the model valid, valuable and useful in stages of the planning process. It is argued that using these concepts provides a good indication of whether Watervision is useful, and answers the main question. Therefore, the answers to different sub-questions are related back to these concepts i.e. credibility and acceptability.

RQ 1.1 *How can the WVA and WVN outputs be used for water level management?*
In order to answer this question both models were used to test the effect of current water management conditions to nature and agriculture, under current climate conditions. The outputs that were produced were evaluated in terms of their use for different steps in the process of water level management. For this question most findings relate to acceptability. In general it can be concluded that the outputs can be used in different stages of the decision making process.

One of the first applications of WVA and WVN is that they can help to identify bottlenecks in water management, as part of the GGOR-methodology. The outputs of Watervision are suitable for this as they provide insight into the different types of damages that occur, the severity of this damage and where it is spatially located. These insights can also be used to find out whether the problems stated by different stakeholders are grounded, and to what extend these problems are a result of insufficient (ground)water levels.

Next, scenarios are developed to improve these bottlenecks. For this purpose, especially outputs such as *(scaled) maximum attainable goal attainment* and *gap to optimal* measures can help to identify locations where there is room for improvement. The effect of different scenarios can be tested with Watervision again to find the most desirable outcome. In this sense, using Watervision to test current conditions fits within policy context and can be used by managers in their planning process.

However, on top of numerically calculating damage and using this to work out different scenarios the outputs are also relevant for the policy process in general. The insight in different types of damages enables managers to start a conversation with different stakeholders with conflicting interests. Especially because Watervision enables to visualize damages as well. This specific visualization aspect of the model can help to increase the chances that other stakeholders accept the outcome of the policy process.
The fact that the outputs can be applied by managers in their planning process, fits within the policy context and can be used to start a conversation with different stakeholders. This was found to positively influence the acceptability of Watervision.

On the other hand, there are also some disadvantages that were found by running different options in the model. Comparing WVN outputs, it appeared that the goal attainment outputs of WVN Watervision and WVN Watervision+ are different in terms of location and severity. A reason for this was pointed out in the results and comes down to the fact that for WVA Waternood and WVA Waternood+ the goal attainment is tested for different variables. This implies that the meta relations behind the two models have been established for different reference periods and different soil classifications (BOFEK and 1:50.000 soil map). Also, the trapezium-shaped graphs have been altered to fit the new variables in Waternood+. Due to these reasons, differences in outputs are emerging and seem to be unavoidable (Werkgroep Waterwijzer Natuur, 2018).
However, from the point of view of groundwater governance this is not advantageous. A manager apparently has to choose between different models that have the same purpose, whereas in the current research it did not become clear when to choose which model and on what grounds to choose between them.
Research shows that a model is more acceptable if it helps to reduce policy makers uncertainty about the strategy to choose (Van de Riet, 2003). In this case uncertainty is actually increased in two ways; 1) it is unknown in what situations and for what reasons one of the two models should be chosen, and 2) the models provide different outcomes in terms of goal attainment. These reasons make that this part of WVN clearly scores lower on acceptability.

A positive finding for the acceptability of Watervision is the addition of the outputs *(scaled) maximum attainable goal attainment.* They provide the user with more insight than previous models. Whereas other models can only tell how severe the damage will be, these do not provide the user with the insight of how much improvement is realistically possible. In Watervision the new measures do tell how much improvement can be gained in one parcel, while taking into account the differences in ground level within a parcel.
However, the question does arise why these measures were included in Watervision Nature only, but not for Watervision Agriculture. As it seems agricultural parcels can deal with a similar problem of having one water level for a parcel with differences in elevation this would be recommended.

***RQ 1.2** What are differences in output in Waternood and the Watervision when the same inputs are used?*
For this purpose different options within both models Waternood and Watervision were compared, both for the nature module and the agricultural module. One of the first practical differences is the fact that Watervision provides a more clear and transparent user interface. The user has more control over the inputs and settings and thereby more control over the quality of the outcomes. This makes it easier for managers to use the model in their planning process, and therefore increases acceptability.

One of the main findings, comparing the outputs from both models, lies in the validity of damage outputs. It was found that Watervision Agriculture overestimates some damage outputs. The higher damage due to drought in these outputs is not recognized by experts in the area, farmers do not seem to experience this. Also in a meeting with the developers of Watervision this overestimation was acknowledged.

Further research could show whether there is a higher damage due to drought in the area, or whether the higher results are due to overestimation. The developers do state to be working on finding a solution for this problem. Nevertheless, overestimation of damages in certain soil types currently decreases the credibility of the model as a whole. This also touches the acceptability, as a models outcomes should be believed to be valid.

RQ 1.3 *How robust are the outcomes of the Watervision (sensitivity analysis)?*
The general method for a robustness check of a model is to evaluate the sensitivity of different model parameters. In this case, such an analysis was performed for the Watervision Agriculture model, as this is a process based model. Minor changes in input variables did not show extreme variations in model outputs. Therefore the outputs can be considered as robust, which implies the model is scientifically sound in that aspect, increasing credibility.

Additionally, the sensitivity analysis allowed for a much higher understanding of how the results are calculated in Watervision. This provided a lot of insight into what sort of effects can result from changes in water management. For certain combinations of soil types, crops and specific ranges of water levels an adjustment can increase goal attainment considerably. For instance most effect (the highest sensitivity) is in the higher groundwater levels (close to the surface), but this does of course differ per soil type.

RQ 2.1 *When running Watervision with climate scenarios in the study area, what does it tell us about the robustness of the water level management in the Langbroekerwetering?*
One of the aims of this research was testing Watervision with climate change scenarios and analysing its usefulness for regional groundwater governance. It was found however that in order to use this function rightfully, an aggregation with groundwater modelling is needed. Watervision does not model the effects of climate change to the groundwater levels. Therefore, to model the robustness of the management strategy for the damage (and goal attainment) to vegetation, first the changes in groundwater levels have to be modelled using a local groundwater model. For the current study this implied that testing Watervision with climate change scenarios could not successfully be executed due to limited time to combine it with groundwater modelling.

Nevertheless, this finding does provide a result to the question of usefulness. For this part of Watervision it can be concluded that the additional step of having to model climate change scenarios for groundwater levels lowers the acceptability. Consultation of one of the potential users within HDSR (A. de Boer, pers. communication, 2019) led to the following clear information: she mentioned that this will keep them from using it in the near future. It does however not influence the added value and acceptability of the other functions of Watervision (testing the current situation).

If the climate scenario function could be used this would be useful for groundwater governance. It could be used to evaluate how current bottlenecks will change over time when climate change comes in. When designing measures to decrease the bottlenecks it could be used to test the long term effect of these adjustments. In this way, the water authority can design more robust measures. However, there are other aspects of robustness in water level governance that the water authority can take into account. Besides water levels for instance also the ability to store peaks (water surpluses) within an area are important.

7.3 Management implications

The application of Watervision in the process of designing water level management plans can be recommended for different reasons. First in terms of practical use Watervision provides more control and is easier to use due to the user interface, in comparison with earlier methods and tools.
Besides that the results show various advantages that should increase the acceptability for the intended users, in this case the regional water authority. This is due to the fact that the outputs fit in the policy context, can be used to provide shared insight between different stakeholders and are relevant for different steps in the planning process. Therefore, compared to the original Waternood it is highly recommended to use Watervision instead.

For the different functionalities of Watervision there are some specific recommendations and cautions. In case of Watervision Agriculture it is advised to first check whether one of the soil types that lead to overestimations is present in the area of interest. When this is the case results may be expected to be overestimated and it may be preferable to wait with applying the model until this flaw has been eliminated.
Regarding Watervision Nature, it is recommended to use WVN Waternood instead of Waternood+ when testing the effect of current water level conditions. This is due to the fact that there are more relevant outputs in the Waternood model.
Lastly, in order to study the robustness of current water level management plans, or use other climate change scenario functionalities the model requires more research in advance.

7.4 Scientific implications

In the field of land evaluation, environmental decision support tools such as Watervision are increasingly important to support complex decisions. Due to the fact that the tool was only recently developed, its application had only been tested to a limited extent. While it had been tested in terms of validity of model outputs in comparison to damages and goal attainment in reality, a study on practical use and implementation in regional groundwater governance was not performed until the present study was carried out.

One of the insights that the current study provided is that the criteria used in other studies to evaluate the usefulness of models also apply to environmental support systems in groundwater governance. Factors such as credibility and acceptability also apply to the application of Watervision. These became apparent in characteristics such as reducing uncertainty, enabling different stakeholders to have a shared understanding despite conflicting interests and whether the model outputs fit in the planning process of policy makers have been found to be relevant.

Recommendations for further research

Because the Watervision model was only recently developed, there are ample opportunities for future research. Both in terms of further development and validation of the tool itself, as research on the application of Watervision as an environmental decision support system in regional groundwater governance.
For instance, developers can further study solutions to avoid overestimation in order to improve the validity of the results. Also, from the findings on climate change scenarios a suggestion for further research is to combine Watervision with groundwater modelling. This combination would enable to test the use of climate change scenarios in regional groundwater governance.
Other recommendations are related to test Watervision with features that have been added to the model later on. One suggestion is therefore to test Watervision Agriculture with the addition of submerged drainage is a peat area. This is something that HDSR is highly involved in so it could also be a very interesting case to again study this together with HDSR.
Focusing on the policy context of groundwater governance, future studies can show how implementation of the tool in the policy process affects the efficiency of the process compared to areas where it is not used. Also the effect on how different stakeholders participate in the process of making water management plans, and how they experience the outcomes could be studied in the future.

8. Conclusions

This study was performed with the aim to answer the following research question:

How useful is Watervision as a decision support tool for regional groundwater governance?

The fact that Watervision has been developed recently and has not yet been applied extensively meant that a case study was an appropriate method to evaluate the usefulness of this tool. The case study focused on the application of the tool for regional groundwater governance in the Langbroekerwetering. Specifically looking at the added value for the regional water authority Hoogheemraadschap Stichtse Rijnlanden (HDSR).

To evaluate usefulness this was further defined by the concepts of credibility and acceptability to the intended users and stakeholders in groundwater management. In general, the answer is that Watervision proved both credible and acceptable in various aspects. The results provided insight in the broad range of applications of the model outputs. Also, the plausibility of the results were evaluated by interviews with experts from the area of the case study. This showed that most outputs provide a positive result in terms of plausibility, except for drought stress on agricultural parcels. Furthermore the sensitivity analysis provided a better idea of the influence of different model parameters and how the water authority can influence agricultural damages.

There are a lot of advantages to the models such as the use of newer climate data, addition of process based models instead of expert opinion and new output measures that provide insight in room for improvement. Besides that there is the increase in practical use compared to earlier methods, this tool is easier to use, provides more control and insight. For instance there is the option to customize the reference year and other types of inputs, which makes that the user knows which data and options are combined to produce a certain result.

However, there were also some disadvantages found. Firstly, in terms of practical use it would have been easier if the two modules (WVA and WVN) were integrated in one Watervision tool. Also, the fact that Watervision Nature provides two similar options to assess the water management conditions produce different outputs increases uncertainty. Furthermore, the idea of using the climate scenarios is more work than the model implies as the inputs require additional modelling. Lastly, the credibility of the tool can still be improved on some aspects. For instance the process based models overestimate some types of damage in some cases.

The fact that developers and researchers are already working on improving some of these points is promising. Furthermore future application of the tool and additional research can help validate the model in different contexts and prove its use to different stakeholders in regional groundwater governance.

To conclude, the idea of Watervision is really useful for groundwater governance. In the past water managers had to rely more on expert knowledge and set norms such as drainage standards. In practice it is often the case that only problematic areas are re-evaluated in a water level plan, making water managers responsive to problems and stakeholders. Watervision on the other hand provides water managers with criteria to evaluate the implications of different water levels. Also by using this tool different stakeholders' opinions can be compared and checked. Thus enabling more pro-active and strategic improvement of water management and land use in the area. This makes that Watervision provides a better preparation for uncertainties and changing climate in the future.

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Appendix I

Methods and tools for water level optimization in regional groundwater governance.

1a. Types of (ground)water level management

The water authority maintains the water levels that are set in the water level management plan in a specific area. There are different options that the water authority can employ. The following list provides an overview of the different types of water level management (HDSR, 2011, Bijlage 3):

- A *fixed water level* implies that the water is controlled to stay at a set water level. This not preferred for most land use functions and is mostly used in built-up areas and some nature areas.
- A winter and a summer level is a commonly used type of water level management by regional water authorities. A *higher summer and lower winter level* is more favourable for agriculture. This reduces drought stress in summer, and in winter a lower level makes sure that the ground is less wet, enabling farmers to enter their land earlier in winter. A *lower summer and higher winter level* is more natural. This is more appropriate for nature areas as it approximates a natural variation over the seasons. An advantages of this type of water management is that it is favourable for nature developments along the water banks. However, it can be unfavourable for water storage in case of extreme rainfall in winter. Also this can increase the subsidence rate due to lower water levels in summer.
- A *flexible water level* means that the water level is able to fluctuate between an upper and lower limit (or only an upper limit). In this case there is variation due to precipitation, evaporation, seepage water and infiltration of water. This type of water level management is also mostly preferred for nature functions.
- A *natural water level* can also be applied. This means that the water level is only influenced by nature and not managed at all. When there is no natural water level, this can be simulated by introducing a flexible water level or a lower summer and higher winter level.

1b. Methods

A traditional method that is used for water level management is determining a set drainage depth of the surface water. With regional groundwater governance, the water levels that are set in the water level plan actually refer to surface water levels of the specific area. More precisely, the specified water level in the water level plan refers to the drainage depth at the weir of the specified area (see figure I). The drainage depth, is the depth of the surface water level in relation to the ground level (HDSR, 2011).

A water level plan can only be made, if the surface water level has a direct effect on the groundwater table. In order to know this effect, groundwater modelling of the management area is necessary. For HDSR, this is modelled with the groundwater model HYDROMEDAH which also calculates the GxGs (GLG[2], GHG[3], GVG[4] and GG[5]) of the area. The GxGs and numerical relation between the surface water and groundwater can be used by water managers to determine the GGOR. (A. de Boer, pers. communication, 2019)

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[2] GLG: Average lowest groundwater level

[3] GHG: Average highest groundwater level

[4] GVG: Average groundwater level in spring

[5] GG: Average groundwater level

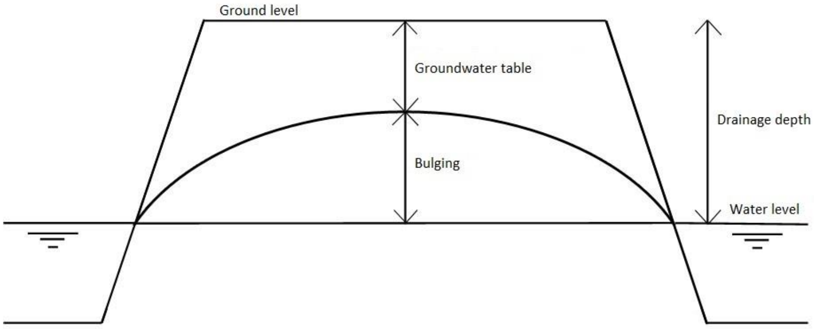


Figure I. Schematic representation of the different concepts that are involved in regional groundwater governance. The water authority aims at a certain groundwater table that support the land use function. This groundwater table is managed by managing the drainage depth (in cm or m under ground level). In order to do this successfully the relation between the surface water level and the groundwater table needs to be determined through groundwater modelling.

The water level requirements are related not only to the land use function but also the soil conditions. For agriculture there are standards for the drainage level depth (Table 7) which are set in the Beleidsnota peilbesluit. These standards are originally derived from the *Cultuurtechnisch Vademecum* (which is a reference work on geohydrology) and give a range of the highest permissible drainage level depths per soil type (Cultuurtechnische Vereniging, 1988, p. 522). HDSR has translated these to the following drainage level depths for their administrative area (in cm under ground level) for agricultural grasslands (HDSR, 2011, p.32):

Table 7 Defined drainage depths per soil type for the administrative area of HDSR (taken from (HDSR, 2011))

Soil type	Drainage depth norm
Clay and clay on sand	70-100 cm
Clay on peat	60-80 cm
Peat	50 (max 60) cm
Sand	50-80 cm

However, these norms are only for grassland and give a general indication of the water management requirements. For crop farming drainage depth norms are generally lower than grassland. In practice, there are often specific characteristics of a location that have to be studied by the regional water authority before an appropriate water level norm can be set.

1C. Previously used EDSSs

As described earlier, decision support tools can help people to manage decision making in complex situations (Matthies et al., 2007). For regional water authorities, decision support tools can help to determine what type of water level management is appropriate in a specific location. The next section describes some of these decision support tools that can support water level optimisation.

When aiming at optimisation of water levels an important aspect is taking into account the different functions in the area and the vegetation linked to that. The performance of vegetation is determined by the availability of solar radiation, CO_2, water, oxygen, salts and nutrients in the soil. Plants experience drought stress when there is not sufficient water available in the soil and experience oxygen stress when the root zone is too wet. Lastly, if the concentration of salt in the soil moisture is too high this will limit the water uptake and therefore the plant growth as well (Hack-ten Broeke et al., 2015).

Water level optimisation for agriculture

In the case of agriculture, these critical conditions are different for every crop and also differentiate per soil type. In order to quantify the amount of drought or oxygen stress, water authorities use different methods. In the case of agriculture, a common method that is used are the HELP tables that date back to 1987, with the most recent update in 2005. The 2005 HELP tables are lookup tables that determine the amount of drought or oxygen damage to the agricultural production for every possible combination of GHG (average maximum groundwater level) and GLG (average low groundwater level) with 72 soil types and 14 crop types (Van Bakel et al., 2005).

Water level optimization for nature

In the case of nature: the Hydrological Constraints Nature (HCN, in Dutch: Hydrologische Randvoorwaarden Natuur) application is a commonly used method. Similar to the HELP tables, the HCN tool provides information on (water)-management requirements for specific vegetation types, except in this case it is not expressed in damage but in goal attainment. Goal attainment is the extent (%) to which the water level is supporting the full realisation of the vegetation (in Dutch: *doelrealisatie*). When 100% is realized this means that the plant can grow without any hydrological restrictions. The relation between the water level and the vegetation realization can be made visible with an attainment-graph (figure 3). The attainment graph presents between which water levels plants are too wet, too dry, or at the optimum to flourish and realize their potential; 100% goal attainment. Outside this range water levels become less appropriate for this type of nature until a point is reached, either too wet or too dry, after which it can no longer exist. A goal attainment graph is made for drought stress, the GLG and the GVG, to be able to test how appropriate the hydrological conditions are on each of those aspects. This method is used to be able to compare the water management needs of different nature areas (H. Runhaar & Hennekens, 2014). The method is still applied in Waternood and Watervision.

Waternood application

Both the HELP tables and the HCN instrument are available to use in the Waternood tool. This GIS tool is developed for water managers and provides the means to do a spatial analysis for water level optimisation in relation to vegetation. The primary aim of the tool is to analyse the current water level (AGOR) and comparing to the optimal water level (OGOR) in order to find the percentage of goal attainment of the specific land use (crops or nature vegetation). This can be used for groundwater governance. In addition, the tool can also be used to evaluate the suitability of a specific land use or vegetation in relation to the current water level management and soil conditions (Jansen et al., 2004).

Appendix II

Nature management types in the Langbroekerwetering

N05.01	Moeras - Marsh	Marshes are located in areas that transition from freshwater to land. In the study area the marshes are a result of seepage water at the edges of sandy soils or in lower areas. The soils are very wet and high in nutrients. The optimal range of GVG lies between -225 to 45 cm below ground level.
N10.01	Nat schraalland - Wet schraalland	Wet Schraalland is a type of wet grassland which are very old farmlands that used to occasionally inundate during winter and partly dry up during summer. In summer the grass has to be mowed and removed in order to sustain the schraalland. Currently there are not many wet grasslands left and therefore they are maintained in nature reserves. Nat schraalland often relies on seepage water and high water levels where GVG is optimal between -10 to 38 cm below ground level.
N10.02	Vochtig hooiland - Moist hay land	Moist hay land is also a type of wet grassland. Both moist hay land and wet schraalland contain rare plant species but hay land has a larger carrying capacity of species. Moist hay land also prefers high water levels where GVG is optimal between -13 and 45 cm under ground level.
N11.01	Droog schraalland Dry schraalland	Dry schraallands contain a variation of different herbaceous species due to the relatively low nutrient levels in the soil. This is mostly low vegetation like grasses and sometimes patches of higher more shrub like vegetation. In terms of water levels the optimal GVG is below 10 cm under ground level
N12.02	Kruiden- en faunarijk grasland Herbaceous and fauna-rich grassland	Herbaceous and fauna-rich grassland and fields have a high variety of species on soils with relatively high nutrient levels. The high variety of species refers not only to plants but also to different animal groups like: butterflies, other insects, birds, reptiles and small mammals. For 12.02 the optimal conditions for GVG are -3 cm and above and for 12.05 this is 60 cm below ground level and lower
N12.05	Kruiden- en faunarijke akker Herbaceous and fauna-rich field	
N14.03	Haagbeuken- en essenbos Hornbeams and ash forest	14.03 is a type of wet forest which are located on relatively wet soils due to high groundwater levels or occasional floods. It contains different tree species like: hornbeam, common ash, acer and field elm sometimes alternated with shrubs. The optimal water level conditions for GVG are > 30 cm below ground level.

N15.02	Dennen-, eiken- en beukenbos Pine, oak and beech forest	15.02 is a type of dry forest which means it contains forest and shrubs that are located on relatively dry soils. Most dry forests date back from the 19th or 20th century and were planted with the purpose of wood production. Currently the production of wood in these forests is less than 20%. It mainly contains European species like pines, oaks, beech and birch and the forests have simple structures. Optimal conditions for GVG are >40 cm below ground level.
N16.01	Droog bos met productie Dry forest with timber production	Forests with production means that they have both the function of nature together with timber production. The dry woods with production have the same species as 15.02. and the wet woods have similar species as 14.03. The optimal water conditions are > 40 cm below ground level for dry forest and -18 cm and lower for wet forest.
N16.02	Vochtig bos met productie Wet forest with timber production	
N17.01	Vochtig hakhout en middenbos Wet coppicing wood	N17 is a class with forests that have a cultural heritage value. N17.01 consists of coppicing woods which is a traditional method of woodland management where trees are cut down to the near ground with the purpose of growing shoots from the copse. Depending on the location and conditions, different tree species can be used like: willow, alder, ash, and oaks. In the Langbroekerwetering, some of the N17.01 areas are also natura 2000 areas. The optimal GVG for 17.01 is -15 cm and lower.

Appendix III
List of UNAT nature targets in the Langbroekerwetering

3.24	Moeras	Marsh
3.29	Nat schraalland	Wet schraalland
3.31	Dotterbloemgrasland van veen en klei	Caltha field on peat and clay
3.33	Droog schraalgrasland van de hogere gronden	Dry schraalland on higher grounds
3.32b	Zilverschoongrasland	Zilverschoongrasland
3.50	Akker van basenrijke gronden	Field on calcareous soils
3.66	Bos van voedselrijke, vochtige gronden	Forest on nutrient-rich, wet soils
3.65	Eiken- en beukenbos van lemige zandgronden	Oak and beech forest on loam soils
3.64	Bos van arme zandgronden	Forest on low-nutrient sandy soils

Appendix IV

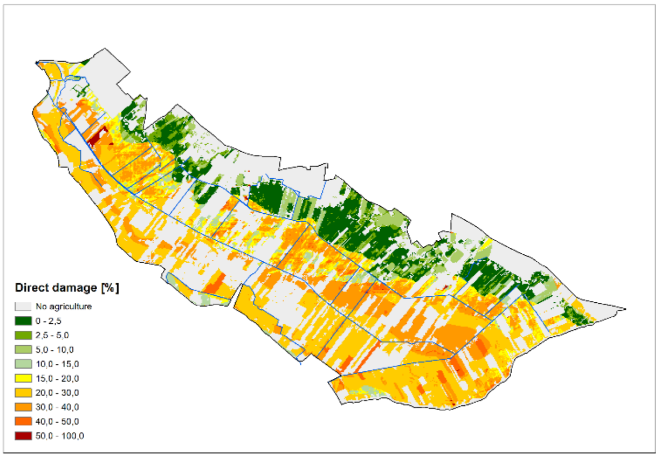
Ecotope classes that are used in Probe (in Dutch). From (Werkgroep Waterwijzer Landbouw, 2018)

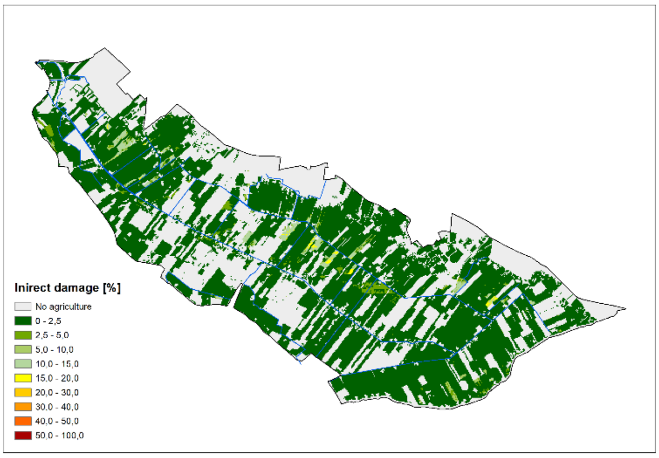
A11	Verlandings- en zoetwatervegetaties van voedselarme, zure wateren (zure vennen, hoogveenplassen)
A12	Verlandings- en zoetwatervegetaties van voedselarme, zwak zure wateren (gebufferde vennen, duinplassen in kalkarme duinen)
A15	Verlandings- en zoetwatervegetaties van matig voedselrijke, zwak zure wateren (sloten en plassen met zacht water, vooral in dekzandgebieden)
A16	Verlandings- en zoetwatervegetaties van matig voedselrijke, basische wateren (sloten en plassen met hard water, vooral in laagveen en klei-gebieden)
A18	Verlandings- en zoetwatervegetaties van zeer voedselrijke wateren (sloten en plassen in laagveen- en kleigebieden)
K21	Pioniersvegetaties en graslanden op natte, voedselarme, zure bodems (natte heiden en hoogvenen)
K22	Pioniersvegetaties en graslanden op natte, voedselarme, zwak zure bodems (veenmosrietlanden, trilvenen, blauwgraslanden, kalkarme duinvalleien)
K23	Pioniersvegetaties en graslanden op natte, voedselarme, basische bodems (natte duinvalleien)
K27	Pioniersvegetaties, graslanden en ruigten op natte, matig voedselrijke bodem (hooilanden in het laagveen en in de middenloop van beekdalen)
K28	Pioniersvegetaties, graslanden en ruigten op natte, zeer voedselrijke bodems (ruigtes langs rivieren en sloten, nat cultuurgrasland)
K41	Pioniersvegetaties en graslanden op vochtige, voedselarme, zure bodems (vochtige heiden en hoogvenen)
K42	Pioniersvegetaties en graslanden op vochtige, voedselarme, zwak zure bodems (heischrale graslanden, kalkarme duinvalleien)
K43	Pioniersvegetaties en graslanden op vochtige, voedselarme, basische bodems (kalkgraslanden)
K47	Pioniersvegetaties en graslanden op vochtige, matig voedselrijke bodems (dijkhellingen, glanshaverhooilanden)
K48	Pioniersvegetaties en graslanden op vochtige, zeer voedselrijke bodems (akkers, bermen, fabrieksterreinen)
K61	Pioniersvegetaties en graslanden op droge, voedselarme, zure bodems (droge heiden)
K62	Pioniersvegetaties en graslanden op droge, voedselarme, zwak zure bodems (droge heiden en Buntgras-graslanden)
K63	Pioniersvegetaties en graslanden op droge, voedselarme, basische bodems (kalkrijke duingraslanden)
K67	Pioniersvegetaties, graslanden en ruigten op droge, matig voedselrijke bodems (ondergroei in graanakkers, ruderale vegetatie in droge duinen)
K68	Pioniersvegetaties, graslanden en ruigten op droge, matig voedselrijke bodems (ondergroei in zwaar bemeste akkers, ruderale vegetatie langs rivieren)

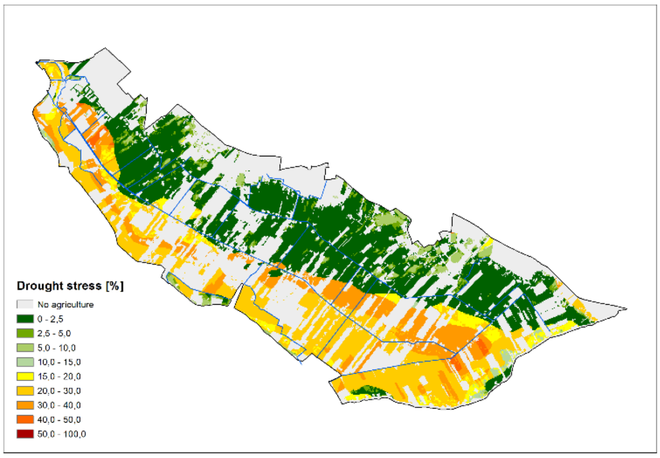
H21	Bossen en struwelen op natte, voedselarme, zure bodems (hoogveenbossen)
H22	Bossen en struwelen op natte, voedselarme, zwak zure bodems (bronbossen)
H27	Bossen en struwelen op natte, matig voedselrijke bodems (elzenbroekbos, nat hellingbos)
H28	Bossen en struwelen op natte, zeer voedselrijke bodems (rivierbossen, grienden)
H41	Bossen en struwelen op vochtige, voedselarme, zure bodems (vochtige eiken-berkenbossen en beuken-zomereikenbossen met Pijpenstrootje)
H42	Bossen en struwelen op vochtige, voedselarme, zwak zure bodems (beuken-zomereikenbossen met Leleitje-van-dalen en armere vormen van eikenhaagbeukenbossen met Witte Klaverzuring en Bosanemoon)
H43	Bossen en struwelen op vochtige, voedselarme, basische bodems (hellingbossen in Zuid-Limburg)
H47	Bossen en struwelen op vochtige, matig voedselrijke bodems (oudere stinzenbossen en andere parkachtige bossen op rivierklei, leem en lemige zandgronden)
H48	Bossen en struwelen op vochtige, zeer voedselrijke bodems (jonge aangeplante bossen op kleigrond)
H61	Bossen en struwelen op droge, voedselarme, zure bodems (droge eiken-berkenbossen en beuken-zomereikenbossen)
H62	Bossen en struwelen op droge, voedselarme, zwak zure bodems (binnenduinrandbossen en droge bossen op weinig uitgeloogd zand met Bosviooltje en Lelietje-van Dalen)
H63	Bossen en struwelen op droge, voedselarme, basische bodems (bossen en struwelen van kalkrijke duinen)
H67	Bossen en struwelen op droge, matig voedselrijke bodems (aangeplante bossen op voormalige landbouwgrond op zand)

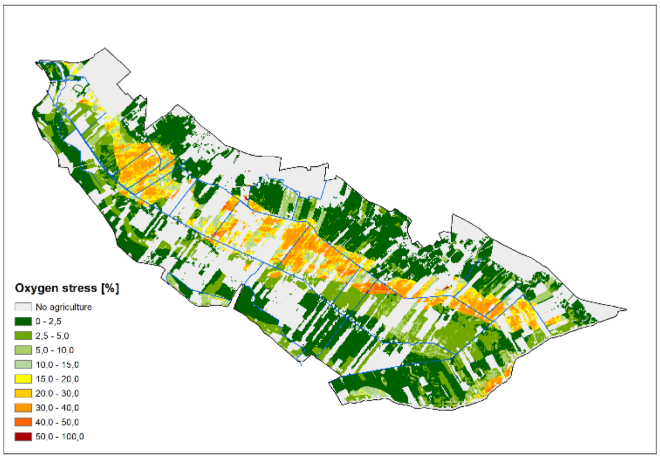
Appendix V

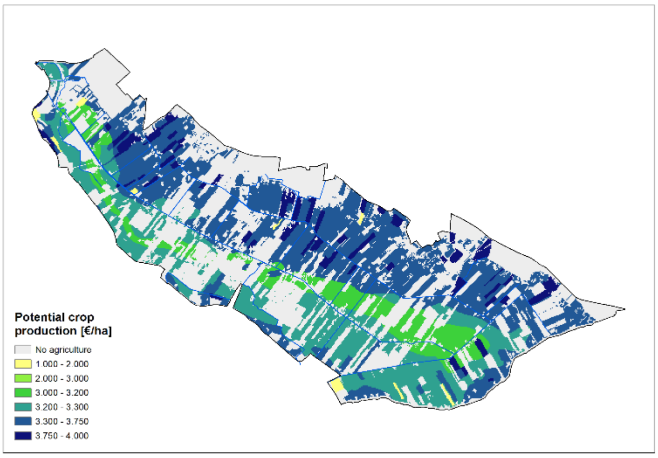
Outputs Watervision Agriculture for the Langbroekerwetering using current conditions.

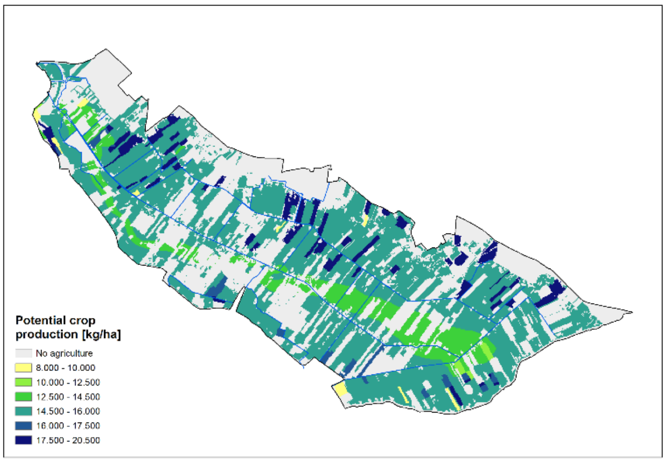






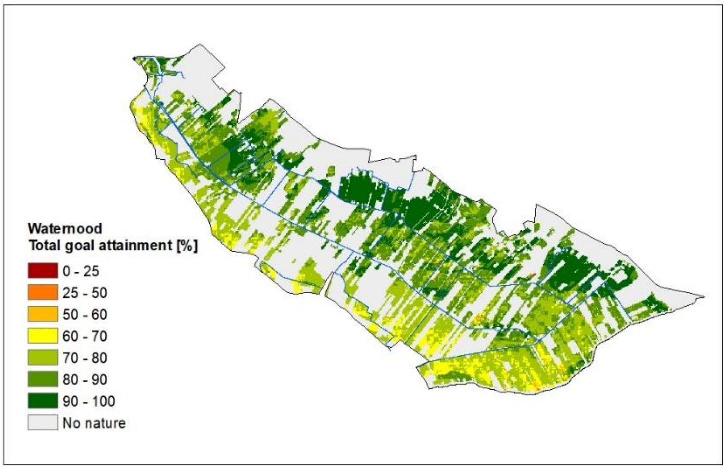


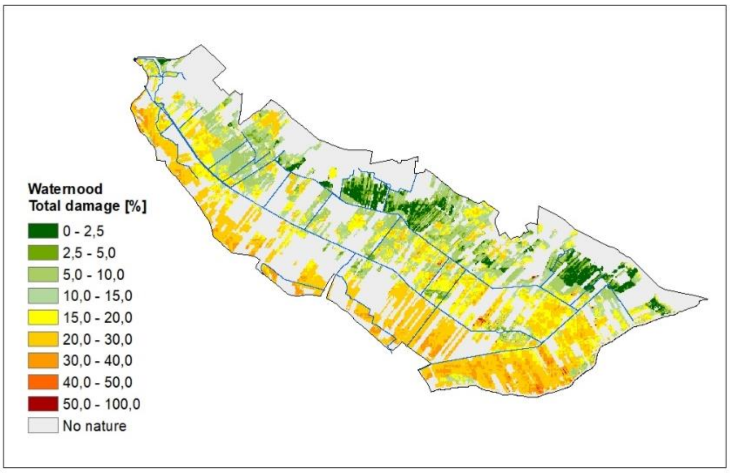


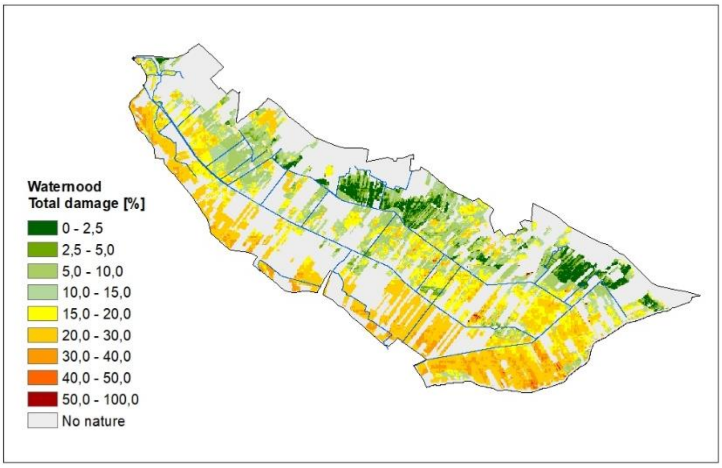


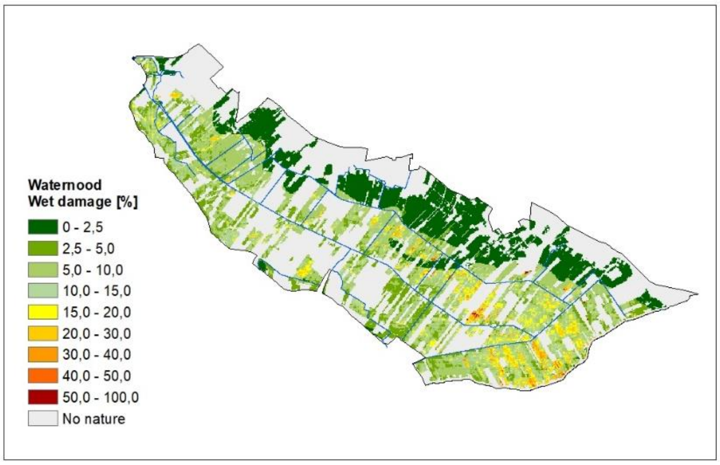
Appendix VI

Outputs Waternood agriculture



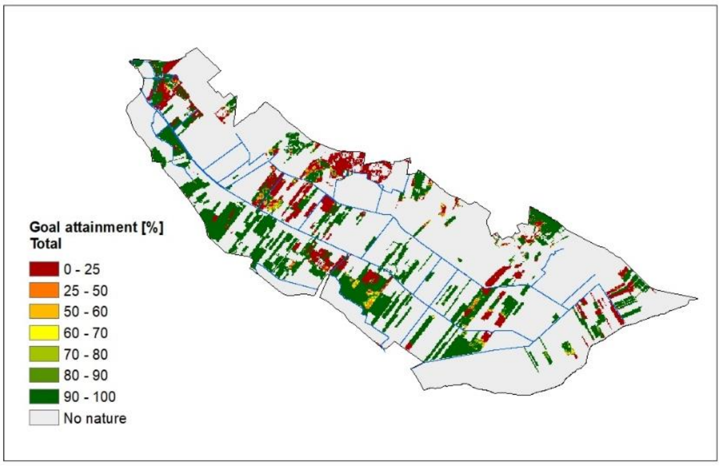


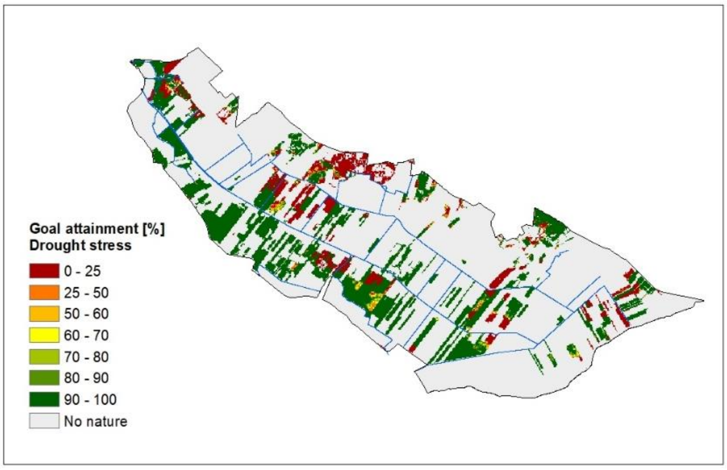


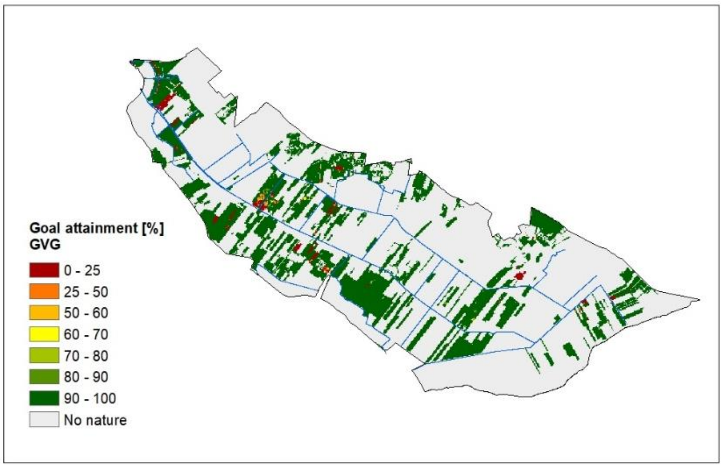


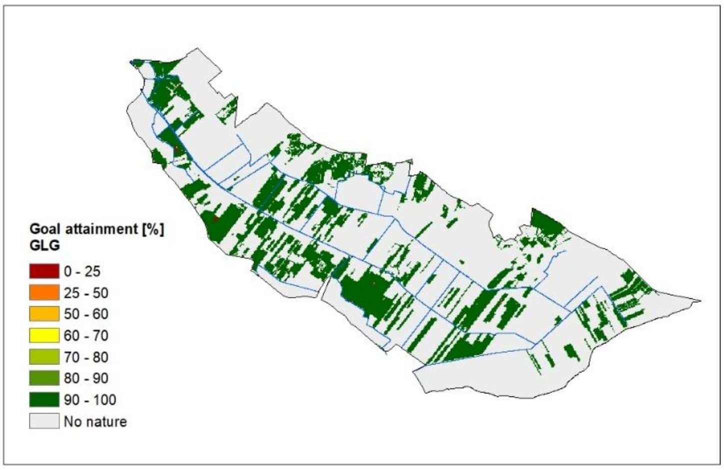
Appendix VII

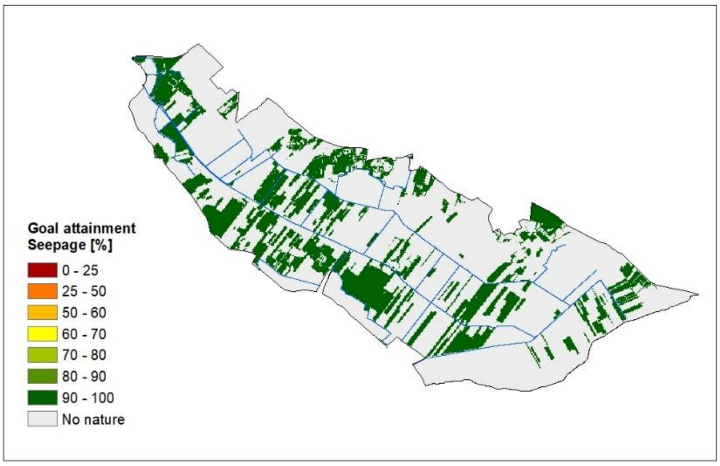
Outputs Watervision Nature (using WVN Waternood), using current conditions

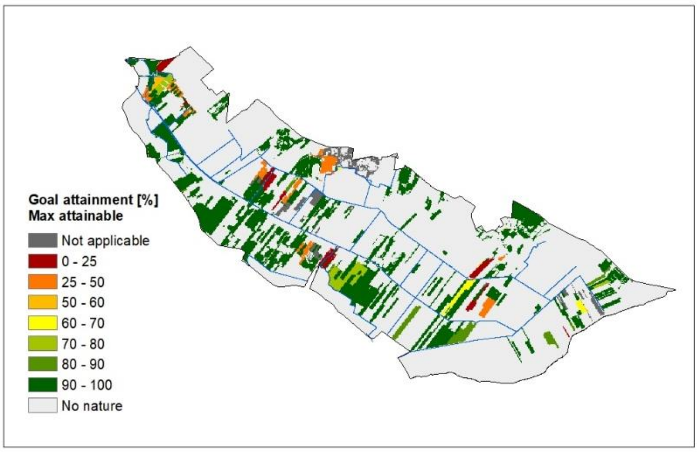


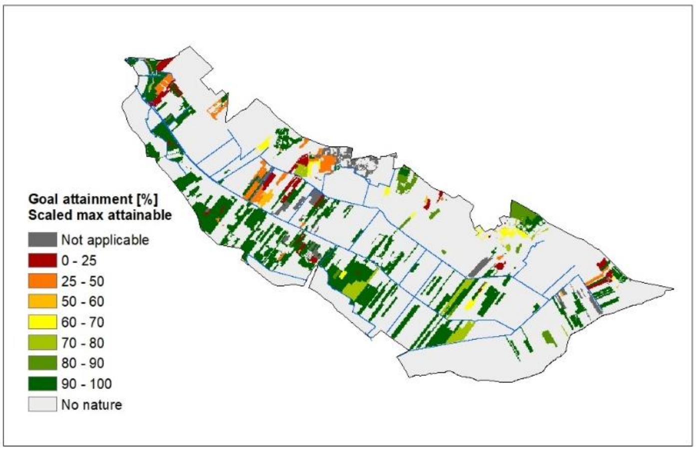









Goal attainment [%]
Max attainable
Not applicable
0 - 25
25 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 100
No nature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80 - 90
90 - 100
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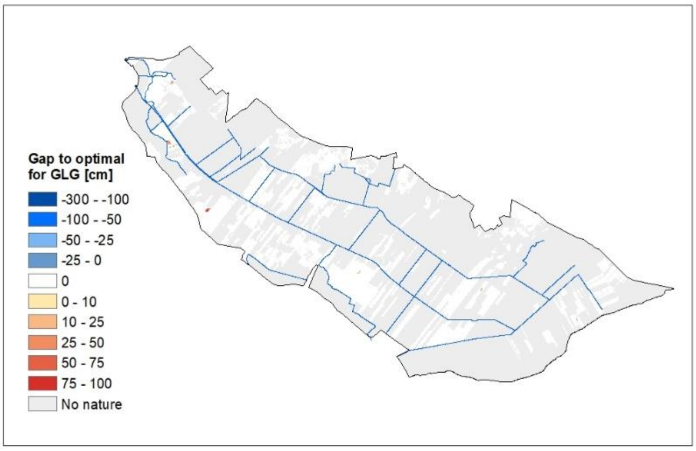
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0
0 - 10
10 - 25
25 - 50
50 - 75
75 - 100
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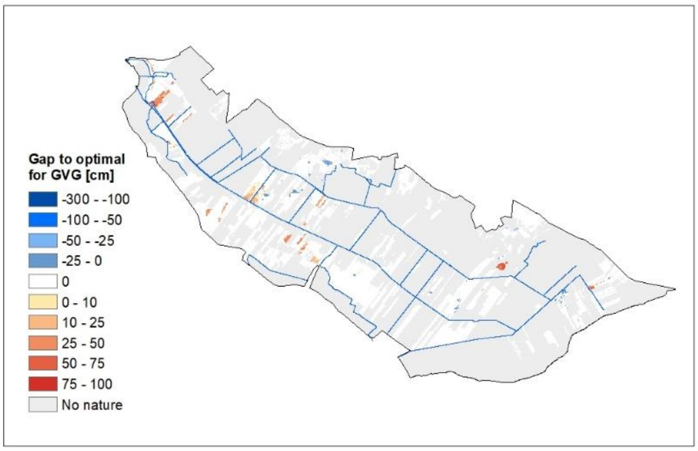
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for GVG [cm]
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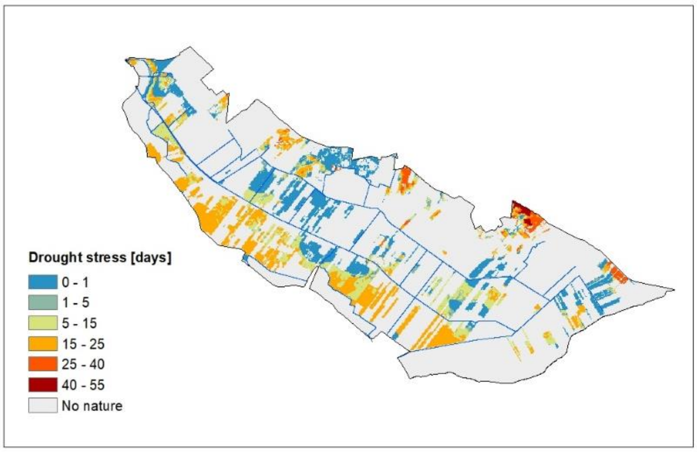
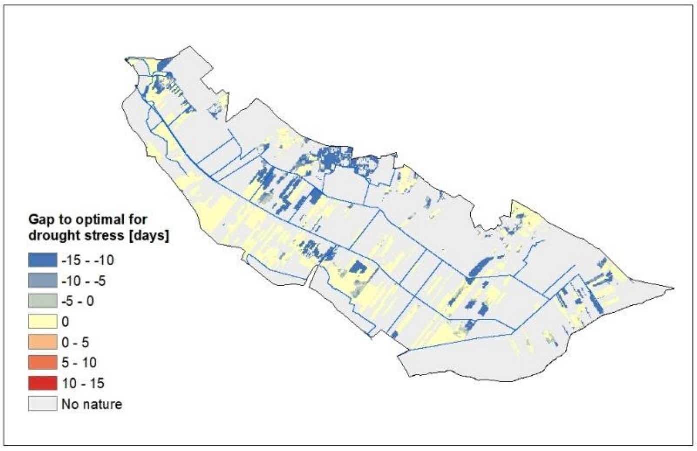
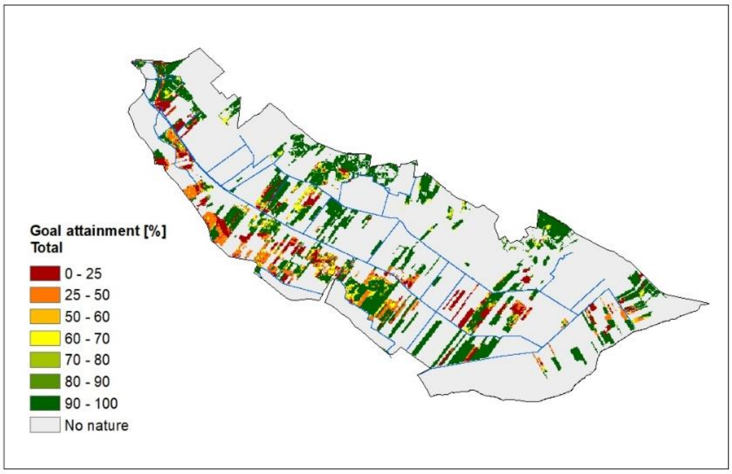
-25 - 0
0
0 - 10
10 - 25
25 - 50
50 - 75
75 - 100
No nature

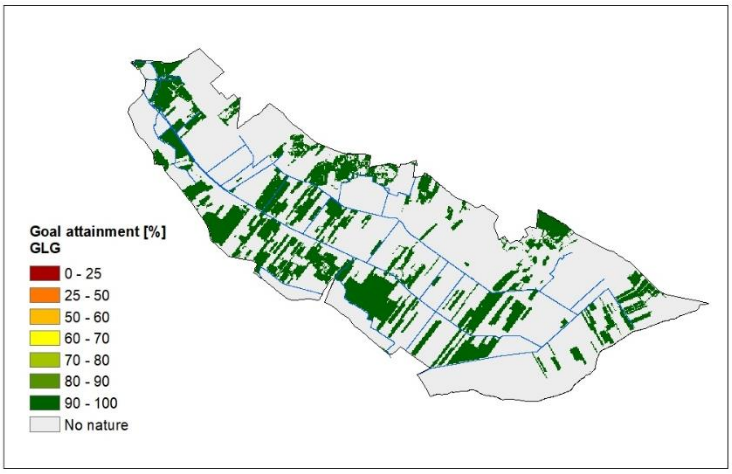

Drought stress [days]
0 - 1
1 - 5
5 - 15
15 - 25
25 - 40
40 - 55
No nature

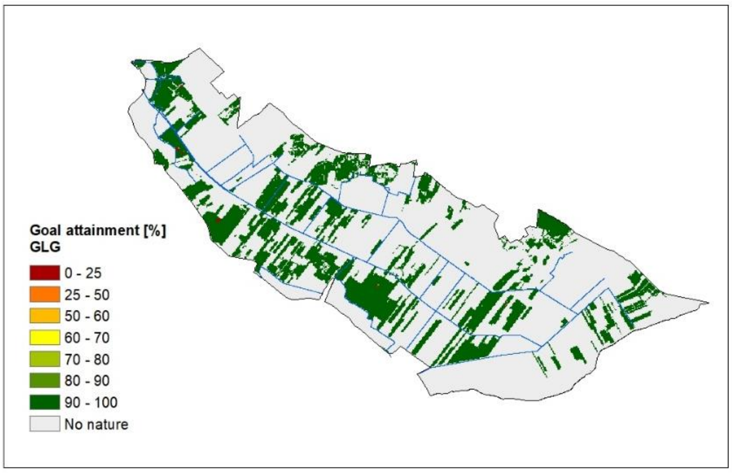

Gap to optimal for
drought stress [days]
-15 - -10
-10 - -5
-5 - 0
0
0 - 5
5 - 10
10 - 15
No nature

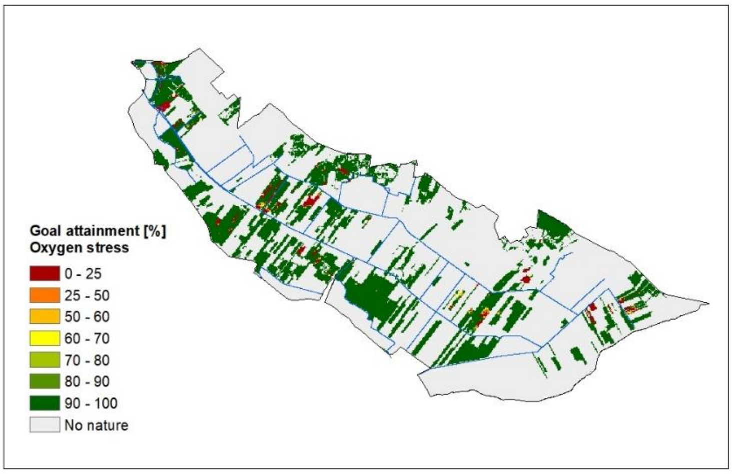
Appendix VIII

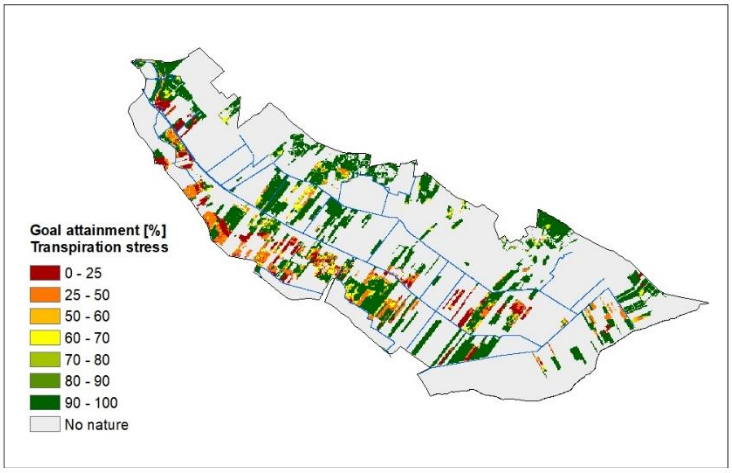
Outputs Watervision Nature (with WVN Waternood+), using current conditions.

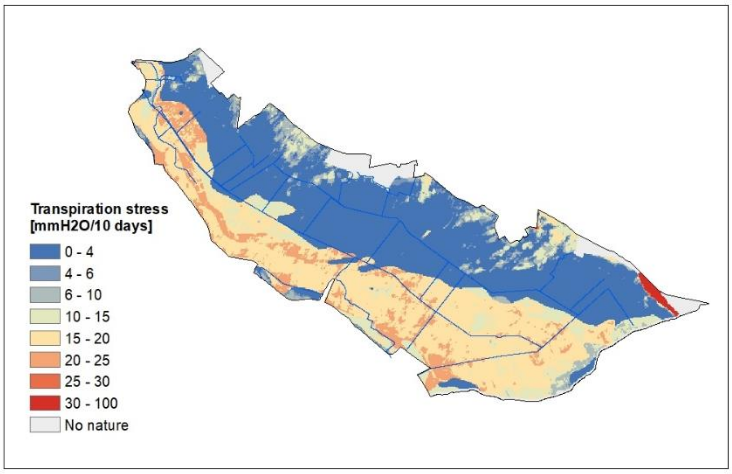


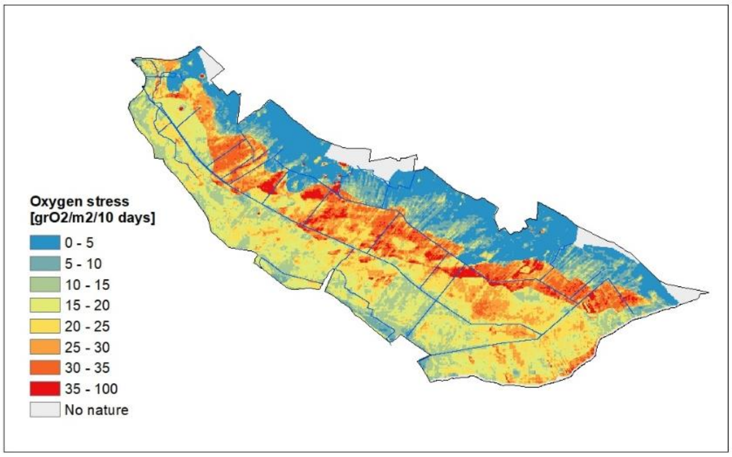






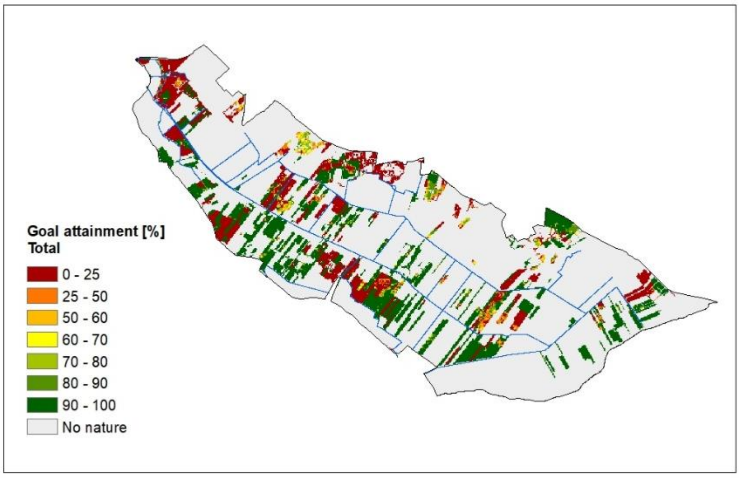


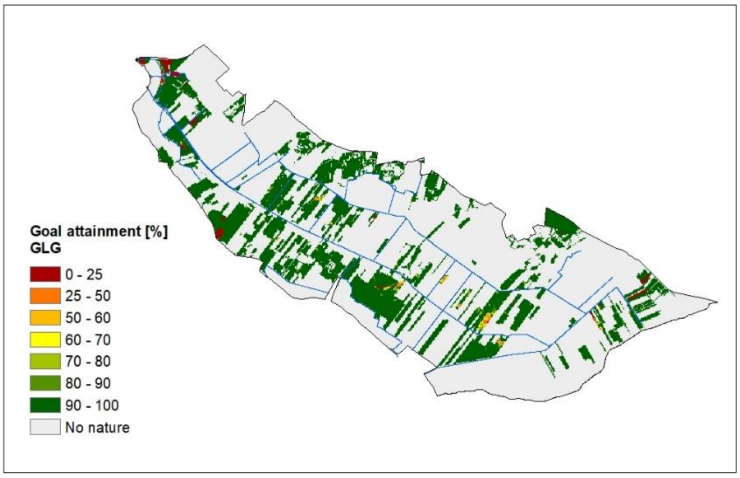


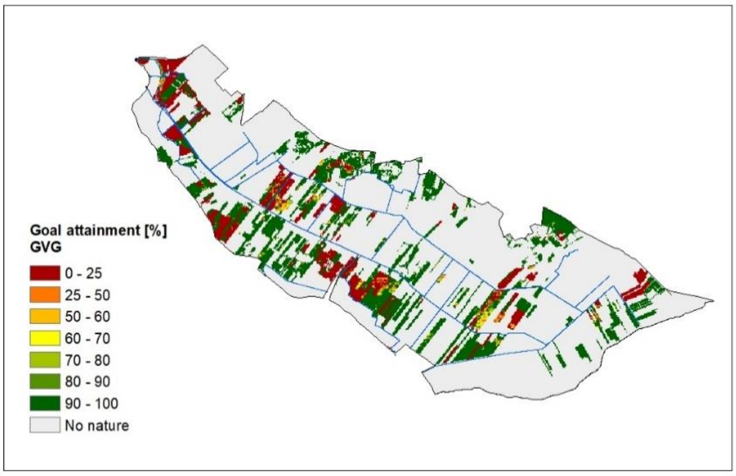


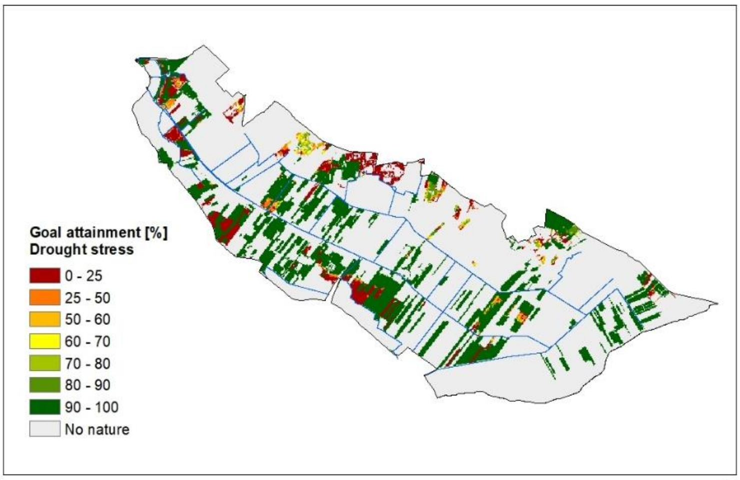
Appendix IX

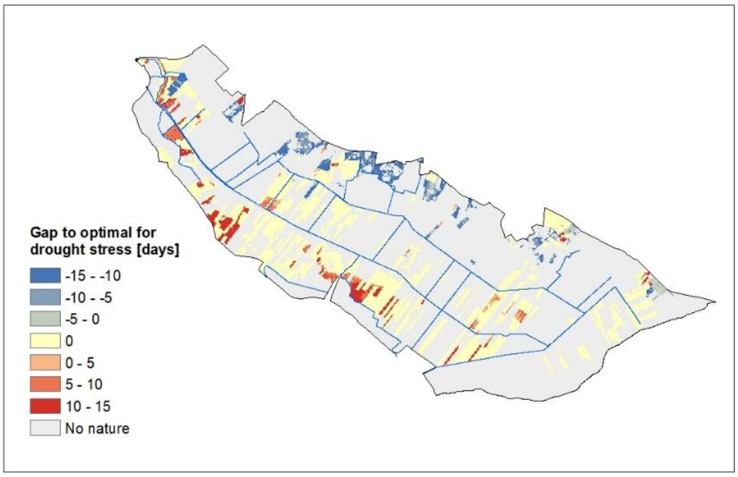
Outputs Watervision Nature (WVN Waternood), using UNATs (old nature targets) as land use input.

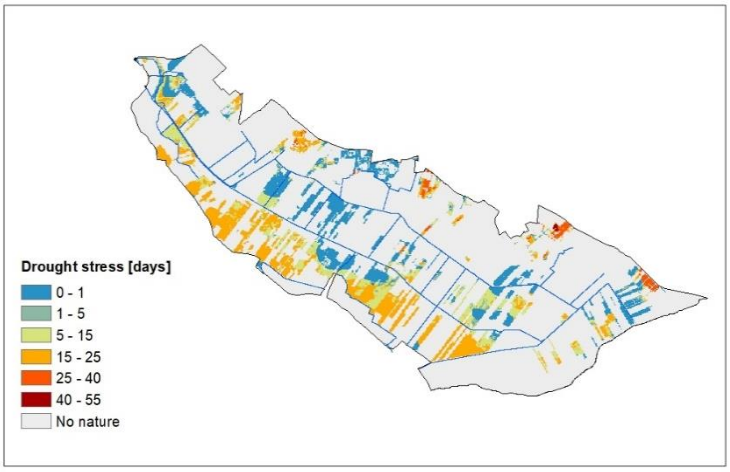


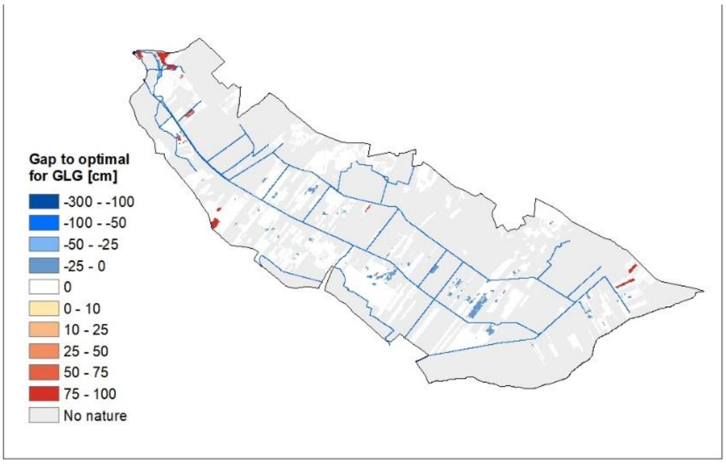


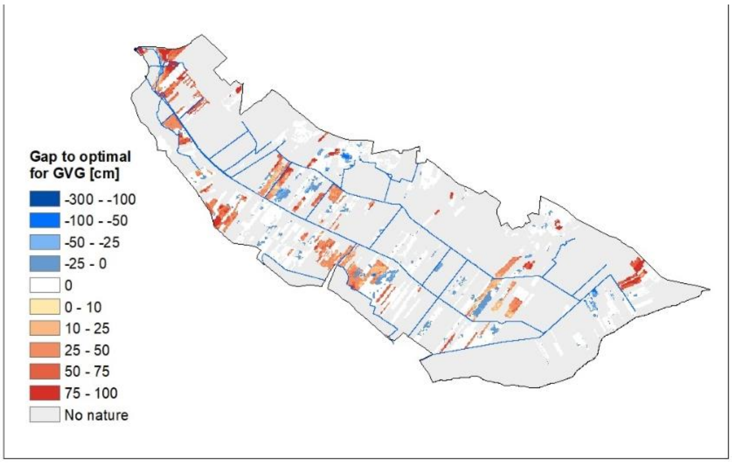






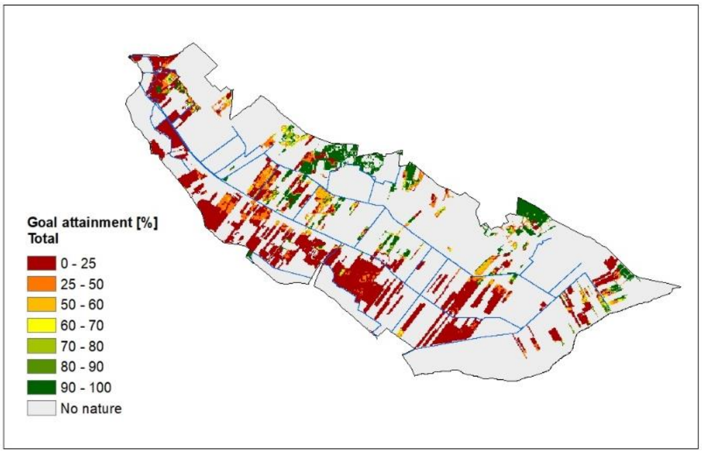


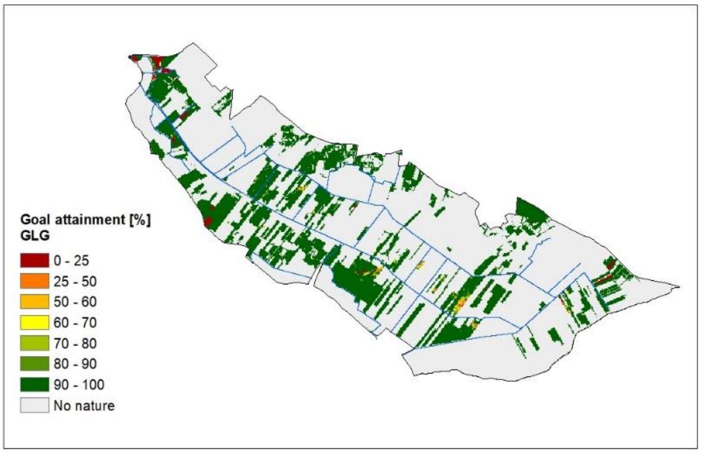


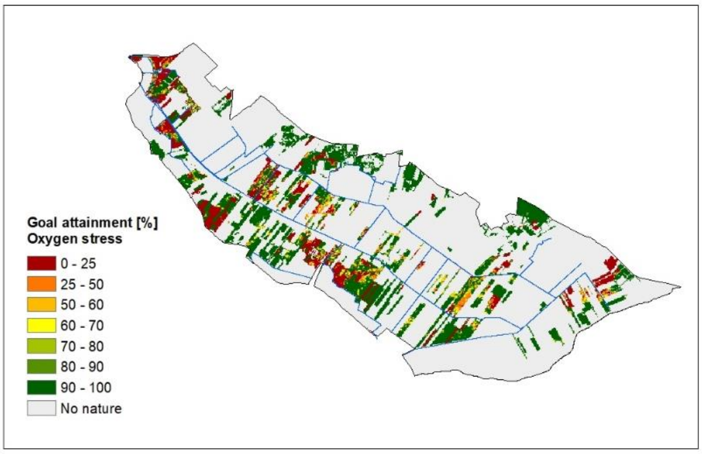


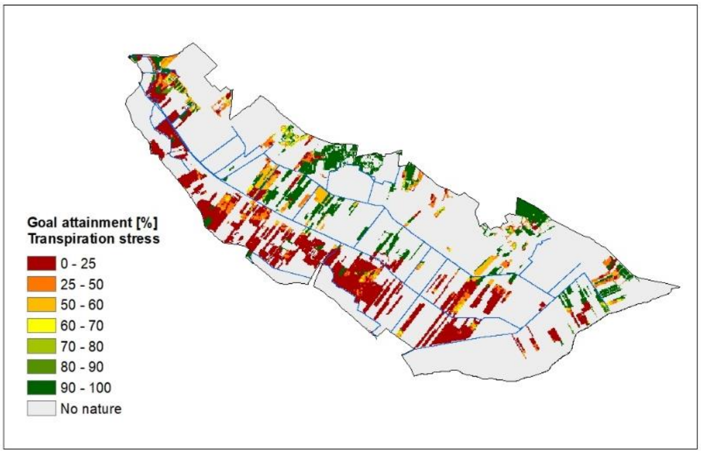
Appendix X

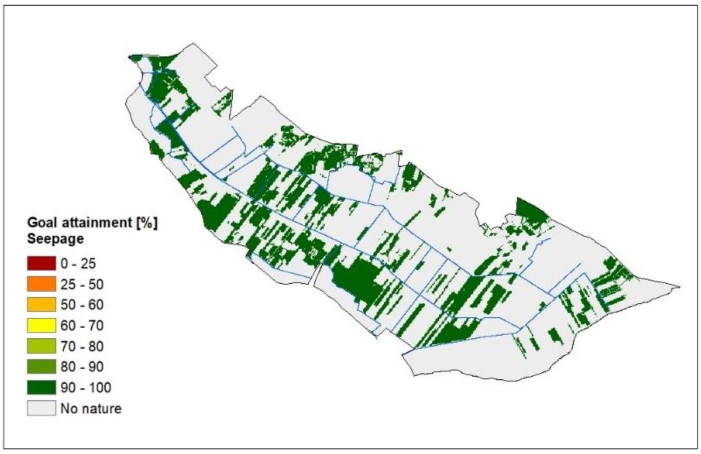
Outputs Watervision Nature (WVA Waternood+), using UNATs (old nature targets) as land use.

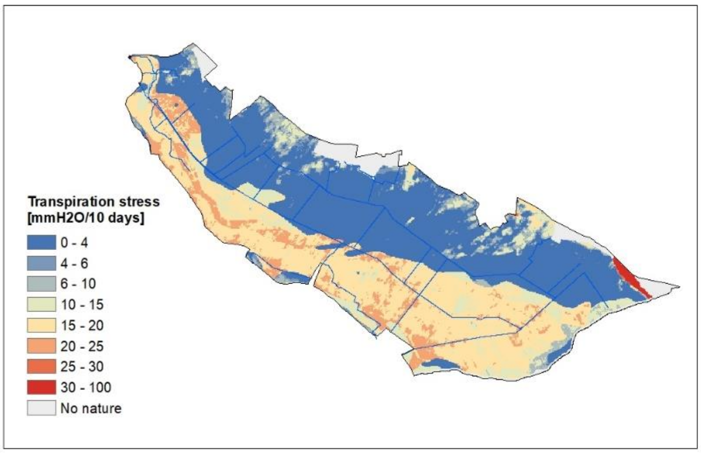


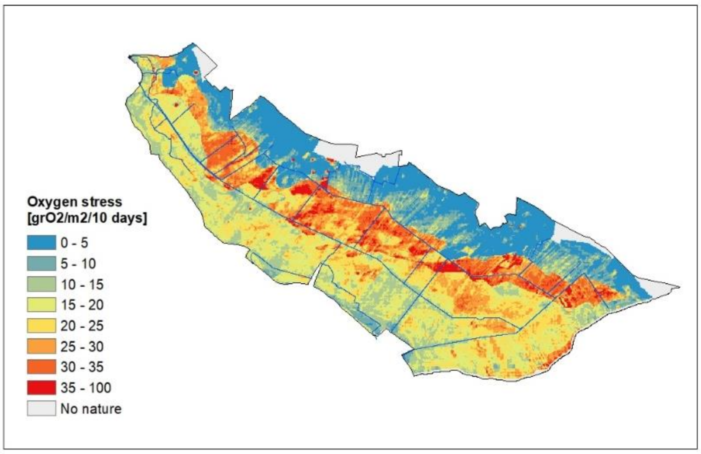






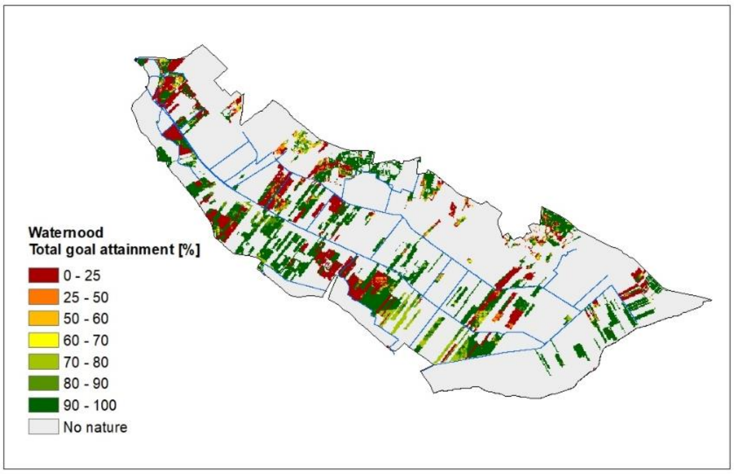


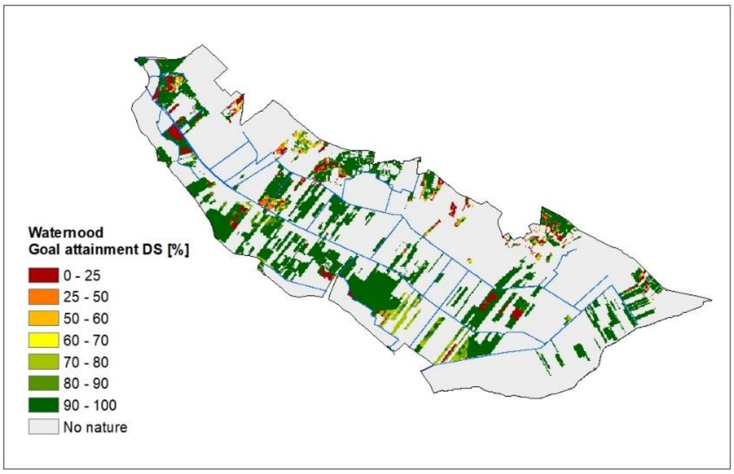


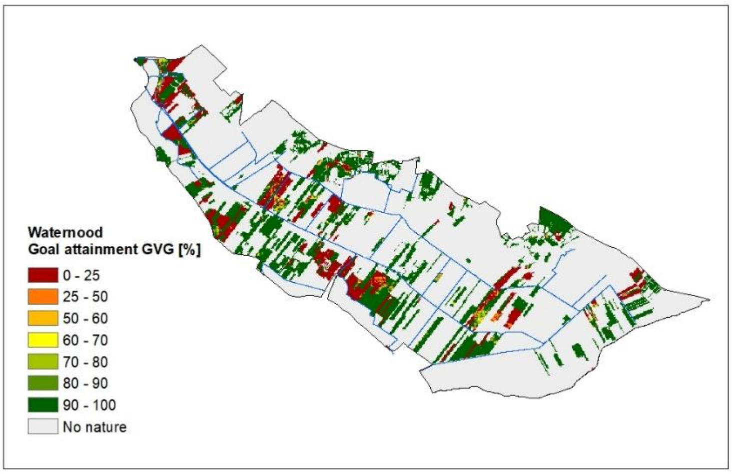


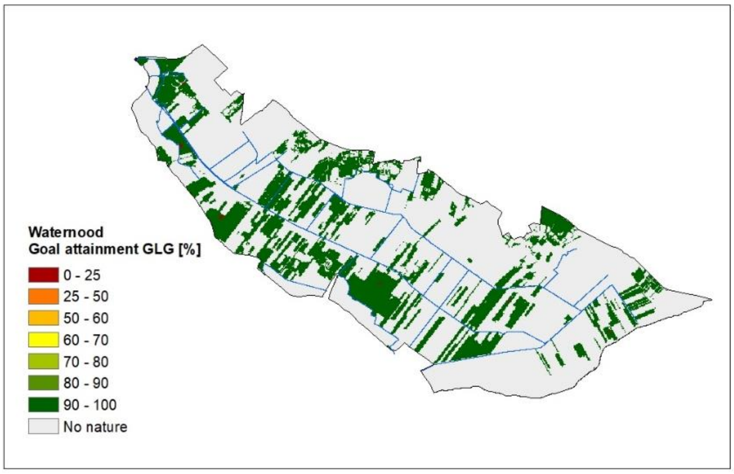
Appendix XI

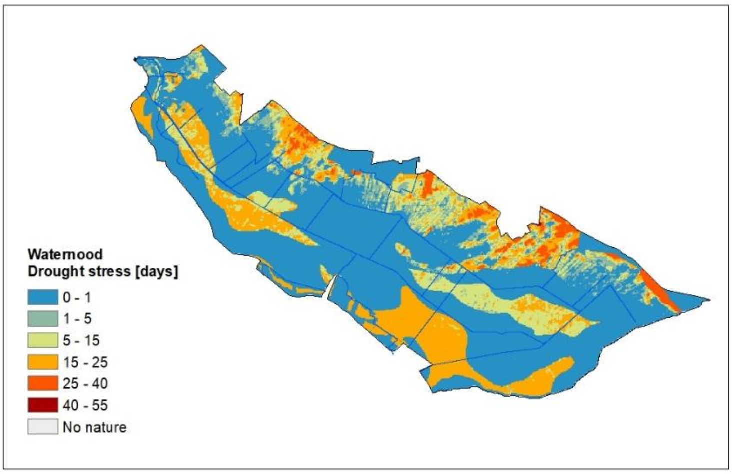
Outputs Waternood Nature (using UNATs)







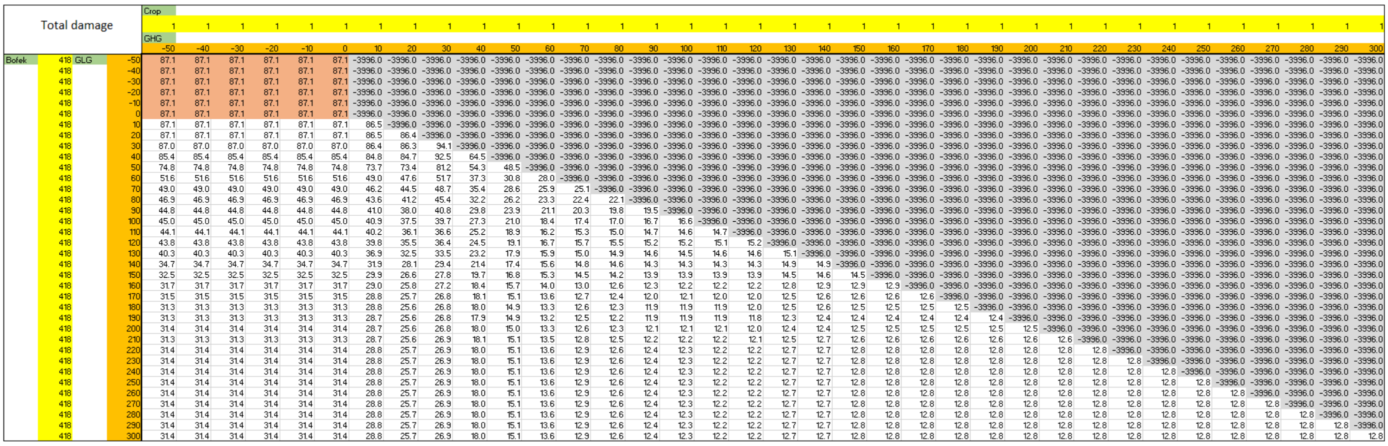




Appendix XII

Example of output matrix from sensitivity analysis.

1 = grass
418 = Heavy sabulous clay (marine and fluvial)

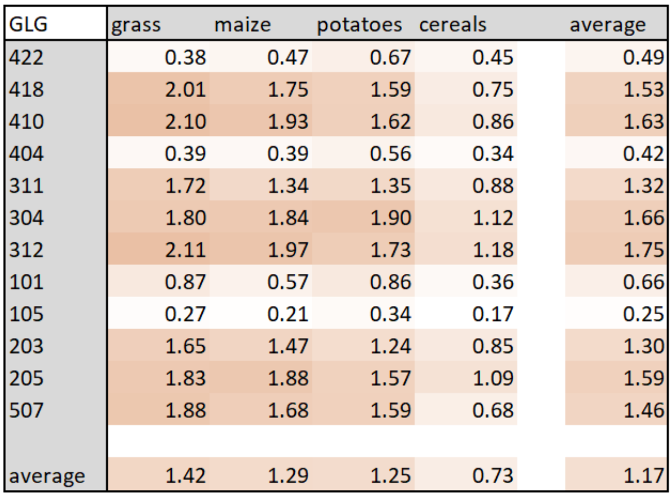


Total damage				Crop																																			
				1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
				GHG																																			
				-50	-40	-30	-20	-10	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200	210	220	230	240	250	260	270	280	290	300
Bofek	418	GLG	-50	87.1	87.1	87.1	87.1	87.1	87.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		-40	87.1	87.1	87.1	87.1	87.1	87.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		-30	87.1	87.1	87.1	87.1	87.1	87.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		-20	87.1	87.1	87.1	87.1	87.1	87.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		-10	87.1	87.1	87.1	87.1	87.1	87.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		0	87.1	87.1	87.1	87.1	87.1	87.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		10	87.1	87.1	87.1	87.1	87.1	87.1	86.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		20	87.1	87.1	87.1	87.1	87.1	87.1	86.5	86.4	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		30	87.0	87.0	87.0	87.0	87.0	87.0	86.4	86.3	94.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		40	85.4	85.4	85.4	85.4	85.4	85.4	84.8	84.7	92.5	64.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		50	74.8	74.8	74.8	74.8	74.8	74.8	73.7	73.4	81.2	54.3	48.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		60	51.6	51.6	51.6	51.6	51.6	51.6	49.0	47.6	51.7	37.3	30.8	28.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		70	49.0	49.0	49.0	49.0	49.0	49.0	46.2	44.5	48.7	35.4	28.6	25.9	25.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		80	46.9	46.9	46.9	46.9	46.9	46.9	43.6	41.2	45.4	32.2	26.2	23.3	22.4	22.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		90	44.8	44.8	44.8	44.8	44.8	44.8	41.0	38.0	40.8	29.8	23.9	21.1	20.3	19.8	19.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		100	45.0	45.0	45.0	45.0	45.0	45.0	40.9	37.5	39.7	27.3	21.0	18.4	17.4	17.0	16.7	16.6	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		110	44.1	44.1	44.1	44.1	44.1	44.1	40.2	36.1	36.6	25.2	18.9	16.2	15.3	15.0	14.7	14.6	14.7	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		120	43.8	43.8	43.8	43.8	43.8	43.8	39.8	35.5	36.4	24.5	19.1	16.7	15.7	15.5	15.2	15.2	15.1	15.2	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		130	40.3	40.3	40.3	40.3	40.3	40.3	36.9	32.5	33.5	23.2	17.9	15.9	15.0	14.9	14.6	14.5	14.6	14.6	15.1	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		140	34.7	34.7	34.7	34.7	34.7	34.7	31.9	28.1	29.4	21.4	17.4	15.6	14.8	14.6	14.3	14.3	14.3	14.3	14.9	14.9	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		150	32.5	32.5	32.5	32.5	32.5	32.5	29.9	26.6	27.8	19.7	16.8	15.3	14.5	14.2	13.9	13.9	13.9	13.9	14.5	14.6	14.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		160	31.7	31.7	31.7	31.7	31.7	31.7	29.0	25.8	27.2	18.4	15.7	14.0	13.0	12.6	12.3	12.2	12.2	12.2	12.8	12.9	12.9	12.9	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		170	31.5	31.5	31.5	31.5	31.5	31.5	28.8	25.7	26.8	18.1	15.1	13.6	12.7	12.4	12.0	12.1	12.0	12.0	12.5	12.6	12.6	12.6	12.6	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		180	31.3	31.3	31.3	31.3	31.3	31.3	28.8	25.6	26.8	18.0	14.9	13.3	12.6	12.3	11.9	11.9	11.9	12.0	12.5	12.6	12.5	12.5	12.5	12.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		190	31.3	31.3	31.3	31.3	31.3	31.3	28.7	25.6	26.8	17.9	14.9	13.2	12.5	12.2	11.9	11.9	11.9	11.8	12.3	12.4	12.4	12.4	12.4	12.4	12.4	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		200	31.4	31.4	31.4	31.4	31.4	31.4	28.7	25.6	26.8	18.0	15.0	13.3	12.6	12.3	12.1	12.1	12.1	12.0	12.4	12.4	12.5	12.5	12.5	12.5	12.5	12.5	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		210	31.3	31.3	31.3	31.3	31.3	31.3	28.7	25.6	26.9	18.1	15.1	13.5	12.8	12.5	12.2	12.2	12.2	12.1	12.5	12.7	12.6	12.6	12.6	12.6	12.6	12.6	12.6	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		220	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		230	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		240	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		250	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0	-3996.0	-3996.0	-3996.0
	418		260	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0	-3996.0	-3996.0
	418		270	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0	-3996.0
	418		280	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0	-3996.0
	418		290	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	-3996.0
	418		300	31.4	31.4	31.4	31.4	31.4	31.4	28.8	25.7	26.9	18.0	15.1	13.6	12.9	12.6	12.4	12.3	12.2	12.2	12.7	12.7	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8	12.8

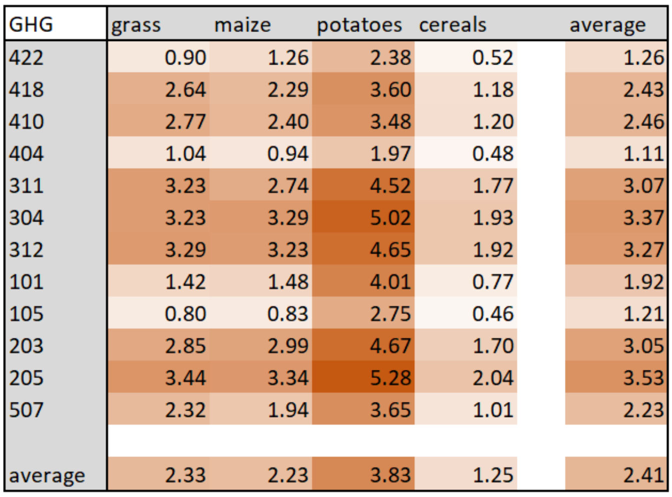
Appendix XIII

Sensitivity outputs showing average sensitivity per soil type, crop, GLG and GHG

Total damage

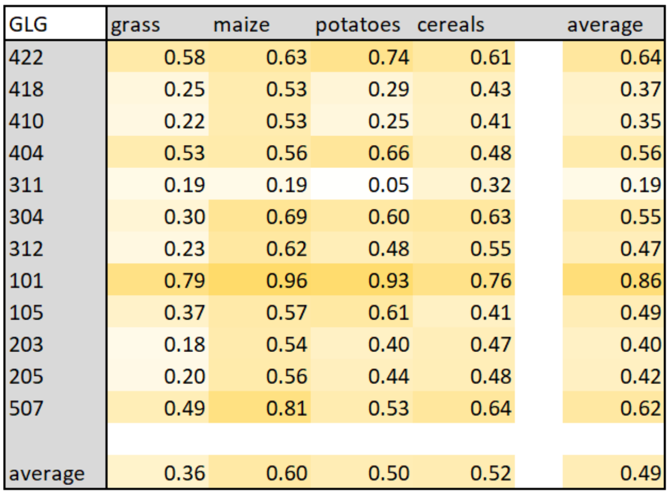


GLG	grass	maize	potatoes	cereals	average
422	0.38	0.47	0.67	0.45	0.49
418	2.01	1.75	1.59	0.75	1.53
410	2.10	1.93	1.62	0.86	1.63
404	0.39	0.39	0.56	0.34	0.42
311	1.72	1.34	1.35	0.88	1.32
304	1.80	1.84	1.90	1.12	1.66
312	2.11	1.97	1.73	1.18	1.75
101	0.87	0.57	0.86	0.36	0.66
105	0.27	0.21	0.34	0.17	0.25
203	1.65	1.47	1.24	0.85	1.30
205	1.83	1.88	1.57	1.09	1.59
507	1.88	1.68	1.59	0.68	1.46
average	1.42	1.29	1.25	0.73	1.17

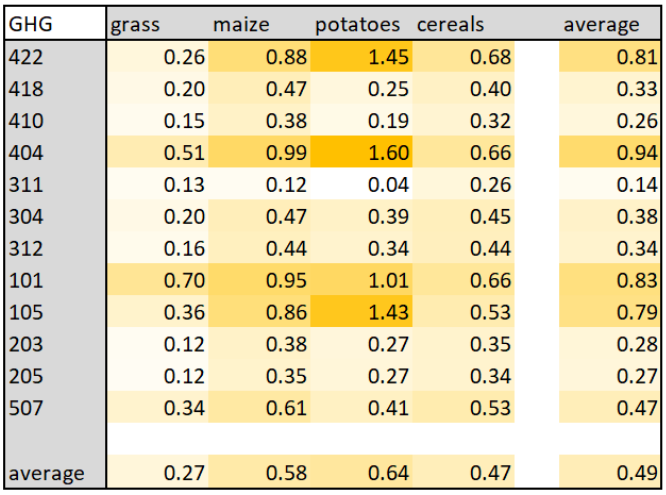


GHG	grass	maize	potatoes	cereals	average
422	0.90	1.26	2.38	0.52	1.26
418	2.64	2.29	3.60	1.18	2.43
410	2.77	2.40	3.48	1.20	2.46
404	1.04	0.94	1.97	0.48	1.11
311	3.23	2.74	4.52	1.77	3.07
304	3.23	3.29	5.02	1.93	3.37
312	3.29	3.23	4.65	1.92	3.27
101	1.42	1.48	4.01	0.77	1.92
105	0.80	0.83	2.75	0.46	1.21
203	2.85	2.99	4.67	1.70	3.05
205	3.44	3.34	5.28	2.04	3.53
507	2.32	1.94	3.65	1.01	2.23
average	2.33	2.23	3.83	1.25	2.41

Drought damage

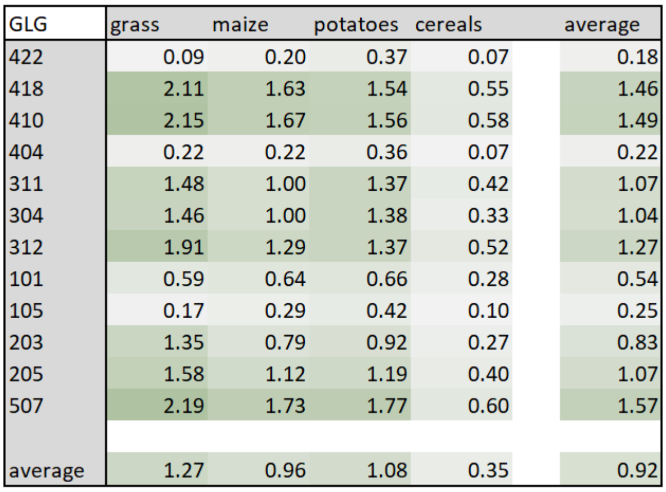


GLG	grass	maize	potatoes	cereals	average
422	0.58	0.63	0.74	0.61	0.64
418	0.25	0.53	0.29	0.43	0.37
410	0.22	0.53	0.25	0.41	0.35
404	0.53	0.56	0.66	0.48	0.56
311	0.19	0.19	0.05	0.32	0.19
304	0.30	0.69	0.60	0.63	0.55
312	0.23	0.62	0.48	0.55	0.47
101	0.79	0.96	0.93	0.76	0.86
105	0.37	0.57	0.61	0.41	0.49
203	0.18	0.54	0.40	0.47	0.40
205	0.20	0.56	0.44	0.48	0.42
507	0.49	0.81	0.53	0.64	0.62
average	0.36	0.60	0.50	0.52	0.49

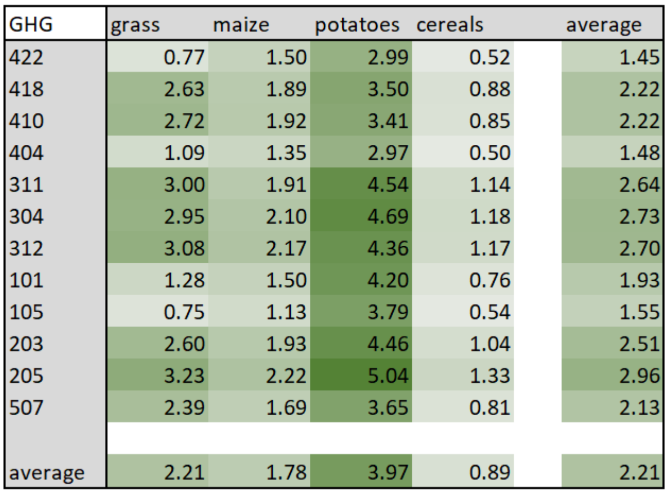


GHG	grass	maize	potatoes	cereals	average
422	0.26	0.88	1.45	0.68	0.81
418	0.20	0.47	0.25	0.40	0.33
410	0.15	0.38	0.19	0.32	0.26
404	0.51	0.99	1.60	0.66	0.94
311	0.13	0.12	0.04	0.26	0.14
304	0.20	0.47	0.39	0.45	0.38
312	0.16	0.44	0.34	0.44	0.34
101	0.70	0.95	1.01	0.66	0.83
105	0.36	0.86	1.43	0.53	0.79
203	0.12	0.38	0.27	0.35	0.28
205	0.12	0.35	0.27	0.34	0.27
507	0.34	0.61	0.41	0.53	0.47
average	0.27	0.58	0.64	0.47	0.49

Wet damage



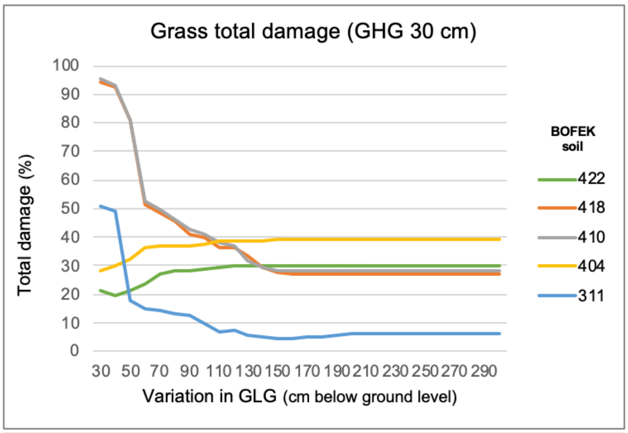
GLG	grass	maize	potatoes	cereals	average
422	0.09	0.20	0.37	0.07	0.18
418	2.11	1.63	1.54	0.55	1.46
410	2.15	1.67	1.56	0.58	1.49
404	0.22	0.22	0.36	0.07	0.22
311	1.48	1.00	1.37	0.42	1.07
304	1.46	1.00	1.38	0.33	1.04
312	1.91	1.29	1.37	0.52	1.27
101	0.59	0.64	0.66	0.28	0.54
105	0.17	0.29	0.42	0.10	0.25
203	1.35	0.79	0.92	0.27	0.83
205	1.58	1.12	1.19	0.40	1.07
507	2.19	1.73	1.77	0.60	1.57
average	1.27	0.96	1.08	0.35	0.92

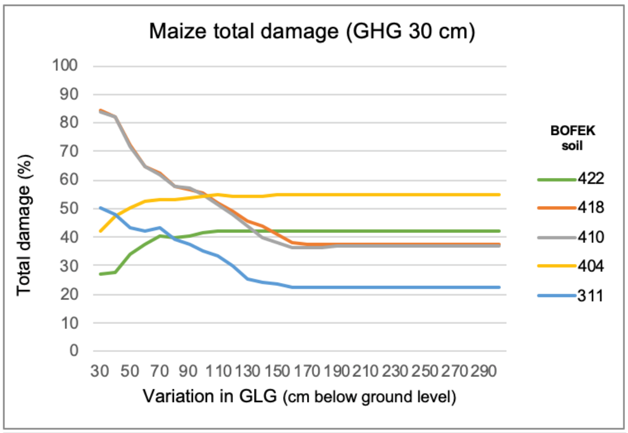


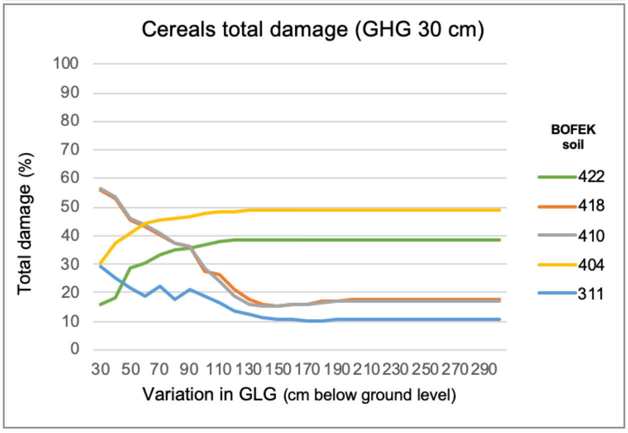
GHG	grass	maize	potatoes	cereals	average
422	0.77	1.50	2.99	0.52	1.45
418	2.63	1.89	3.50	0.88	2.22
410	2.72	1.92	3.41	0.85	2.22
404	1.09	1.35	2.97	0.50	1.48
311	3.00	1.91	4.54	1.14	2.64
304	2.95	2.10	4.69	1.18	2.73
312	3.08	2.17	4.36	1.17	2.70
101	1.28	1.50	4.20	0.76	1.93
105	0.75	1.13	3.79	0.54	1.55
203	2.60	1.93	4.46	1.04	2.51
205	3.23	2.22	5.04	1.33	2.96
507	2.39	1.69	3.65	0.81	2.13
average	2.21	1.78	3.97	0.89	2.21

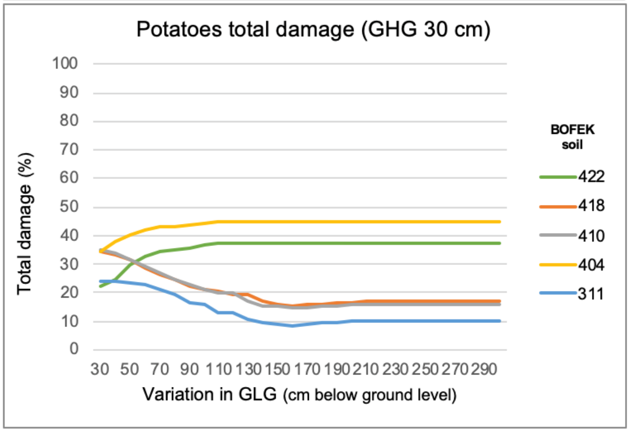
Appendix XIV

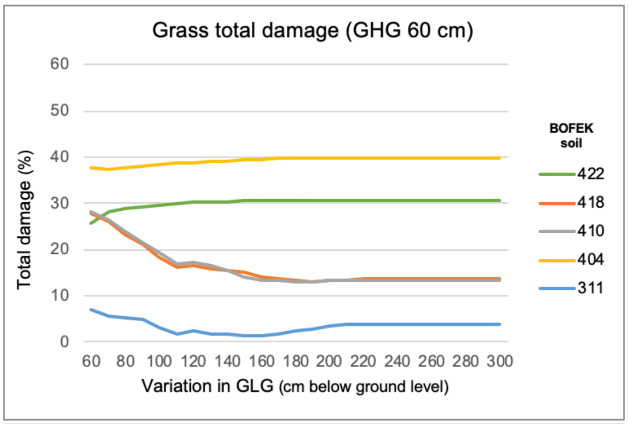
Sensitivity results showing how the total damage changes for a variation in GLG or GHG while keeping one constant groundwater level (GHG 30 cm, GHG 60 cm, GLG 100 cm and GLG 130 cm)

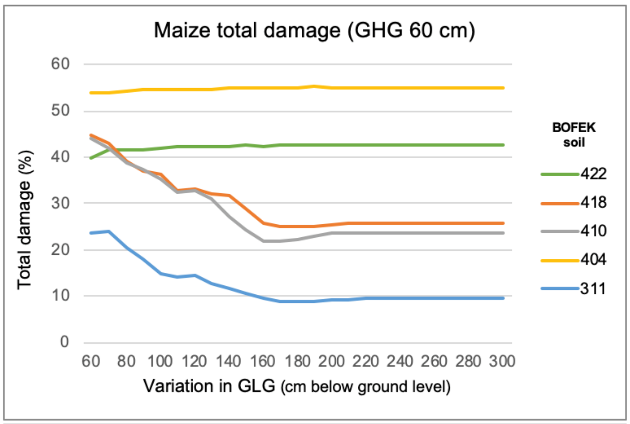


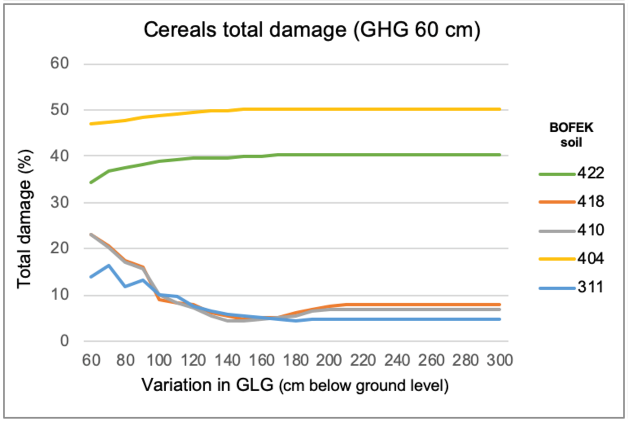


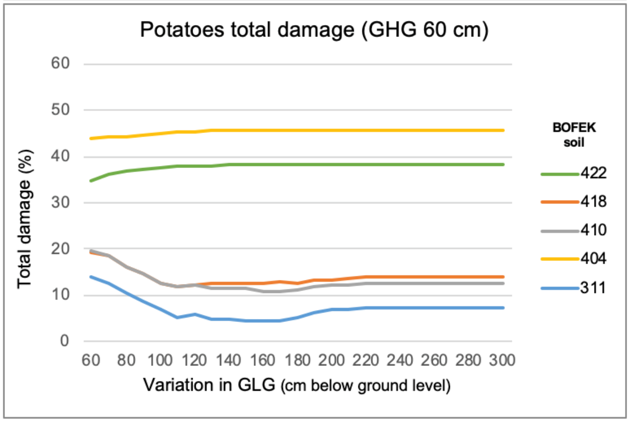


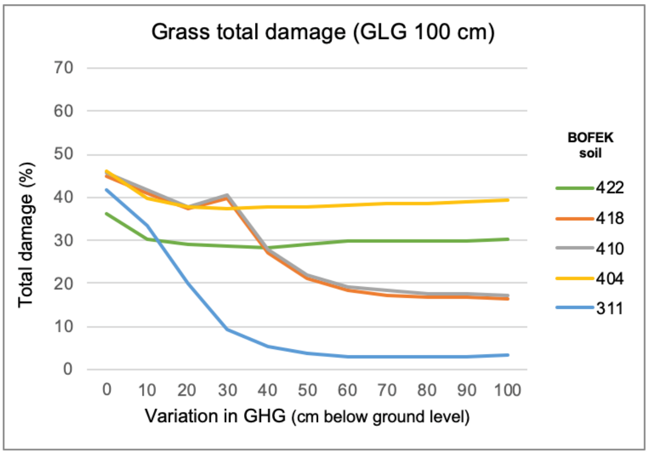


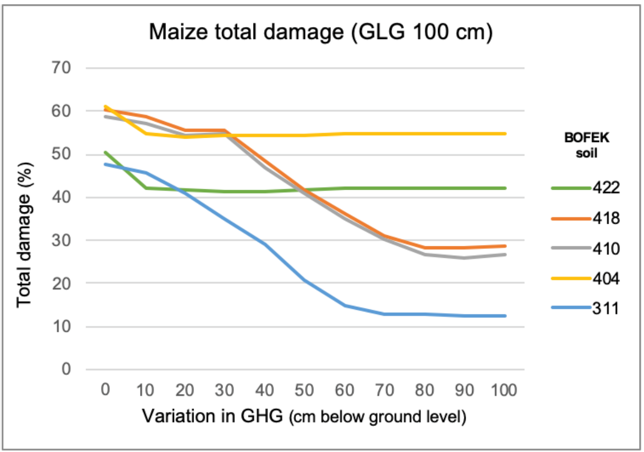


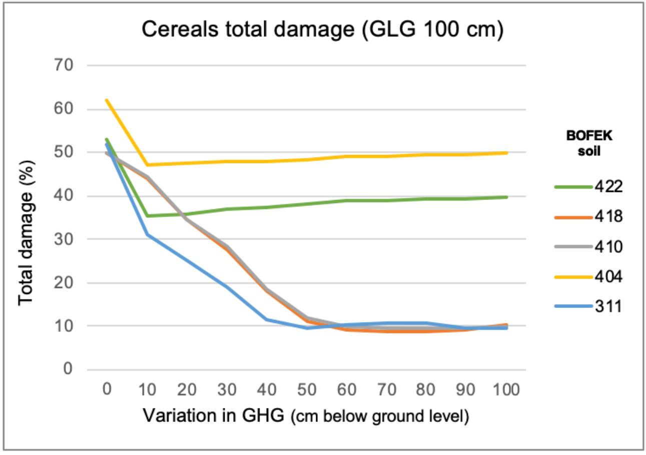


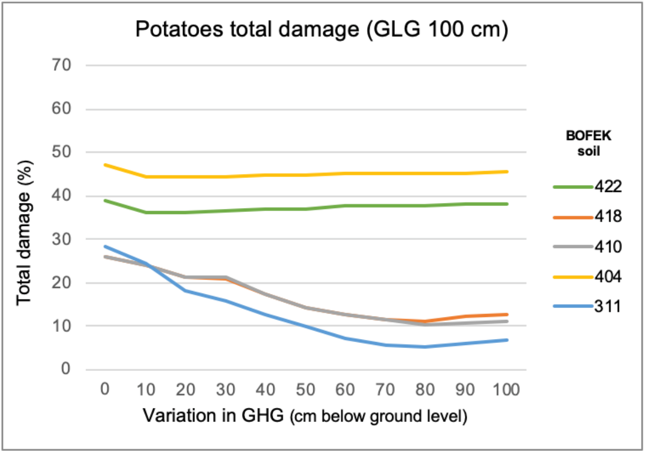


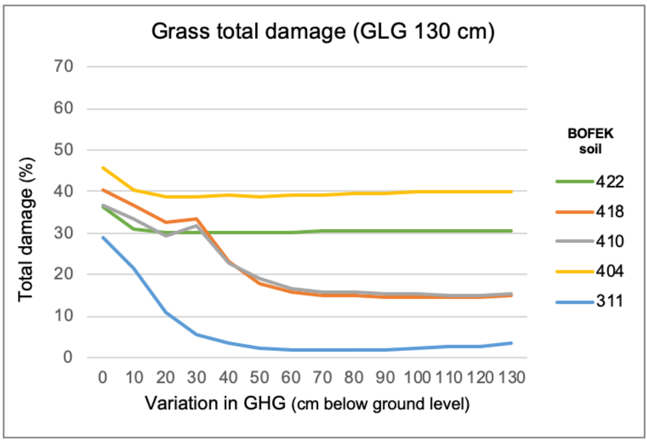


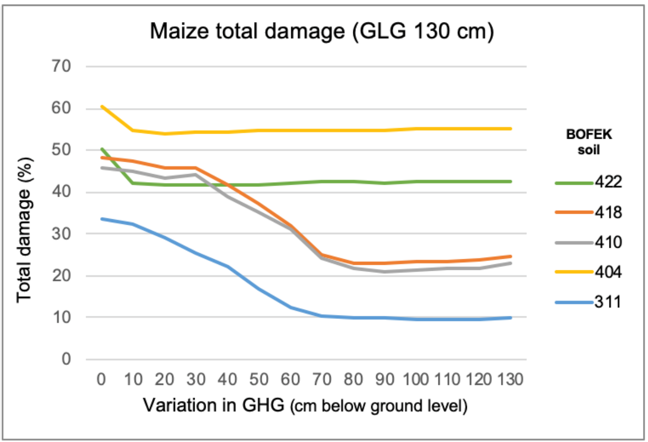

Grass total damage (GLG 100 cm)

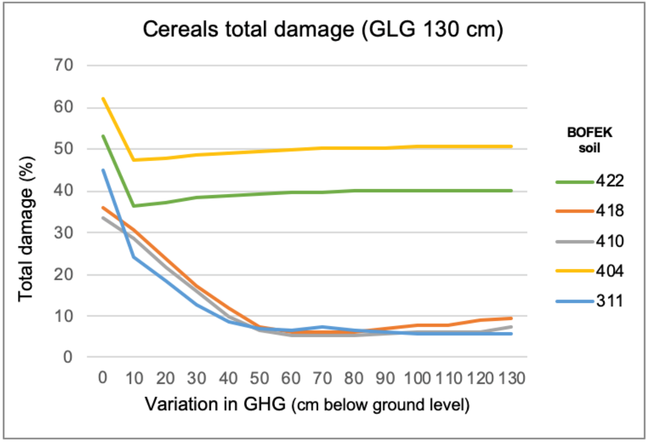

Maize total damage (GLG 100 cm)

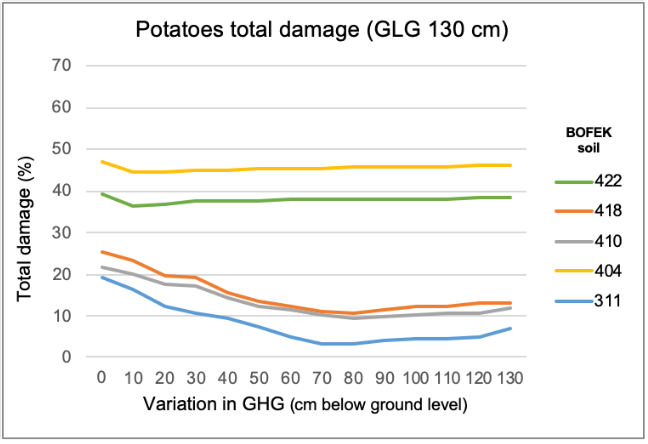

Cereals total damage (GLG 100 cm)


Potatoes total damage (GLG 100 cm)


Grass total damage (GLG 130 cm)


Maize total damage (GLG 130 cm)


Cereals total damage (GLG 130 cm)


Potatoes total damage (GLG 130 cm)