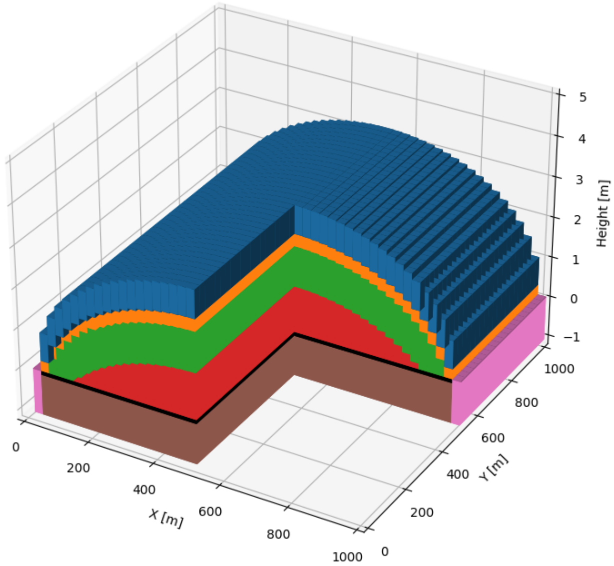
Towards a realistic representation of raised bog characteristics in a conceptual, regional groundwater model



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Towards a realistic representation of raised bog characteristics in a conceptual, regional groundwater model

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Abstract

Peat soils provide important ecosystem services, like carbon storage. Raised bog is a peat type that used to be present on a big scale in the Netherlands, but has almost completely disappeared. Nowadays, there is increasing attention for representing raised bogs in hydrological models in order to improve raised bog conservation and restoration. In this research, the effects on the modelled water balance of implementing two specific hydrological processes occuring in raised bogs are examined. Therefore, a conceptual 3D groundwater model of an undisturbed raised bog system was build using MODFLOW6 in iMOD Python. The two processes implemented are: peat volume change and an evapotranspiration - water table feedback. The results of the implementation of the peat volume change showed a decrease in water table depths and heads up to 70% and the implementation of the evapotranspiration - water table feedback showed a decrease in water table depths and heads up to 49%. However, the effects on the outgoing flux from the peat system towards the environment seem limited, which most likely is caused by a glyde layer at the base of the bog. Furthermore, the effects of the implementation of the processes seem most pronounced under dry circumstances, suggesting the processes become increasingly important when the peat system experiences drought. An important point of discussion is that the observed effects depend on the simulated landscape setting of the raised bog system. This landscape setting differs between bog systems. A sensitivity analysis is needed to determine how sensitive the observed effects are to changes in the landscape setting.

Contents

1 | Introduction

1.1 Context and motivation

Peatlands provide a vital ecosystem service by storing enormous amounts of carbon (Pörtner et al., 2022; Morris et al., 2022). They account for only 3% of the total terrestrial surface, but store about 21% of the total terrestrial soil carbon worldwide (Nijp, 2015; Leifeld and Menichetti, 2018; Grzybowski and Glińska-Lewczuk, 2020). Peatlands act like a carbon sink and can therefore have a net cooling effect on the global radiation balance (Wieder and Vitt, 2006; Dise, 2009; Morris et al., 2022; Pörtner et al., 2022).

Furthermore, there are indications that peatlands can reduce floods (Andersen et al., 2017; Acreman and Holden, 2013), as some peatlands have the capability to act like a sponge. The peatsoil is then storing water during wet periods and releasing it during dry periods. The peat matrix rises and falls in response to rainfall or a mild drought, maintaining a rather constant water level relative to the surface (Dise, 2009; Acreman and Holden, 2013; Waddington et al., 2015; Thorslund et al., 2017). This effect is called *peat volume change*, *bog-breathing*, or *mooratmung*. It is this sponge effect that can potentially contribute to flood and drought alleviation and the buffering of peak discharges (Acreman and Holden, 2013; Waddington et al., 2015; Thorslund et al., 2017; Nijp et al., 2021)

Despite their socio-ecological value, extensive areas of peat have been lost over the last 1000 years. Peatlands have been drained to convert it into agricultural land and big areas of peatland are excavated to be used as fuel and for horticulture (Dise, 2009; Pörtner et al., 2022). Next to this, global warming also forms a threat to peatlands as the frequency of droughts will increase, which induces lowering of the water table depth (Dise, 2009; Waddington et al., 2015; Pörtner et al., 2022). It should be emphasized that peatland hydrology is crucial for the biogeochemical processes happening in the peatland, and changes in the peatland hydrology can have disastrous consequences for the capability of peatlands to provide its ecosystem services (Waddington et al., 2010; Acreman and Holden, 2013; Waddington et al., 2015; Nijp et al., 2017; Thorslund et al., 2017; Andersen et al., 2017; Leifeld and Menichetti, 2018; Nijp et al., 2019; Pörtner et al., 2022). Indications were found of a reduction in compressibility under drier circumstances (Nijp et al., 2019), reducing the peat volume change magnitude. This low compressibility reduces the magnitude of the peat volume change, and thus the capability of the peatland to act like a sponge and to store water (Waddington et al., 2010; Nijp et al., 2019). This leads to relatively deep water tables, which may introduce the establishment of species that are adapted to deep water tables, but have lower compressibility, which further decreases the magnitude of the peat volume change (Nijp et al., 2019). Furthermore, disturbed peatlands may loose the ability to store water due to human-constructed macropores and pipe networks, if these pathways allow water to easily escape (Acreman and Holden, 2013).

To stop the degradation of peatlands and its ecosystem services, there is increasing attention in the restauration and conservation of peatlands via programmes such as Natura 2000 and EU-LIFE (Andersen et al., 2017; Grzybowski and Glińska-Lewczuk, 2020; Pörtner et al., 2022). Such restauration and conservation asks for effective governance and an effective decision-making process (Pörtner et al., 2022), for which hydrological models provide an useful tool (Nijp et al., 2017). However, it still remains unclear which peatland specific hydrological processes need to be included in such models, as these processes are complex and governed by a number of interacting feedbacks (Waddington et al., 2010; Morris et al., 2011, 2022). Nowadays, peatland water balances are often represented in a too simplified manner, thereby missing important feedbacks between peatland and the surroundings. Therefore, there is increasing attention for providing a satisfactory representation of peatland specific processes, without wasting costly computational time on superfluous processes (Morris et al., 2011; Waddington et al., 2015; Nijp et al., 2017, 2021).

In this research, peat-specific ecohydrological feedbacks will be implemented in a conceptual groundwater model in more detail than is commonly applied to regional groundwater models in the Netherlands, in order to contribute to a better representation of peatlands within groundwater models. More specifically, the aim of this study is to implement peat-specific storage behaviour and a peat-specific evapotranspiration feedback of an undisturbed raised bog in a conceptual groundwater model and determine the effects of this implementation on the modelled water balance. This way, this research will contribute to the ultimate goal of improving efficient decision-making and conservation of remaining peatland by improving groundwater models in their prediction of the impact of e.g. peat restoration measures, or water abstraction activities, on the water balance of the peat and its interaction with the surroundings.

The focus will be on raised bogs laying on sandy soils, as this landscape type historically occured on a big scale in the North, East and South-East of the Netherlands, before large-scale excavations occured (van Beek et al., 2015; Andersen et al., 2017). Nowadays, not much of these areas is left and the raised bog areas still remaining are seriously disturbed, despite being protected nature areas (van Beek et al., 2015; Andersen et al., 2017; Nijp et al., 2021). There is increased attention to gain a better understanding in raised bogs with the aim of protection these bogs. This research proposes to improve the representation of two different peatland-specific ecohydrological processes and feedbacks, namely: (1) peat volume change ("bog-breathing"), and (2) evapotranspiration. More about these feedbacks can be read in chapter 2

Peat volume change, or bog-breathing, is an important feedback mechanism for hydrological self-regulation in peatlands. It helps in maintaining a rather constant water level relative to the surface, making sure the peatmosses stay in close contact with the water table, protecting themselves against dry periods (Dise, 2009; Waddington et al., 2015; Howie and Hebda, 2018). In the research of Howie and Hebda (2018) it turned out this feedback is important for assessing the restoration success and storage capacity of raised bogs. The research of Nijp et al. (2017) showed peat volume change can significantly improve peatland model results when examining peatmoss drought stress. This raises the question what the effect will be on the model results of a groundwater model, when peat volume change is accounted for.

Evapotranspiration always is a large component on the water balance of peatlands and from previous research it turned out that the depth to the water table has a strong control on peatland evaporation (Lafleur et al., 2005). However current regional groundwater models only provide a very simplistic representation of evaporation responses to changing hydrological conditions (Nijp et al., 2021). Often, *potential* evapotranspiration (PET) is used as an estimator for actual evapotranspiration, as PET is much more easy to compute (Lafleur et al., 2005). However, this often gives an overestimation of the actual evapotranspiration (Lafleur et al., 2005). The research of Schouwenaars (1993) showed that peatland evapotranspiration is mainly influenced by the vegetation type growing in the peatland area. Waddington et al. (2015) describes how peat mosses growing on top of a peat soil increases its evaporative resistance, if the water table depth reaches a certain threshold value (see chapter 2 for more explanation on those feedbacks). Because of these dependencies, this research aims to also include a peat-specific evapotranspiration feedback in a groundwater model.

1.2 Research objective and research questions

The objectives of this study are to develop a conceptual 3D groundwater model of an *undisturbed* raised bog and implement a peat-specific storage behaviour and a peat-specific evapotranspiration feedback in this model, to determine the effects of this implementation on the modelled water balance. Gaining an understanding about these hydrological processes happening in raised bogs is important to show the original impacts of these processes on the water balance and to see the differences between the influence on the water balance of undistured and disturbed raised bogs. The model will be built in MODFLOW6, using the Python language and the Spyder environment. MODFLOW6 will be imported via the iMOD package, which is developed by Deltares. From these objectives, the following research questions are formulated:

1. How does peat volume change and peatland specific evaporation influence the water system of a raised bog?
2. To what extent is a simple, conceptual model capable of simulating the behavior of an undisturbed raised bog?
3. How can *peat volume change* be parameterized and incorporated into Modflow and how does this affect model simulations?
4. How can *peatland specific evaporation feedback* be parameterized and incorporated into Modflow and how does this affect model simulations?

1.3 Thesis outline

This thesis contains five chapters. In chapter 2, a theoretical framework is given with some background information about the relevant hydrological processes of a raised bog system and some information on the basics of modelling in MODFLOW. This should help the reader to better understand the Methodology. Chapter 3 describes the methods and the structure of the model. In chapter 4, the results of the described methods are given. Then chapter 5 describes the limitations of the current research as well as some recommendations for future research. The last chapter, chapter 6, provides the conclusions of the research.

2 | Theoretical Framework

Within intact peatlands, numerous of self-regulating feedbacks occur (Waddington et al., 2015), of which two were already shortly introduced in chapter 1. In this section, the self-regulating hydrological processes that are implemented in this model study, peat volume change and an evapotranspiration-water table depth feedback, are explained in more detail. Also, some explanation on modelling in MODFLOW is given in order to understand choices made in the modelling process better, and to become familiar with terms used in the Methodology chapter (chapter 3)

2.1 Hydrological processes in intact peatlands

Peatlands are terrestrial environments where, over the long term, year-round waterlogged conditions slow down plant decomposition, leading to the net primary production of organic matter exceeding the decomposition. This leads to a substantial accumulation of a deposit that is rich in incompletely decomposed organic matter, named *peat* (Wieder and Vitt, 2006; Dise, 2009; Grzybowski and Glińska-Lewczuk, 2020; IUCN, 2023). Via photosynthesis, plants growing in peatlands capture CO2 from the atmosphere. As those plants do not fully decompose, they do not release carbon and this carbon is thus stored from the atmosphere within peat soils (IUCN, 2023). Therefore, peatlands provide a vital ecosystem service by storing enormous amounts of carbon (Wieder and Vitt, 2006; Leifeld and Menichetti, 2018; Grzybowski and Glińska-Lewczuk, 2020; Pörtner et al., 2022).

2.1.1 Structure of a peatsoil

The formation of boreal peatlands can be initiatied via multiple processes, which all have in common that the peatland initiation process started under waterlogged conditions (Wieder and Vitt, 2006). Those waterlogged conditions can be due to, e.g., a regional water table rise or a shallow body of water gradually filling in with vegetation (Wieder and Vitt, 2006). The origin of this water influences the form and the hydrological functioning of the peatland (Wieder and Vitt, 2006). Therefore, a broad division between *fens* and *bogs* can be made. Fens are dominated by groundwater flows and therefore have both water and nutrients moving into and out of the ecosystem. Bogs are hydrologically 'isolated' and mainly rely on precipitation as the only water and nutrient input source (Lafleur et al., 2005). This study is about *raised bogs* (in Dutch: *hoogvenen*), thus a peatland type that mainly relies on precipitation for its water supply.

Due to its formation process, an intact raised bog has a specific structure. With an *intact*, or *undisturbed* raised bog is meant: a raised bog where the peat-forming vegetation has not been destroyed by reclamation or peat extraction. Such a system is characterized by a core of humified peat: the *catotelm*. The catotelm occupies most of the deposit and is overlain by a thin (25-50 cm) 'active' layer: the *acrotelm* in which most of the soil's biological activity is taking place. (Ingram, 1982). A vegetation type that often grows on top of the acrotelm are peatmosses (*Sphagnum*) (Ingram, 1982; Schouwenaars, 1993). For the catotelm to remain it's stability and to not decompose further, the water table must stay sufficiently close enough to the surface to remain perennial saturation of the entire depht of the catotelm. Therefore, the thickness of the acrotelm and the maximum water depth are roughly the same, seldom exceeding 50 cm.

Below the acrotelm, thus in the catotelm, the degree of humification of the plant litter increases with depth. This impacts the porosity and the hydraulic conductivity within the peat soil. The pores are increasingly becoming smaller, and the hydraulic conductivity is decreasing with depth (Waddington et al., 2015; Morris et al., 2022). At the bottom of the peatsoil, at the interface between the organic peat material and the mineral deposits, a *glyde layer* can be found. This is a (very) thin layer (around 10 cm) with high amounts of organic illuvium and therefore has a very low hydraulic conductivity and may act as a resistance layer (Wieder and Vitt, 2006; Sevink et al., 2014). Typical conductivities for such a glyde layer lay between 0.00005 and 0.008 md^{-1} (Sevink et al., 2014).

In Letts et al. (2000), the acrotelm and catotelm are divided into three different layers, namely a fibric, hemic and sapric layer. *Fibric peat* consists out of highly permeable, undecomposed organic soil and can be found near the surface of a peatland, therefore representing the acrotelm. *Sapric peat* is deeply humified peat with a very low hydraulic conductivity and can be found at the bottom of the peat soil, thus representing the glyde layer. *Hemic peat* is an intermediate peat type. The sapric layer and the hemic layer together represent the catotelm.

Zooming-out, it can be seen that the peatland itself is characterized by a mosaic of landforms. In the case of a raised bog area, hummocks and hollows of a raised bog can be recognized. *Hummocks* are laying slightly higher in the landscape than *hollows* (Wieder and Vitt, 2006).

2.1.2 Peat volume change

The previously mentioned peatmosses growing on peatsoils do not have roots and are therefore not capable of actively taking up water from their direct environment (Nijp, 2015). Therefore, under dry circumstances, the peatmoss strongly relies on capillary rise in the soil for their photosynthesis (Schouwenaars, 1993; Nijp, 2015). When peatland water tables become deeper than a certain threshold value, the ability of moss to conduct water upwards via capillarity will become greatly constrained, due to the porous soil structure. However, via *peat volume change*, or *bog-breathing*, a peat matrix is able to expand and contract in response to rainfall or mild drought. This enables the peat soil to maintain a rather constant water level relative to the surface, which helps the peatmosses to stay in close contact with the water table. (Dise, 2009; Waddington et al., 2015; Howie and Hebda, 2018) This feedback contributes to the "sponge effect" of peatlands and is also the reason why peat is called to be 'elastic' (Waddington et al., 2010).

This expanding and contracting of the peat matrix is mostly referred to as *swelling* and *shrinking* of the peat surface and is translated into the *specific storage* (Ss) (Waddington et al., 2010; Nijp et al., 2017). It can be due to the change in effective pore space after an increase or decrease of the head. The porous material is then decompressed respectively compressed, and this creates a smaller respectively larger pore space (Deltares, 2023b). Thus, this Ss depends on the elasticity of the aquifer and is therefore also called the *elastic storage*, or the *elastic storativity*. Although every soil type shows somewhat elasticity, peat soils show considerably more elasticity and therefore have much higher values for specific storage (Deltares, 2023b). Sandy soils, for example, have Ss values ranging from $1E^{-5}$ to $1E^{-4}$ m^{-1}, while peat soils can have values ranging from 0.02 to 0.27 m^{-1} (Nijp et al., 2019). In this study, these high values for specific storage are referred to as *peat volume change* (PVC).

Next to the specific storage, another storage term is relevant, namely: the *specific yield* (Sy). This describes the process of water draining out of a porous medium and being replaced by air (Nijp et al., 2017; Deltares, 2023b), or vice versa. Note that the dimensions of the Ss and Sy differ: Ss has a dimension of m^{-1} and Sy is dimensionless. Typical values for Sy range from 0.125 to 0.655, depending on the degree of decomposition of the plant litter (Letts et al., 2000).

2.1.3 Evapotranspiration feedback

As already mentioned, when water tables become deeper than a certain threshold value, the ability of the peatmoss growing on the peat soil to conduct water upwards via capillarity will become greatly constrained. For intact Sphagnum peatlands, this reduces the rate of water supply from the saturated zone and slows down evaporative losses (Waddington et al., 2015). The capillarity is constrained due to the fact that unsaturated hydraulic conductivity is a function of the volumetric water content: A lower volumetric water content will result in a lower hydraulic conductivity for a given water table (McCarter and Price, 2014). This water content in turn is controlled by the pore-size distribution of the peatsoil and thus by the degree of humification: in the upper layer, young, poorly decomposed peat is present which has an open structure and so a high hydraulic conductivity. However, as this poorly decomposed peat dries when the water table lowers, its volumetric water content and so also its unsaturated hydraulic conductivity declines rapidly as water is escaping from the large pore spaces. (Waddington et al., 2015). Also, the degree of decomposition of peat increases with depth, which leads to a weakening of the internal structure and so to closing and collapsing of pore spaces and pore spaces becoming icreasingly disconnected. This leads to a more narrower and tortuous pathhway for flow and thus to strong vertical gradients in the conductivity (Waddington et al., 2015; Morris et al., 2022). Because of these feedbacks, it is essential to include a feedback between peatland evapotranspiration and the water table depth in hydrological models (Lafleur et al., 2005).

2.2 Modelling in MODFLOW

2.2.1 Aquifer types

Aquifers can be divided in confined and unconfined aquifers. A *confined* aquifer is an aquifer that is saturated with water and overlain by a material that is (almost) not permeable. This causes the aquifer to be under pressure and as a consequence, the groundwater in the confined aquifer cannot rise as high as its corresponding hydrostatic pressure. When the aquifer is penetrated by a well, the water will rise above the top of the aquifer (Hölting and Coldewey, 2019; U.S. Geological Survey, 2023). In a confined aquifer, the only storage term that is relevant is the *specific storage* (Ss).

An *unconfined* aquifer is an aquifer in which the water level is open to the atmosphere via overlying permeable material. The upper water surface in an unconfined aquifer is the water table and because it is open to the atmosphere, it is at atmospheric pressure and is therefore able to rise and fall (Hölting and Coldewey, 2019; U.S. Geological Survey, 2023). In an unconfined aquifer, next to the Ss, another storage term is relevant, namely: the *specific yield* (Sy). As in confined aquifers, no air can enter the pore space, the Sy is only relevant in unconfined aquifers (Deltares, 2023b). For an unconfined aquifer, the total storativity is then represented by:

$$S = Sy + Ss * b \tag{2.1}$$

in which:

- $b =$ the aquifer thickness $[m]$.

2.2.2 Confined and convertible cells

In MODFLOW, confined systems are represented by *confined* cells. In confined cells, the transmissivity (k times the layer thickness: $T = kD$) is constant throughout the simulation, regardless of whether or not the calculated head in the cell is above or below the cell top elevation. Unconfined systems can be represented using *convertible* cells: cells in which the transmissivity varies during the simulation, based on the calculated head in the cell. The transmissivity is then computed during each solver iteration based on the saturated cell thickness (Langevin et al., 2017).

In Deltares (2023b) it is explained that it is general practice to set layers to be confined (*unconvertible*), even though they represent unconfined aquifers. The transmissivity of an unconfined aquifer is then approximated by a constant. This is done because a head-dependent transmissivity creates non-linearity, which is more difficult to solve than linear problems, and may result in non-convergence. To still be able to represent unconfined aquifers, containing a specific yield, this Sy can be represented via the Ss term. In order to do so, the Sy must be divided by layer thickness, as MODFLOW internally multiplies the entered number by layer thickness to compute storativity. It should also be noted that Sy should only be assigned to one single layer (the upper layer), as most of the storage occurs at the water table, where air is replaced by water. Thus, all layers except one must be given only a specific storage, representing only the compressibility of the aquifer and the water. If this is not done, a too high specific yield is simulated. (Deltares, 2023b)

3 | Methodology

In this chapter, the development of the model is explained. It should be noted that first a Base Model was built, which did not include peat volume change or an evapotranspiration feedback. This model was then expanded, in order to examine the effects of implementing peat volume change and an evapotranspiration feedback. This expanding of the model results in different model versions, of which a general overview is given in section 3.1. This gives the reader a general idea of the steps taken in this study. The section 3.2 gives a technical explanation of how the Base Model was built, and information on the input values that remained constant in further model versions, is given. Then, section 3.3 gives a description of the verification process of the model. In section 3.4 is explained how peat volume change was implemented and in section 3.5 is explained how the evapotranspiration feedback was implemented. Lastly, in section 3.6 is described how the effects of the implementation of peat volume change and an evapotranspiration feedback are evaluated.

3.1 General overview of model versions

The aim of this study is to implement peat volume change and a feedback between the evapotranspiration and the water table and determine the effects of this implementation on the modelled water balance. It is not the goal to build a model that comes close to reality, but to build a model in which the effects of the mentioned peat characteristics can be tested. In order to reach this goal, 11 versions of a simple, conceptual model were built with increasing complexity, see table 3.1.

Model type 1, referred to as Base Model (BM), was used for verification in order to obtain estimates of the parameter values used in the boundary conditions. Those parameter values could then be used in later, more complicated model versions. In this model type, peat volume change and an evapotranspiration feedback were not yet included. Also, no distinction was made yet between specific yield and specific storage: all layers got the same storage term. This was done for two reasons, namely: 1) in order to get an elementary understanding of the impact of the parameter values on the model behaviour 2) to be able to find general estimates of parameter values that can be used in later model versions, in which the peat volume change and an evapotranspiration feedback are implemented.

In this model version, the evapotranspiration package was not implemented yet and evapotranspiration was simplified via a recharge term: evapotranspiration measurements done in an undisturbed Swedish mire were subtracted from precipitation measurements done in the same undisturbed, Swedish mire. The choice for a Swedish mire was made, as data of groundwater tables of this mire were available to validate the model with. Such data of an undisturbed mire in the Netherlands was not available. In this simplification, positive recharge was treated as net groundwater recharge and negative recharge was treated as evaporating groundwater. The storage term was simplified by using only one storage term for the whole modelled soil depth and not making a distinction between Sy and Ss. Therefore, the system was assumed to be a confined aquifer.

In model types 2 to 5, the peat system was no longer treated as a confined aquifer anymore, but as an unconfined aquifer. Here, *unconfined* means that the cells are still *confined cells*, but the specific yield is taken into account via the specific storage, see chapter 2 for more explanation on this.

Model types 2 and 3, referred to as $Ss_{zero}ET_{off}$, $Ss_{low}ET_{off}$, $Ss_{med}ET_{off}$, $Ss_{high}ET_{off}$, were used to investigate the effects on the modelled fluxes when taking peat volume change into account. Model version $Ss_{zero}ET_{off}$ was used as a reference, as in this version the specific storage was set to zero for all layers. In those model versions, precipitation measured at the Eindhoven KNMI station was used as input and evapotranspiration was simplified via a recharge term, also based on measurements done at the Eindhoven KNMI station. Here, measurements of a Dutch meteorological

Table 3.1: The five different model versions. Note that the Sy is only added to the upper layer of a model version, as shown in table 3.3. The Ss is given for layer 1 to 6, from left to right. More explanation on the Ss and Sy is given in section 3.4.1

type	**version**	**Ss** $[m^{-1}]$	**Sy** $[m^{-1}]$	**evaporation type**	**(un)confined**	**cell type**
1	Base Model (BM)	0.2	0	Sweden data	confined	only confined
2	$Ss_{zero}ET_{off}$	0.0, 0.0, 0.0, 0.0, 0.0, 0.0	0.37	Eindhoven data	unconfined	only confined
3	$Ss_{low}ET_{off}$	0.02, 0.02, 0.02, 0.02, 0.02, 1.0E-5	0.37	Eindhoven data	unconfined	only confined
	$Ss_{med}ET_{off}$	0.125, 0.125, 0.125, 0.125, 0.125, 1.0E-5	0.37	Eindhoven data	unconfined	only confined
	$Ss_{high}ET_{off}$	0.27, 0.27, 0.27, 0.27, 0.27, 1.0E-5	0.37	Eindhoven data	unconfined	only confined
4	$Ss_{zero}ET_{on}$	0.0, 0.0, 0.0, 0.0, 0.0, 0.0	0.37	basic ET feedback	unconfined	only confined
5	$Ss_{low}ET_{on}$	0.02, 0.02, 0.02, 0.02, 0.02, 1.0E-5	0.37	basic ET feedback	unconfined	only confined
	$Ss_{med}ET_{on}$	0.125, 0.125, 0.125, 0.125, 0125, 1.0E-5	0.37	basic ET feedback	unconfined	only confined
	$Ss_{high}ET_{on}$	0.27, 0.27, 0.27, 0.27, 0.27, 1.0E-5	0.37	basic ET feedback	unconfined	only confined
6	$Ss_{zero}ET_{ssn}$	0.0, 0.0, 0.0, 0.0, 0.0, 0.0	0.37	seasonal ET feedback	unconfined	only confined
7	$Ss_{med}ET_{ssn}$	0.125, 0.125, 0.125, 0.125, 0125, 1.0E-5	0.37	seasonal ET feedback	unconfined	only confined

station were used, to account for Dutch circumstances. Measured Penman-Monteith evapotranspiration times a correction factor to correct for the vegetation type was subtracted from measured precipitation. Again, positive recharge was treated as netto groundwater recharge and negative recharge was treated as evaporating groundwater.

In model types 4 and 5, referred to as $Ss_{zero}ET_{on}$, $Ss_{low}ET_{on}$, $Ss_{med}ET_{on}$, $Ss_{high}ET_{on}$, a *basic evapotranspiration feedback*, was implemented using the *Evapotranspiration package* from MODFLOW. The *Evapotranspiration package* simulates the effects of plant transpiration and direct evaporation by removing water from the saturated groundwater regime. In these models, the evapotranspiration feedback is called *basic*, because a seasonal variation in the maximum evapotranspiration rate was not taken into account. Thus, with this package, evapotranspiration depends on the groundwater table, but not yet on a seasonality in the maximum possible evaporation. Note that from now on, in this report 'evapotranspiration' will be used instead of 'evaporation', similar to the name of the used MODFLOW package. Exceptions are made when talking about input data that reflects evaporation and not evapotranspiration, and in the research questions.

Model version $Ss_{zero}ET_{on}$ shows the effects when implementing only the basic evapotranspiration feedback, while model versions $Ss_{low}ET_{on}$, $Ss_{med}ET_{on}$, $Ss_{high}ET_{on}$ show the effects when both peat volume change as the basic evapotranspiration feedback are active. These model versions were used to see how peat volume change and the basic evapotranspiration feedback influence each other.

In model types 6 and 7, reffered to as $Ss_{zero}ET_{ssn}$ and $Ss_{med}ET_{ssn}$, the *Evapotranspiration package* is also implemented, but is also accounted for a seasonal variation in maximum evapotranspiration rate. Model version $Ss_{zero}ET_{ssn}$ shows the effects of only implementing the seasonal evapotranspiration feedback, while model version $Ss_{med}ET_{ssn}$ shows the effects when both a medium specific storage and a seasonal evapotranspiration feedback is implemented.

The first research question: *How does peat volume change and peatland specific evaporation influence the water system of a raised bog?* (1) was answered in the Theoretical Framework. The second research question: *To what extent is a simple, conceptual model capable of simulating the behavior of an undisturbed raised bog?* (2) was answered in the verification phase, by comparing the simulated groundwater tables in model version $Ss_{off}ET_{off}$ with measured water table depths from an undisturbed, Swedish mire. For answering the third research question: *How can peat volume change be parameterized and incorporated into MODFLOW and how does this affect model simulations?* (3), a comparison was made in modelled heads and fluxes from the peat system towards the environment of model types 2 and 3. The fourth research question: *How can a peatland specific evaporation feedback be parameterized and incorporated into MODFLOW and how does this affect model simulations?* (4), was also answered by a comparison in modelled heads and fluxes from the peat system towards the environment, but now of model types 4, 5, 6 and 7.

3.2 Model discretization

In this section is explained how the Base Model was discretized and which assumptions were done for the discretization. First, a general explanation on *packages* is given, then the structure of the model is described. Note that for further model versions, the same discretization was used, only some additional features were implemented to represent peat volume change and the evapotranspiration feedback.

MODFLOW packages

The model was constructed from scratch in MODFLOW 6, using the iMOD Python package. The term *package* can have multiple definitions, dependent on the context: in MODFLOW, a *package* is the part of the model that deals with a single aspect of simulation. In Python, a *package* is an extension that imports extra functionalities (Guta, 2022). The iMOD Python package is such an extension, importing MODFLOW functionalities. In this study, the term *package* refers to a MODFLOW package, which is included in iMOD Python. Below, an overview of the packages used for this study is given. Further in this chapter is explained how and for wat reasons these packages are used in this study. The used packages are:

- *Structured Discretization Package*
- *Initial Conditions Package*
- *General Head Boundary Package*
- *Drain Package*
- *Recharge Package*
- *Specific Storage Package*
- *Evapotranspiration Package* (only in model versions with an evapotranspiration feedback)

Note that the usage of these packages is explained in a different order than the above mentioned list with used packages.

Model grid and layer system

To set up the grid and the layer system of this model, the *Structured Discretization Package* was used. The model created for this study is a 3D model with a regional spatial scale, in order to model one undisturbed raised bog system. Based on dimensions of raised bogs given in Streefkerk and Casparie (1987) and Ingram (1982), the model has a width and a length of 1000 m and resulting in a surface of 1 km^2. This surface is constructed out of a structured grid of 1600 cells divided over 40 rows and 40 columns. Thus, every cell has a width and a length of $1000/40 = 25$ m.

Furthermore, the model has six layers, each varying in depth, in soil type and thus in hydraulic characteristics. The division of layers is based on a parameterization done in Letts et al. (2000) and on measurements done in the Degerö Stormyr mire (ICOS Sweden Network, 2023), which is an undisturbed raised bog in Sweden. As already explained in chapter 2, Letts et al. (2000) divides the acrotelm and catotelm into three different layers, namely a fibric, hemic and sapric layer. In this study, this division of Letts et al. (2000) over the division into an acrotelm and catotelm was used for parameterization. This was done, as in this study main interest is in the processes in the catotelm and the underlying soil, and not so much in the processes in the acrotelm. In Letts et al. (2000), detailed information on the hemic and sapric layer is given, together representing the catotelm. In this study, the upper four model layers represent hemic peat and the fifth horizon represents sapric peat, or a glyde layer (see Theoretical Framework. The peat system lays on a sandy soil, represented in the sixth model layer. Note that the hydrological characteristics of the fibric peat are neglected, as this type of peat is found in the unsaturated zone. In the unsaturated zone, groundwater flow does not occur and Darcy's Law, used by MODFLOW to describe the movement of groundwater, is

Table 3.2: Layer division of the model

layer	soil type	D_{start} $[m\ -mv]$	D_{end} $[m\ -mv]$	D_{total} $[m]$	kD $[m^2d^{-1}]$	average K_{sat} $[md^{-1}]$	model value $[md^{-1}]$
1	peat	0.3	0.7	0.4	1.723	2.462	2.46
2	peat	0.7	1	0.3	0.066	0.221	0.22
3	peat	1	2	1	0.009	0.009	0.01
4	peat	2	3	1	0.003	0.003	0.003
5	glyde	3	3.1	0.1	0.0001	0.0001	0.0001
6	sand	3.1	4.1	1	5	5	5

not valid (Langevin et al., 2017; Moene and Van Dam, 2014). Describing the movement of water in the unsaturated zone is possible using MODFLOW, but is out of the scope of this research. Thus, in this research, only the part of the profile that contributes to groundwater flow is used to calculate the layer-averaged K_{sat}. Furthermore, a Swedish mire was used, as detailed measurements with which the model could be verified were available for this region.

The depth of each model layer and the associated hydraulic conductivity is based on a parameterization function representing the saturated hydraulic conductivity (K_{sat}) of a peat profile in an undisturbed Sphagnum dominated peatland. This parameterization function is based on measurements done in the Degerö Stormyr mire (Sweden) (Van Westrene, 2017; Arens, 2017; ICOS Sweden Network, 2023): each depth-interval contains depths with K_{sat}-values in the same order of magnitude. Of those K_{sat}-values the average K_{sat}-value was determined and used as the K_{sat}-value for the whole layer. For the layer division and the K_{sat}-values, see table 3.2. Only for the first layer an exception on these calculations was made, as in the measurements, at this depth, the soil is unsaturated. In an undisturbed peat soil, this unsaturated zone is only up to 50 cm deep (Ingram, 1982). In this study, the top 30 cm was assumed to be the unsaturated zone and the hydraulic characteristics of this top 30 cm were neglected in calculating an average K_{sat}-value for the first layer. Thus, despite the first layer ranges from the surface to 70 cm below the surface, for the parameterization of the K_{sat}-value, only the K_{sat}-values of depth from 30 cm to 70 cm below the surface were considered, giving a kD-value valid for this 40 cm. This kD-value was then divided by 70 cm instead of 40 cm, to obtain a K_{sat}-value for the upper 70 cm.

For the sand layer, the soil characteristics of the soil underlaying a disturbed raised bog area in the Netherlands, were studied via Dinoloket (TNO Geologische Dienst Nederland, 2023). Mainly medium to fine sand was found here. So, for the K_{sat} of the sixth layer, a value in the range of medium to silty sand as given in Hölting and Coldewey (2019) was used (range from 34 to 0.9 md^{-1}).

At the bottom of the model, thus at the bottom of the sixth layer, a *No Flow Boundary* was assumed. This means no water can leave or enter the system via the bottom.

Ditches and surface mounding

In the first and last column of layer 6, ditches are implemented via the General Head Boundary Package (GHB package). In figure 3.2, the ditches at the sides of the model are clearly visible. The cells around the bog are inactive cells and drains are placed on top of the surface, see section 3.2. Therefore, water cannot flow over the surface, towards the ditches. As the ditches are only placed in layer 6, water in the upper four peat layers, flowing through the peat system, can only reach the ditches by first flowing through the glyde layer and through the sand layer.

The GHB package takes two variables: a conductance and a head. The conductance has a value of 10 m^2d^{-1}. This conductance is assumed to be a parameter and the value is found in the verification phase, which will be explained in section 3.3. The head is used as a reference value and therefore assumed to be 0m. This has to do with a typical characteristic of a raised bog, namely: the mounding surface Ingram (1982). By assuming the head of the ditches to be 0m, the mounding peat horizons all have positive heights and only layer five and six, which are not mounding, have negative heights.

Thus, in the first four layers, between the first and the last column, the model has a mounding surface. Note that in this model, hummocks and hollows, which occur at the bog surface, are neglected. The slope (and diameter) of the mounding surface depend on the multi annual average amount of precipitation in the raised bog area (Streefkerk and Casparie, 1987). In Ingram (1982) a raised bog system in Scotland with a diameter of 500 m and a mounding surface of 8 m is described. In Streefkerk and Casparie (1987) for a raised bog system in Sweden values for surface mounding up to 5 m and a diameter up to 1000 m are found. The model in this study uses values for the surface mounding from Streefkerk and Casparie (1987) at a diameter of 1000 m as reference. The mean annual precipitation in the area of Degerö Stormyr is 523 mm (ICOS Sweden Network, 2023). Following the study of Streefkerk and Casparie (1987), this would give a maximum surface mounding of around 2 m. However, the depth of the peat layer measured at Degerö Stormyr is generally between 3 and 4 m (ICOS Sweden Network, 2023). In this study, the maximum height of the mounding surface is therefore assumed to be in the range of 2 to 4 m. To obtain a height of the surface at every location in the x-direction, the formula of Bear was used (Bear, 1979):

$$h^2(x) = h_0^2 - \frac{h_0^2/h_0^L}{L}x + \frac{N}{K}(L-x)x \tag{3.1}$$

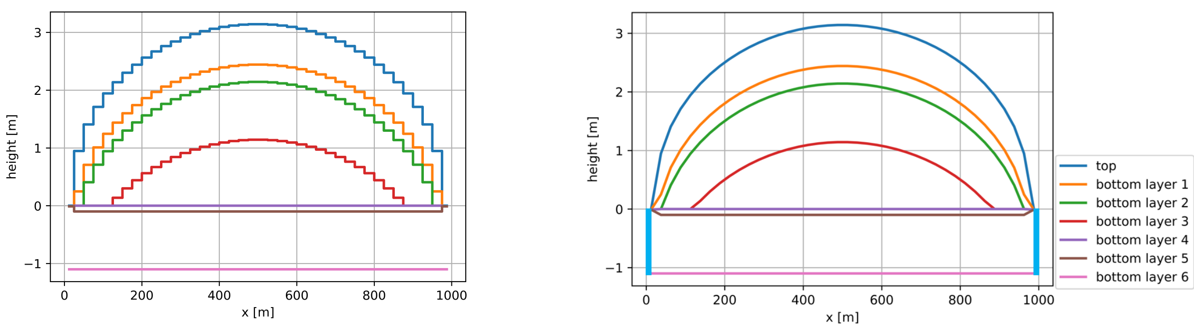
in which:

- h_0^2 = head at $x = 0$ $[m]$
- h_0^L = head at $x = L$ $[m]$
- L = distance between ditches $[m]$
- x = distance to left edge $[m]$
- N = recharge $[md^{-1}]$
- k = hydraulic conductivity $[md^{-1}]$

This formula is actually used to calculate groundwater mounding. To account for the unsaturated zone, 0.3 m of peat soil was added up to the outcome of Bear's formula. Using a hydraulic conductivity of 20 md^{-1} and a recharge of 523/2 (Bertil, A, 1980), this formula gives a maximum surface mounding of 3.14 m, which is in the range of 2 to 4 m and thus is a realistic value. The hydraulic conductivity used for this calculation is based on the K_{sat} measurements done by Van Westrene (2017); Arens (2017) in the Degerö Stormyr mire (ICOS Sweden Network, 2023). In figure 3.1 the layer system of the model is plotted.

Overland flow

Next to the General Head Boundary package draining water from the system, the *Drain Package* was used to place drains on top of the mounding surface to account for overland flow. These drains only become active when the peat



(a) (b)

Figure 3.1: The layer system plotted in two different ways. In a) the modelled layer system with discretization steps is given. In b) the modelled layer system without discretization steps is given, but with the modelled ditches drawn in the figure.

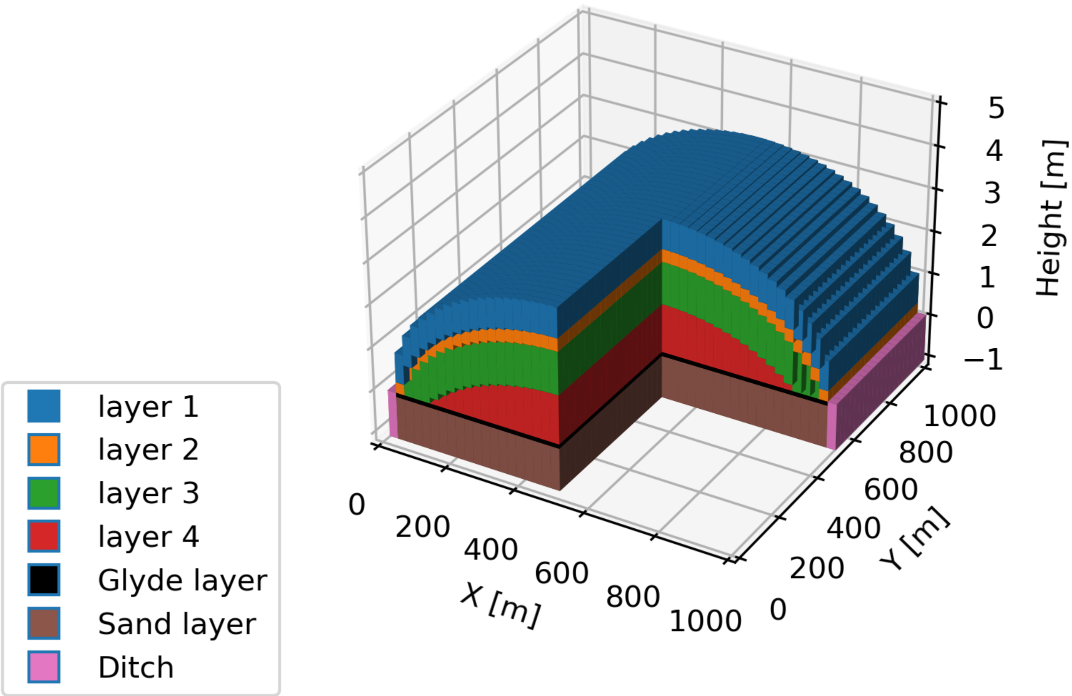


Figure 3.2: A 3D representation of the model (Van Heelsum, J, 2023).

system overflows and water starts accumulating on top of the surface. In reality, this water would runoff via the surface towards lower laying parts of the landscape. Using these drains, this surface runoff can be removed from the model and can be quantified.

These drains take a conductance and an elevation as variables. The elevation was set equal to the surface level, in order to place them on top of the mounding surface. Furthermore, just as in the GHB package, this conductance is assumed to be a parameter and is considered constant throughout this study. A value of 150 m^2d^{-1} for the conductance of the drains was found in the verification phase, see sections 3.3 and 4.1.

Initial Conditions

To run the model, initial heads needed to be assigned to every model cell via the *Initial Conditions Package*. For all model scenario's, the initial conditions for the heads were calculated using Bear's formula (equation 3.1), only no 30 cm was added up to the equation. The only exception was made for the heads in the sand layer, here the initial heads for all the cells was set to be 3 m.

3.3 Verification of the Base Model

The Base Model was used for verification, with the goal to find plausible estimates for the conductivity of the ditches and the drains. Those estimates could then be used in further model versions. In this section, the criteria on which the model verification is based is given. Next, the input data needed to start the verification with is given. The final paramater values used in further model versions can be found in section 4.1.

3.3.1 Verification criteria and method

Estimates of the conductance of the ditches and the drains were found by looking at the maximum height and depth of the modelled groundwater table and by comparing the modelled groundwater table dynamics with the groundwater table dynamics in the Degerö Stormyr mire. A parameter set was assumed to be valid if the simulated heads were in accordance with the in the Netherlands broadly accepted raised bog criteria as given in (Stuurman R, 2021), with a focus on the maximum depth of the groundwater table. This should not be more than 40 cm. Furthermore, as peatlands are wet ecosystems, the groundwater table may be located several centimeters above the peat surface for some time of the year (Nijp et al., 2017).

The verification was done by trial and error. An educated guess of the starting values for the storage, the conductance of the ditches and the conductance of the drains are given in the next section. Based on the simulated heads, those values were systematically adjusted and a new run was done until the verification criteria were met.

3.3.2 Input data

During the verification phase, precipitation and evaporation measured in the Degerö Stormyr mire was used. The measured evaporation was substracted from the measured precipitation and this outcome was used as *recharge* into the model. Positive recharge was then treated as net groundwater recharge and negative recharge was treated as evaporating groundwater.

For the storage term, a starting value to start the verification with had to be chosen. As in this phase, the model was assumed to be a confined system the storage term only consists out of a specific storage (see chapter 2 for a description of the Ss). In Kruseman et al. (1970) this specific storage is defined as:

$$Ss = \rho \cdot g \cdot (\alpha + \eta\beta) \tag{3.2}$$

- ρ = mass density of water $= 997 kg/m^3$
- g = gravitational acceleration $= 9.81 m/s^2$
- α = compressibility $[Pa^{-1}]$, can be defined as: the change in volume or strain induced in an aquifer (or aquitard) under a given stress:

$$\alpha = \frac{-dV_t/V_t}{d\sigma_e} \tag{3.3}$$

  - V_t = total volume of a given mass of material
  - $d\sigma_e$ = change in effective stress
- η = porosity
- β = compressibility of water = 4.4E-10 m^2N^{-1}

A value for compressibility, was calculated using Price (2003). In this paper, volume changes at disturbed and undisturbed peat sites were measured, and effective stresses were measured, but only at a disturbed peat site. As both peat volume change and effective stress is needed to calculate the compressibility, the choice was made to use the values given in Price (2003) of a disturbed peat site. In this paper, with *disturbed* is meant: a peat site that was drained and of which the upper 0.35 to 0.6m of peat was removed by block cutting with heavy machines. Afterwards, the site was abandoned for seven years, before the measurements were done. The found values were: a peat volume change of 1% at 100cm depth and a change in effective stress of around 1000 Pa. With this data, the α can be calculated:

$$\alpha = \frac{-0.01}{1000} \tag{3.4}$$

For the porosity, a value of 0.88 was assumed, found in (Letts et al., 2000). However, due to the small value of β, the $\eta\beta$ term is almost negligable.

Based on these assumptions, the Ss resulted to be 0.097 m^{-1}. This value was used as a starting value for the model verification. The starting value for the conductance of the ditches and the drains both were based on a resistance of 100 days.

3.4 Parameterization peat volume change

As already explained in the Theoretical Framework, the peat volume change (PVC), or elastic storativity can be implemented via the specific storage (Ss). With model types 2 to 5 (see table 3.2), the effects of implementing specific storage on the modelled heads and fluxes was tested. These effects were evaluated for four different Ss scenario's. These four different Ss scenario's differ from no Ss to a high Ss and are explained in more detail later in this section. In model types 2 and 3, a simplified evapotranspiration was assumed, which is different than the measured ET used in the verification phase and is also different from the evapotranspiration feedback. How this simplified evapotranspiration is obtained, is explained in section 3.4.2.

3.4.1 Scenario's

To test the influence of peat volume change on the modelled heads and the fluxes to the environment, four different scenario's were set up, in which the Ss varied. All the scenario's assume the system to be unconfined and thus a Sy was added to the upper layer, for which a value of 0.26 (dimensionless) was found in Letts et al. (2000). This value had to be converted in a value per meter. As the upper layer has a thickness of 70 cm, the Sy became: $0.26/0.7 = 0.37$m^{-1} . In the first scenario, the Ss was assumed to be 0, thus only a Sy-term in the upper layer represented the soil's storage capacity. In the second scenario, a Ss of 0.02 m^{-1} was assumed, in the third scenario a Ss of 0.125 m^{-1} and in the fourth scenario a Ss of 0.27 m^{-1} was assumed. Those values are based on Nijp et al. (2019). In scenario two till four, for the underlaying sand layer, a value of 1.0E-5 m^{-1} was assumed, based on Deltares (2023b). The scenario's are referred to as respectively, Ss_{zero}, Ss_{low}, Ss_{med} and Ss_{high} (for which 'med' stands for 'medium'). In table 3.3 an overview of the used values for the storage terms is given.

3.4.2 Simplified evapotranspiration

As meteorological input for model types 2 to 5, measurements of rainfall and potential Penman-Monteith evaporation of a KNMI-station in Eindhoven were used (table 3.1). The years of which those measurements are used are mentioned in section 3.6. In order to obtain a netto recharge, the measured potential Penman-Monteith evapotranspiration was multiplied with a correction factor of 0.5, coming from Lafleur et al. (2005). This 0.5 was a mean ET/PET ratio for all days during the growing season, with growing season defined from 1 May to 31 October. In this study no distinction for the evapotranspiration between growing season and winter time was made. This assumption was done for simplification reasons, because the growing season in the Netherlands may also be assumed to start earlier than the first of May already, and because in this study there is specific interest in droughts.

Table 3.3: Values for Ss and Sy used in the different model runs

layer	**D_{end}**	**Ss_{zero}**			**Ss_{low}**			**Ss_{med}**			**Ss_{high}**		
		Sy	**Ss**	**Sy+Ss**	**Sy**	**Ss**	**Sy+Ss**	**Sy**	**Ss**	**Sy+Ss**	**Sy**	**Ss**	**Sy+Ss**
$[-]$	$[m]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$	$[m^{-1}]$
1	0.7	0.37	0	0.37	0.37	0.02	0.39	0.37	0.125	0.495	0.37	0.27	0.64
2	1	0	0	0	0	0.02	0.02	0	0.125	0.125	0	0.27	0.27
3	2	0	0	0	0	0.02	0.02	0	0.125	0.125	0	0.27	0.27
4	3	0	0	0	0	0.02	0.02	0	0.125	0.125	0	0.27	0.27
5	3.1	0	0	0	0	0.02	0.02	0	0.125	0.125	0	0.27	0.27
6	4.1	0	0	0	0	1.00E-05	1.00E-05	0	1.00E-05	1.00E-05	0	1.00E-05	1.00E-05

3.5 Parameterization of the evapotranspiration feedback

To account for the evapotranspiration feedback that occurs in raised bog areas, the *Evapotranspiration Package* (EVT package) was implemented into the model. With this package, the evapotranspiration became dependent on the groundwater table. The EVT package uses *segments*, which represent intervals between portions of the *extinction depth* in which only a portion of the maximum evapotranspiration rate takes place. The *extinction depth* is the depth of the groundwater table at which no water is evaporated from the groundwater anymore. Thus, for every segment a *proportion rate* and a *proportion depth* is given. The *proportion rate* [-] is the proportion of the maximum evapotranspiration rate at the bottom of a segment and the *proportion depth* [-] is the proportion of the extinction depth at the bottom of a segment. (Deltares, 2023a; Langevin et al., 2017). Furthermore, the EVT package needs an *elevation surface* [m], which is the height or the depth where the evapotranspiration rate equals the maximum evapotranspiration rate.

In this study, two different approaches to use the *Evapotranspiration Package* were used. First, seasonal variation in the maximum evapotranspiration rate was not taken into account and thus this maximum evapotranspiration rate was assumed to be constant. This was done for all four specific storage scenario's and represented by model versions $Ss_{zero}ET_{on}$, $Ss_{low}ET_{on}$, $Ss_{med}ET_{on}$ and $Ss_{high}ET_{on}$. In this first approach, a maximum evapotranspiration rate of 3 mmd^{-1} was used, coming from Lafleur et al. (2005).

In the second approach, seasonal variation in the maximum evapotranspiration rate was taken into account using the following sinus-function:

$$EVT_{max}(x) = \frac{1}{2}\alpha \cdot sin(\frac{2\pi}{365}x) + \frac{1}{2}\alpha \tag{3.5}$$

where:

- EVT_{max} = the maximal evapotranspiration rate on day x $[md^{-1}]$
- x = the day number, with day 0 being the start of the hydrological year $[d]$
- $\alpha = 0.003[mmd^{-1}]$ = highest maximum evapotranspiration rate during a year

In this approach, the highest maximum evapotranspiration rate was assumed to be 3 mmd^{-1}. However, opposed to the approach without seasonal variation, the highest maximum evapotranspiration now varied through the year. In figure 3.3 is shown how the maximum evapotranspiration rate varied through the years.

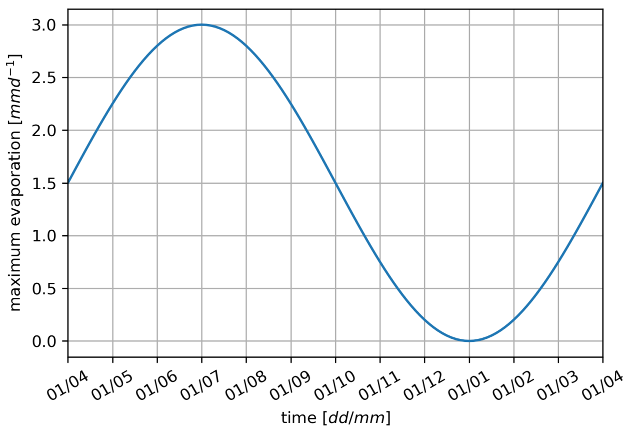


Figure 3.3: Maximum evapotranspiration rate plotted over one hydrological year. At the 1st of July, the rate is at its maximum, namely 3 mmd^{-1} and at the 1st of January, the rate is at its lowest, namely 0 mmd^{-1}

Furthermore, in both situations an extinction depth of 60 cm below the surface was used, coming from In progress, Nijp, J.J. Huseby-Karlsen, R, Nilsson, MB, Bishop, K (2023). From this source, also water table break points were taken and used to calculate the proportion depth. This was done by dividing the water table break point by the extinction depth. For the water table break points, the proportion depths and the proportion rates see table 3.4. For a visual representation of the values in this table, see figure 3.4. Note that for both evapotranspiration feedbacks, the same precipitation input data was used.

Table 3.4: The proportion depths and proportion rates per segment

segment [-]	water table break points [m]	proportion depth [-]	proportion rate [-]
1	-0.030	0.050	0.944
2	-0.093	0.154	0.651
3	-0.242	0.404	0.536
4	-0.367	0.612	0.116
5	-0.436	0.726	0.019

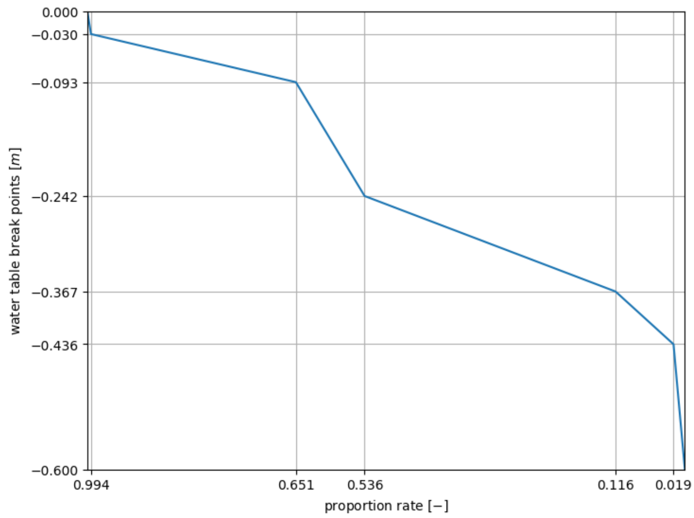


Figure 3.4: Water table break points $[m]$ and proportion rates $[-]$. Note that the x-axis goes from 1 to 0, reflecting a decrease in proportion rate with depth. The lines between the break points represent the segments used by MODFLOW.

3.6 Evaluating the effects of peat volume change and an evapotranspiration feedback

To test the effects of the implementation of peat volume change and the evapotranspiration feedback, the modelled heads and the average flow from the glyde layer towards the sand layer were evaluated over three different weather scenarios in terms of the amount of precipitation: a dry year, an intermediate year and a wet year. Also, the average flow from the glyde layer towards the sand layer was evaluated for the summer and winter months separately in each year. This average flow from the flyde layer towards the sand layer is interpreted as a flux to the environment of the bog system, as its water leaving the bog system. Thus, the underlying sand layer is interpreted as the environment. For the different storage terms representing peat volume change, comparisons between the different storage terms were made, as well as comparisons within the same weather scenarios.

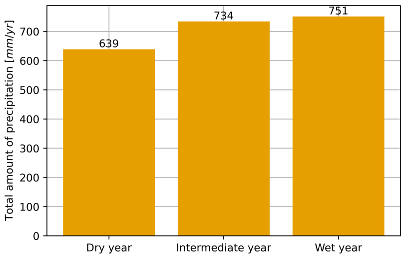
Defining a dry, intermediate and wet year was done using yearly summaries of the KNMI of the amount of precipitation. Those summaries indicated that the hydrological years 2018/2019, 2017/2018 and 2021/2022 were respectively dry, intermediate and wet years, in comparison with each other (KNMI, 2023b,c,d). So, for clarity, the three different years that were used in this study to test the effects are:

- *dry year*: 2018-04-01 till 2019-03-01
- *intermediate year*: 2017-04-01 till 2018-03-01
- *wet year*: 2021-04-01 till 2022-03-01

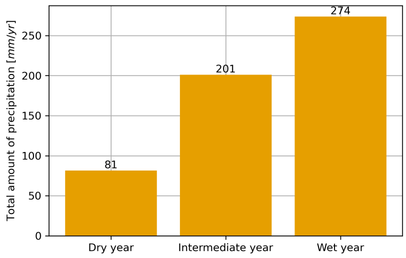
To evaluate for the differences between summer and winter, the following months were evaluated for each year:

- *summer*: 06-01 till 08-31
- *winter*: 12-01 till 02-28

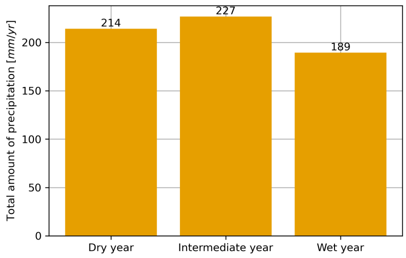
The total amounts of precipitation that were used as input data in this study are given in figure 3.5.



(a) yearly totals



(b) summer months totals



(c) winter months totals

Figure 3.5: Total amount of precipitation that was added to the model for the dry, intermediate and wet year. Calculated as yearly totals, totals of only the summer months and totals of only the winter months.

4 | Results

In this chapter, the results will be discussed. Firstly, the results of the model verification and some observations are described. Then, the results of implementing the peat volume change and implementing the evapotranspiration feedback are given. These results are given per observed effect, instead of per implemented feedback, so cross-effects can immediately be discussed. Effects of implementing the peat volume change and evapotranspiration feedback are quantified in terms of water availability in the peatland and its exchange with the environment. The first is quantified using the phreatic water level, which is represented by model layer 1 and the second is quantified using the heads in layer 6, as this layer represents the underlaying sand layer and therefore represents the environment of the peatland.

4.1 Model verification

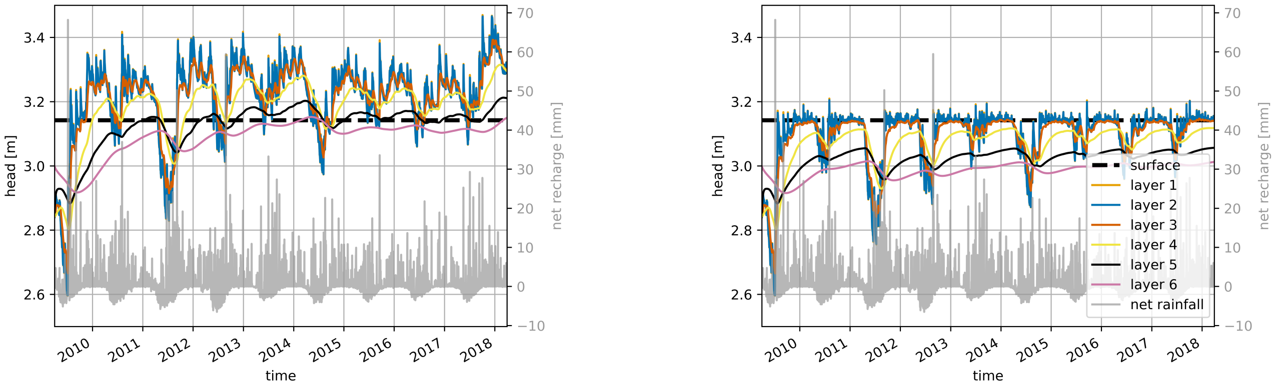
The goal of the model verification was to see how the storage, the conductivity of the drains (C_{drains}) and the conductivity of the ditches ($C_{ditches}$) influence the modelled heads and to obtain optimal estimates for C_{drains} and $C_{ditches}$. In section 3.3 is explained that the Base Model with Swedish input data was used for the verification. It should also be emphasized that during the verification phase, no conclusions connected to the value of the storage term are drawn. It was only used to see if the water table dynamics of the Swedish mire could be simulated and to see how the storage influences the modelled heads. In chapter 3.3.1 is described which criteria the modelled heads had to match for a set of $C_{ditches}$ and C_{drains} to be assumed 'optimal'. An overview of the tested values for every parameter and the optimal value that was found is given in table 4.1.

In figure 4.1 it can be seen that the C_{drains} mainly influenced the height of the water level standing on top of the surface. In figure 4.2, it can be seen the $C_{ditches}$ not have much influence on the modelled fluxes. In figure 4.3 it can be seen the storage strongly influences the amplitude of the simulated heads: a higher storage term leads to a smaller amplitude. For example, the lowest groundwater table in figure 4.3a for layer 1 is 2.28 m and the lowest head for layer 6 is 2.65 m. Subtracting these values of the surface height of 3.15 m, this gives amplitudes of 0.86 m respectively 0.49 m. In figure 4.3b, the lowest groundwater table for layer 1 is 2.78 m and the lowest head for layer 6 is 2.95 m, resulting in amplitudes of 0.36 m respectively 0.19 m. Thus, by an increase of the storage of 0.2-0.07 = 0.13 m^{-1}, the amplitude of the groundwater table lowers with 58% and the amplitude of the head in the sand layer lowers with 61%.

The parameter set of a $C_{ditches}$ of 10 m^2d^{-1} and a C_{drains} of 150 m^2d^{-1} turned out to be best capable of simulating the water tables measured at the Swedish mire Degerö Stormyr. In figure 4.4 the simulated heads using this parameter set are plotted together with water tables measured in the Swedish mire Degerö Stormyr, with two different storage terms. Note that, for model type 1, which is used during the verification, as model input also Swedish precipitation data and evapotranspiration data were used, measured at the same location as the water tables were measured. The groundwater recharge in the modelled situation can thus be considered equal to the groundwater recharge in the Swedish mire. In figure 4.4b it can be seen that the Base Model is capable of simulating the measured groundwater tables of the Swedish mire, as the lines of the upper three model layers are lying on top of, or closely to the measured Swedish water table differences. Note that here only the phreatic table is evaluated, not the behaviour of the underlying heads.

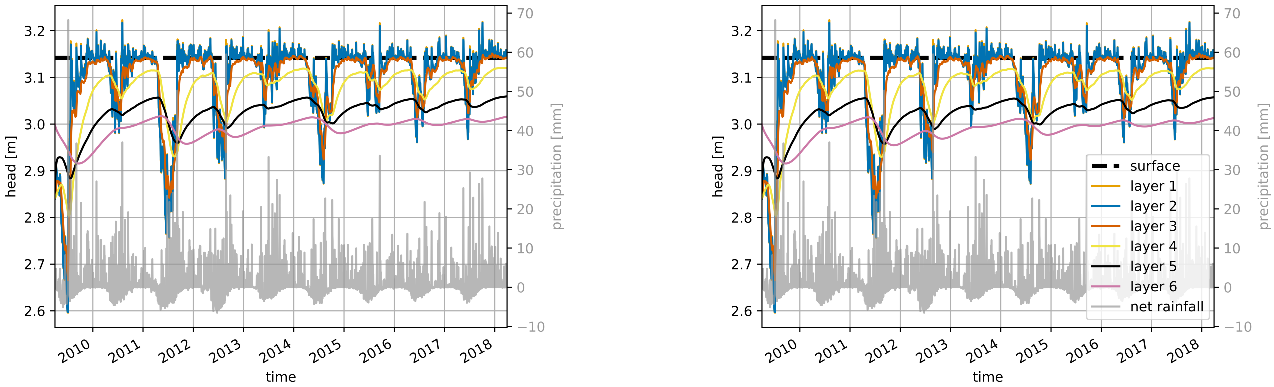
Table 4.1: An overview of the tested values of different parameters and the optimal value

parameter	**description**	**tested range** $[m^2d^{-1}]$	**optimal value** $[m^2d^{-1}]$
$C_{ditches}$	conductance of the general head boundary	5 - 1000	10
C_{drains}	conductance of the drains	5 - 200	150
S	storage	0.07 - 0.5	0.2



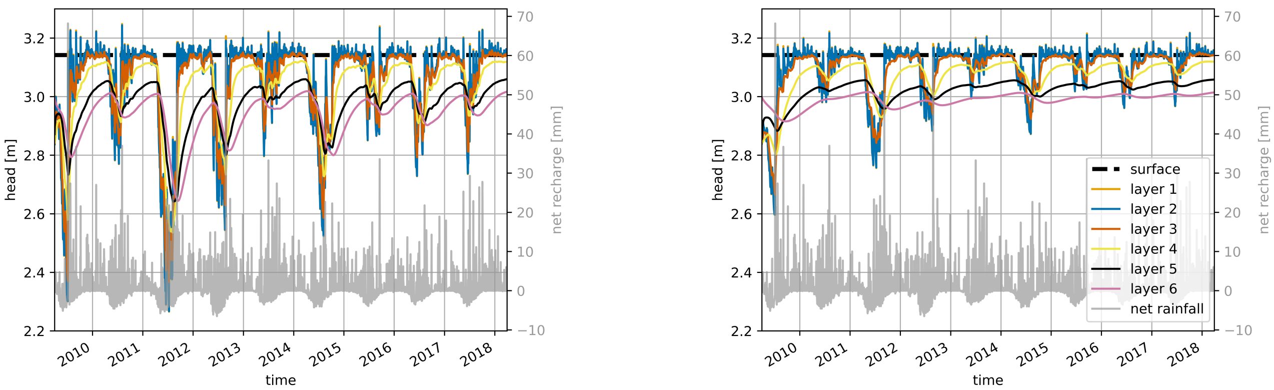
(a) (b)

Figure 4.1: Simulated heads with different values for the C_{drains}. The horizontal, striped line represents the surface. On the left y-axis, the heads are given in m, on the right y-axis the net recharge *is given. As explained in section 3.3.2, positive recharge is treated as net groundwater recharge and negative recharge was treated as evaporating groundwater. In a) simulated heads with a C_{drains} of 5 m^2d^{-1} are plotted, in b) simulated heads with a C_{drains} of 200 m^2d^{-1} are plotted. In both simulations, a storage of 0.2 m^{-1} was assumed and the $C_{ditches}$ was assumed to be 10 m^2d^{-1}. Note the difference in water level on top of the surface. A higher conductance results in lower water levels on top of the surface.*



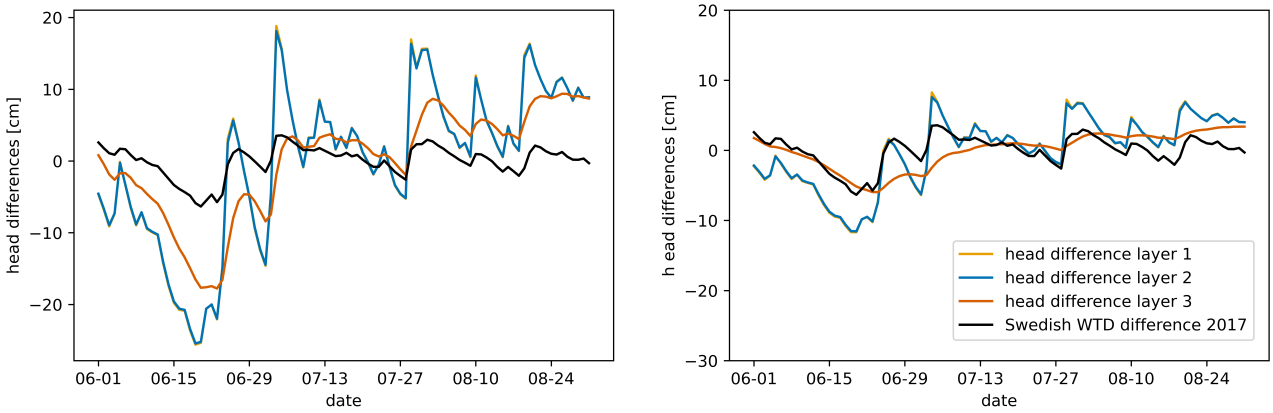
(a) (b)

Figure 4.2: Simulated heads with different values for the $C_{ditches}$. In a) simulated heads with a $C_{ditches}$ of 5 m^2d^{-1} is given, in b) simulated heads with a $C_{ditches}$ of 1000 m^2d^{-1}. In both simulations, a storage of 0.2 m^{-1} was assumed and the C_{drains} was assumed to be 150 m^2d^{-1}.



(a) (b)

Figure 4.3: Simulated heads with different storage values and optimal values for the parameters $C_{ditches}$ and C_{drains}. In a) the simulated heads with a storage of 0.07 m^{-1} are given and in b) the simulated heads with a storage of 0.2 m^{-1} are given. Note the difference in amplitude in the heads.



(a) (b)

Figure 4.4: Simulated head differences plotted with water table dynamics measured in the Swedish Mire Degerö Stormyr. In a) simulated head differences with the optimal parameter values and a storage of 0.07 m^{-1} are plotted, in b) simulated head differences with the optimal parameter values and a storage of 0.2 m^{-1} are plotted. In both figures, the upper layer of the simulated heads is plotted as this one represents the water table dynamics. The second layer is plotted to see if it behaves differently at any point from the upper layer. The third layer is plotted to see how it differs from the first two layers. Also in this plot the effect of the storage term is visible.

4.2 Effects of implementing peat volume change

4.2.1 The influence of peat volume change on the modelled heads

Peat volume change, implemented in the model via the specific storage (Ss), influences the modelled heads in two ways. The first effect that is observed is the effect of increasing the Ss leading to a shallower maximum depth of the modelled groundwater table and a shallower maximum depth of the modelled heads. In figure 4.5 this effect is made visible for a dry, an intermediate and a wet year for layer 1, representing the phreatic level and for layer 6, representing the head in the sand layer. In appendix A, also the figures for the remaining layers are given. In table 4.2 the differences between the surface and the lowest head and the percentual difference with respect to Ss_{zero} are given. The highest change in maximum depth of the groundwater table is found in the dry year. In this year, when no specific storage is implemented, the maximum groundwater depth is 0.69 m while with the highest storage term implemented (Ss_{high}=0.27 m^{-1}), the maximum groundwater depth reduces to 0.21 m. This is a reduction of 70%. In the wet year, the smallest difference is found: implementing a low specific storage (Ss_{low}=0.02 m^{-1}) reduces the maximum groundwater depth with 15%.

Table 4.2: For layer 1 and 6 is given: the water table depth (WTD), the difference between surface level and the water table depth and a percentage difference calculated as follows: percentage difference $= \frac{ET_{on/ssn} - ET_{off}}{ET_{off}} \cdot 100\%$

	dry year						intermediate year						wet year					
	lowest WTD $[m]$		**surface level – lowest WTD** $[m]$		**percentage diff.** $[-]$		**lowest WTD** $[m]$		**surface level – lowest WTD** $[m]$		**percentage diff.** $[-]$		**lowest WTD** $[m]$		**surface level – lowest WTD** $[m]$		**percentage diff.** $[-]$	
	L1	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**
Ss_{zero}	2.45	2.34	0.69	0.80	-	-	2.76	2.65	0.38	0.49	-	-	3.01	2.90	0.13	0.24	-	-
Ss_{low}	2.58	2.49	0.56	0.65	-19%	-19%	2.83	2.75	0.31	0.39	-18%	-20%	3.03	2.96	0.11	0.18	-15%	-25%
Ss_{med}	2.84	2.79	0.30	0.35	-57%	-56%	2.96	2.93	0.18	0.21	-53%	-57%	3.07	3.01	0.07	0.13	-46%	-46%
Ss_{high}	2.93	2.91	0.21	0.23	-70%	-71%	3.02	2.98	0.12	0.16	-68%	-67%	3.09	3.00	0.05	0.14	-62%	-42%

The second effect that is observed, is the effect of the Ss on the timing at which the lowest heads are reached in the soil. From the comparison between the behaviour of the heads in the different layers during a dry year and an intermediate year, it became visible that there is a delay in timing at which the phreatic level reaches its lowest level, compared to the timing at which the head in the sand layer reaches its lowest level. This effect depends on both the height of the storage term as well as on the amount of precipitation in a year. In figure 4.6 this effect is made visible. For the dry, the intermediate and the wet year, both the top peat layer (layer 1) and the sand layer (layer 6) are plotted for both a low specific storage (Ss_{low}=0.02 m^{-1}) and a high specific storage (Ss_{high}=0.27 m^{-1}). In table 4.3,

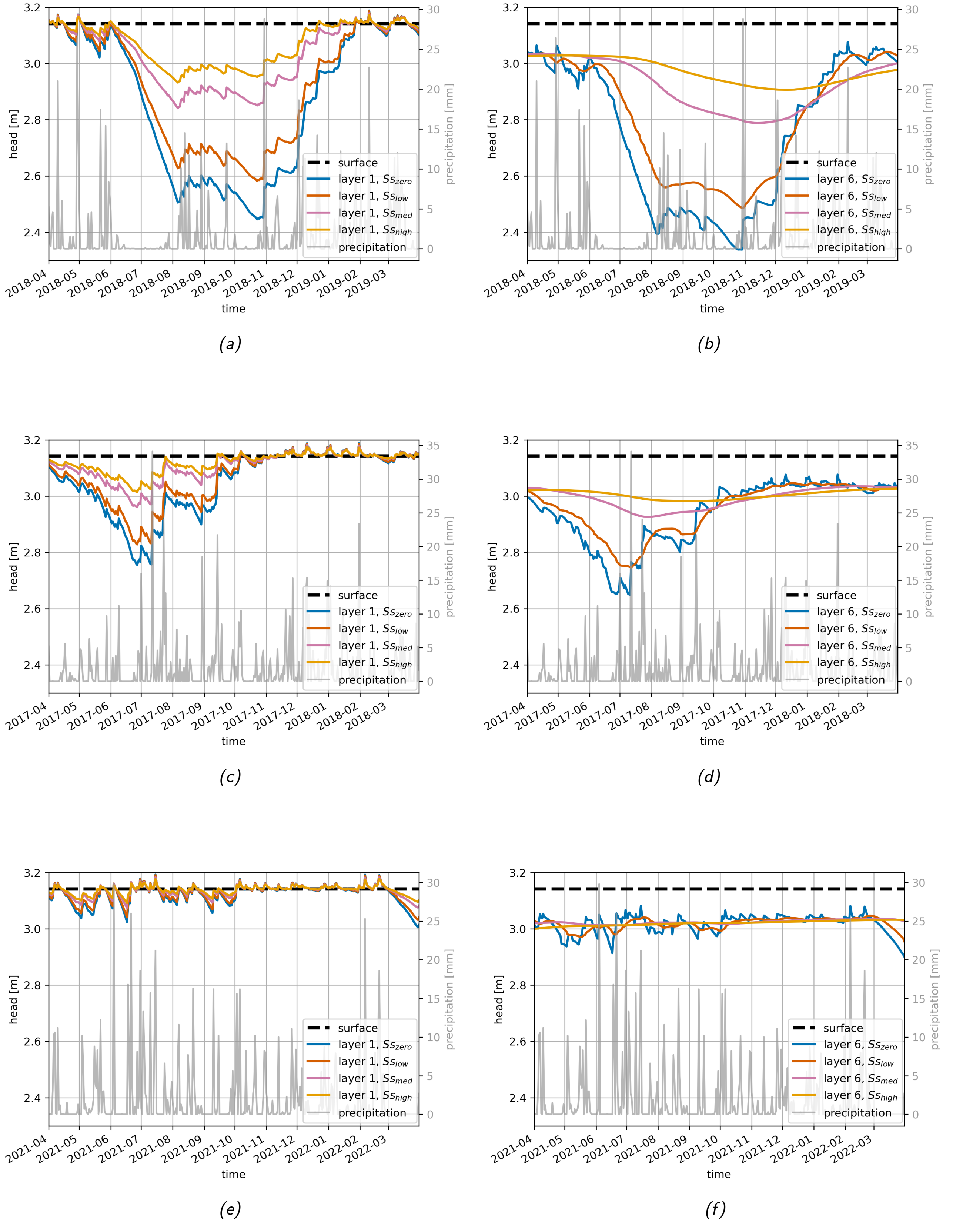
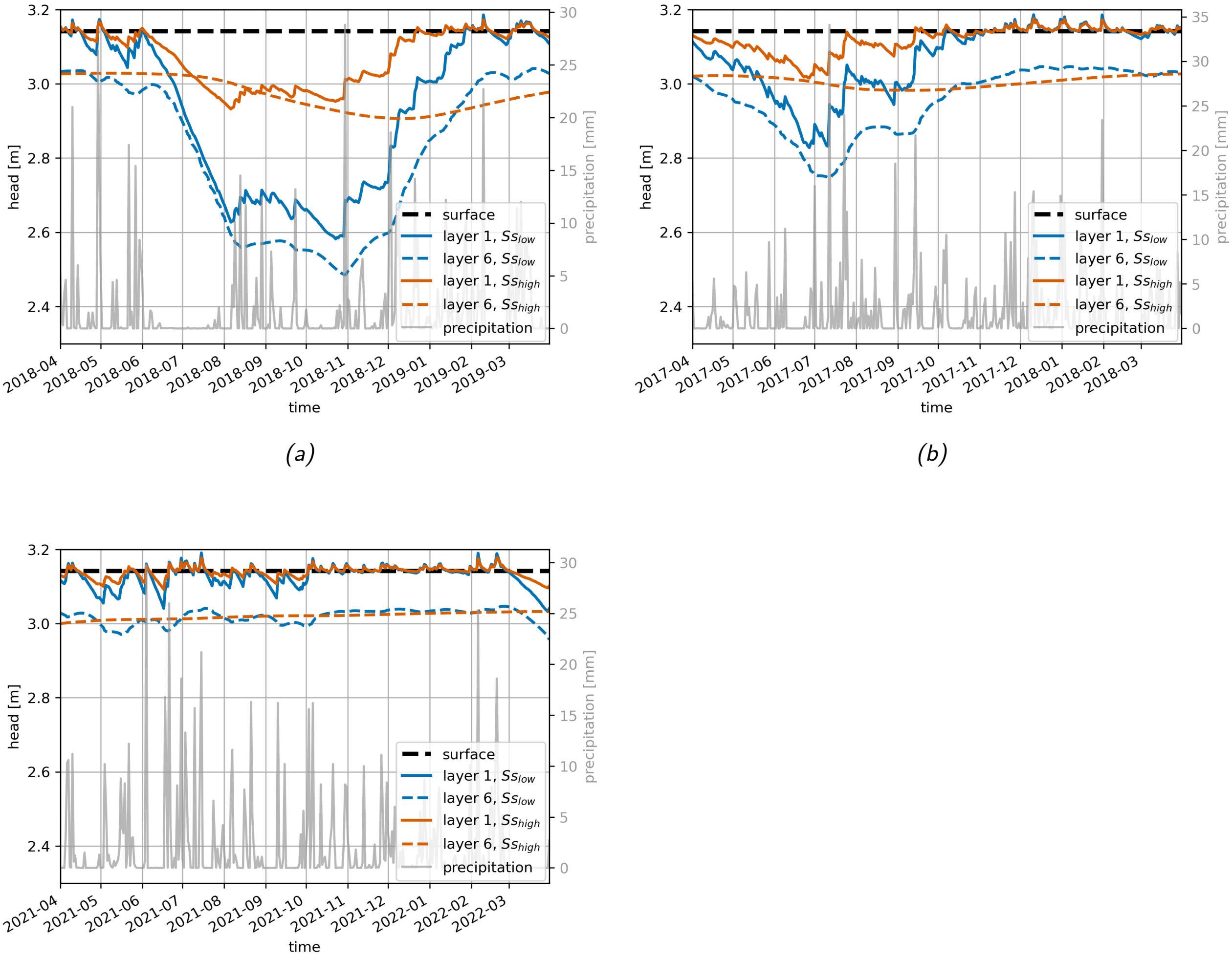


Figure 4.5: The simulated phreatic levels (layer 1) and heads (layer 6) for different Ss, namely: Ss_{zero}=0m^{-1}, Ss_{low}=0.02m^{-1}, Ss_{med}=0.125m^{-1}, Ss_{high}=0.27m^{-1}. From top to bottom: the dry, intermediate and wet years are simulated. At the left side, the phreatic levels in layer 1 are plotted and at the right side, the heads in layer 6 are plotted.

the exact dates of the lowest groundwater tables are given. In appendix B, the remaining Ss-scenario's are plotted.

The results in figure 4.6 and table 4.3 show that, independent of the amount of precipitation, for the scenario's with no or a low specific storage, the delay is relatively small, namely in between 1 and 15 days. However, with increasing specific storage and a decreasing amount of precipitation in a year, the delay increases up to 128 days. Only the Ss_{high} in a wet year (figure 4.6c) makes an exception, which might be due to the lack of groundwater dynamics under wet circumstances.



(a) *(b)* *(c)*

Figure 4.6: Results of runs done with model versions $Ss_{low}ET_{off}$ and $Ss_{high}ET_{off}$, showing the groundwater delay under three different weather scenario's. In a) groundwater delay during the dry year, in b) groundwater delay during the intermediate year and in c) groundwater delay during the wet year is plotted.

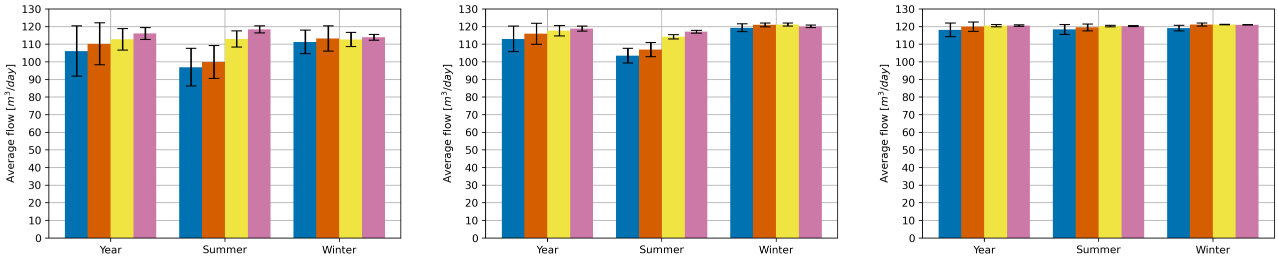
Table 4.3: Dates of which the layers reach their lowest groundwater levels, including the delay between that timing in days.

	dry year			**intermediate year**			**wet year**		
	date $[dd/mm]$		**delay** $[d]$	**date** $[dd/mm]$		**delay** $[d]$	**date** $[dd/mm]$		**delay** $[d]$
	layer 1	**layer 6**		**layer 1**	**layer 6**		**layer 1**	**layer 6**	
Ss_{zero}	23/10	29/10	6	27/06	11/07	14	30/03	31/03	1
Ss_{low}	23/10	30/10	7	27/06	12/07	15	30/03	31/03	1
Ss_{med}	06/08	14/11	100	27/06	29/07	32	17/06	27/06	10
Ss_{high}	06/08	12/12	128	27/06	14/09	79	17/06	01/04	-77

4.2.2 The influence of peat volume change on the outgoing fluxes

Next to affecting the heads, peat volume change also affects the flux from the glyde layer towards the sand layer. This flux is assumed to be a flux towards the surrounding environment, as it is water leaving the bog system. In figure 4.7 the effects are presented and in appendix E.1 the exact numbers of the barplots are given. Note that the data is not normally distributed, so the standard deviations should be interpreted with caution. Also note that the y-axis gives values in m^3d^{-1}. If one is interested in the median in mm d^{-1}, these values can be divided by 950, as the model surface without the ditches is 950000 m^2. In table E.1 the exact values of the barplots are given.

In general, under relatively dry circumstances, a higher storage term leads to a higher outgoing flux. The most pronounced effects are in the summer months of the dry year, where implementing a high specific storage leads to an increase of the outgoing flux of 118 - 97 = 21 m^3d^{-1}. Under wet circumstances, the effects are minimal, and independent of the season, an increase in specific storage does not influence the outgoing flux anymore.



(a) dry year *(b) intermediate year* *(c) wet year*

Figure 4.7: Barplots giving the average (median) flow from the glyde towards the sand layer for model runs $Ss_{zero}ET_{off}$, $Ss_{low}ET_{off}$, $Ss_{med}ET_{off}$, $Ss_{high}ET_{off}$, for a dry, an intermediate and a wet year. Per barplot, the average is taken over a whole year and over the summer and winter months separately. Note that the data is not normally distributed, so the standard deviations should be interpreted with caution.

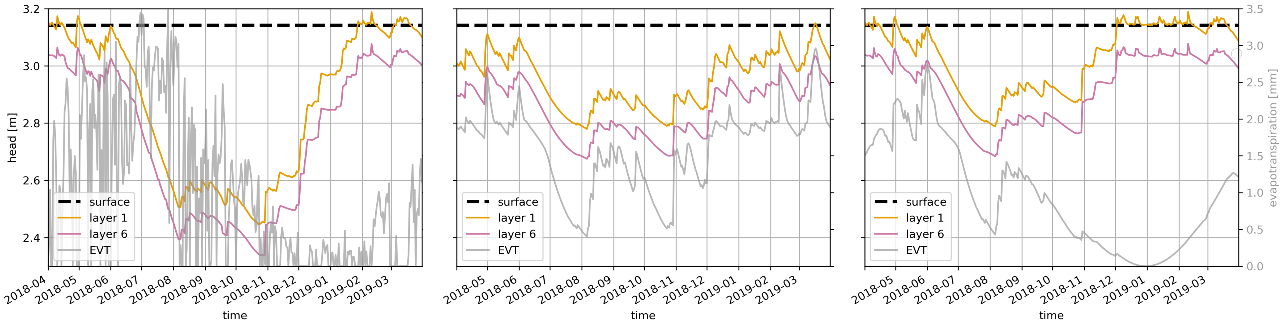
4.3 Effects of implementing an evapotranspiration feedback

4.3.1 The influence of the evapotranspiration feedback on the modelled heads

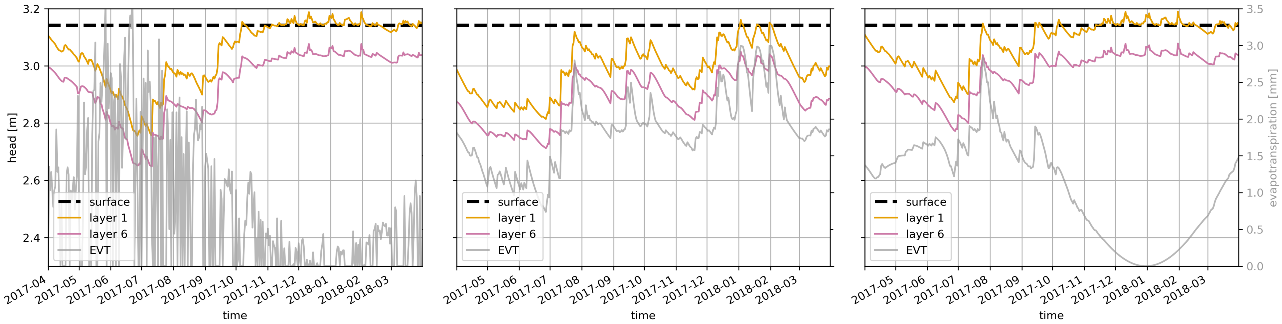
Under relatively dry circumstances, the implementation of an evapotranspiration feedback (ET_{on} or ET_{ssn}) leads to increased groundwater- and head levels. In figure 4.8 the simulated heads and evapotranspiration for model versions $Ss_{zero}ET_{off}$, $Ss_{zero}ET_{on}$ and $Ss_{zero}ET_{ssn}$ are compared for a dry year, an intermediate year and a wet year. In table 4.4, the differences between the surface and the phreatic level (layer 1) and the differences between the surface level and the hydraulic head in the underlying sand layer (layer 6) are given, including the percentage difference.

The first thing that stands out from figure 4.8 is the difference in the evapotranspiration flux between the simulations without the evapotranspiration feedback implemented ($Ss_{zero}ET_{off}$), with the basic evapotranspiration feedback implemented ($Ss_{zero}ET_{on}$) and with the seasonal evapotranspiration feedback implemented ($Ss_{zero}ET_{ssn}$). In all the figures at the left hand side, without the evapotranspiration feedback, the evapotranspiration flux depends on the Penman-Monteith equation for potential evapotranspiration and resembles a sinusoidal shape. This shape is similar for the dry, intermediate and wet year. In all the figures in the middle, with the basic evapotranspiration feedback implemented, the evapotranspiration flux differs much more between the years. In these figures, the interaction between the groundwater level and the evapotranspiration leads to a similar shape of the groundwater levels in the peat layer (layer 1), the hydraulic head in the sand layer (layer 6) and the evapotranspiration flux.

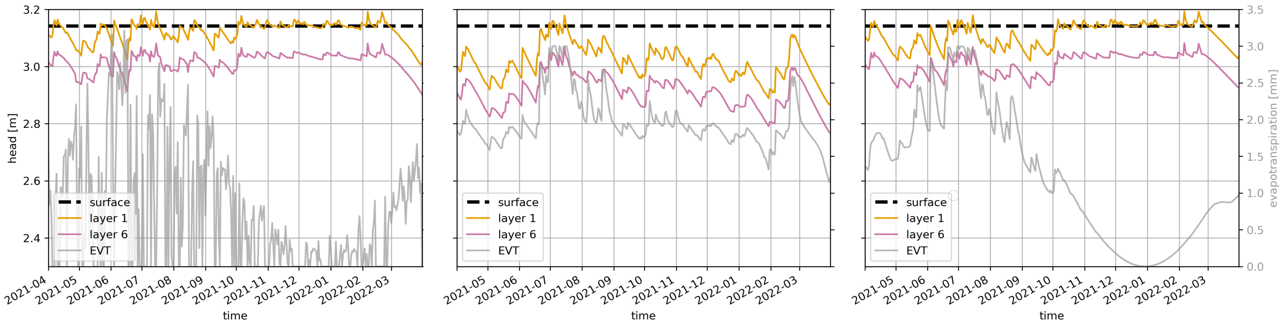
In the figures at the right hand side, with the seasonal evapotranspiration feedback implemented, the evapotranspiration also differs between the years. However, contrary to the middle figures, the shape of the groundwater levels



(a) dry year, $Ss_{zero}ET_{off}$ *(b) dry year, $Ss_{zero}ET_{on}$* *(c) dry year, $Ss_{zero}ET_{ssn}$*



(d) intermediate year, $Ss_{zero}ET_{off}$ *(e) intermediate year, $Ss_{zero}ET_{on}$* *(f) $Ss_{zero}ET_{ssn}$*



(g) wet year, $Ss_{zero}ET_{zero}$ *(h) wet year, $Ss_{zero}ET_{on}$* *(i) wet year, $Ss_{zero}ET_{ssn}$*

Figure 4.8: On the left side, figures without the evapotranspiration feedback are given ($Ss_{zero}ET_{off}$), in the middle figures with the basic evapotranspiration feedback are given ($Ss_{zero}ET_{on}$) and on the right side, figures with the seasonal evapotranspiration feedback implemented are given ($Ss_{zero}ET_{ssn}$). From top to bottom: dry, intermediate and a wet year are given. On the left axis, the heads are given in meters and on the right axis, the evapotranspiration flux is given in millimeters.

Table 4.4: For layer 1 and 6 is given: the water table depth (WTD), the difference between surface level and the water table depth and a percentage difference calculated as follows: percentage difference $= \frac{ET_{on/ssn} - ET_{off}}{ET_{off}} \cdot 100\%$

	dry year						intermediate year						wet year					
	lowest WTD $[m]$		**surface level – lowest WTD** $[m]$		**percentage diff.** $[-]$		**lowest WTD** $[m]$		**surface level – lowest WTD** $[m]$		**percentage diff.** $[-]$		**lowest WTD** $[m]$		**surface level – lowest WTD** $[m]$		**percentage diff.** $[-]$	
	L1	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**	**L1**	**L6**
$Ss_{zero}ET_{off}$	2.45	2.34	0.69	0.80	-	-	2.76	2.65	0.38	0.49	-	-	3.01	2.90	0.13	0.24	-	-
$Ss_{zero}ET_{on}$	2.78	2.68	0.36	0.46	-48%	-43%	2.81	2.71	0.33	0.43	-13%	-12%	2.87	2.77	0.27	0.37	108%	54%
$Ss_{zero}ET_{ssn}$	2.79	2.68	0.35	0.46	-49%	-43%	2.87	2.77	0.27	0.37	-29%	-24%	3.02	2.92	0.12	0.22	-0.08%	-0.08%

in the peat layer and the head in the sand layer differ from the shape of the evapotranspiration flux. Especially after the lowest groundwater levels and heads are reached, in the beginning of August, the behaviour of the groundwater level and the heads from model runs $Ss_{zero}ET_{on}$ differs from the behaviour of the groundwater level and heads in model runs $Ss_{zero}ET_{ssn}$. Due to a decrease in maximum evapotranspiration rate, as described in the methods, the groundwater level and head level are increasing faster for model run $Ss_{zero}ET_{ssn}$, compared to model run $Ss_{zero}ET_{on}$.

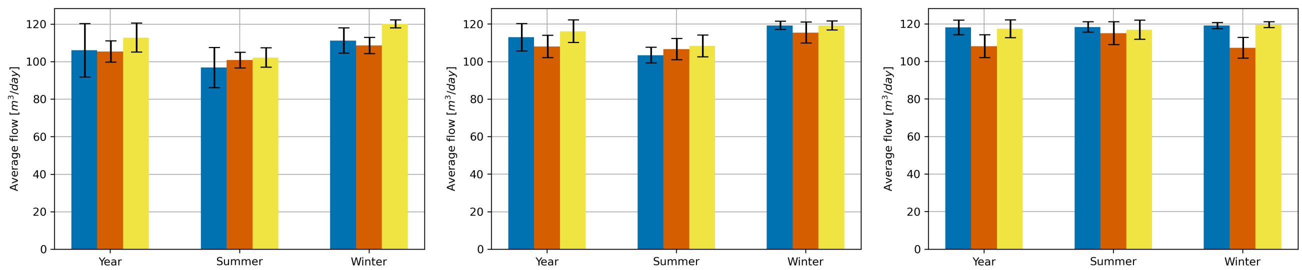
Thus, in summary, the evapotranspiration flux of model runs $Ss_{zero}ET_{off}$ has a sinusoidal shape with relatively high evapotranspiration during summer and a low evapotranspiration during winter. In the model runs $Ss_{zero}ET_{on}$, the evapotranspiration flux, the groundwater levels and the heads have the same shape, with relatively high evapotranspiration during winter and therefore low groundwater levels and head levels during winter. In the model runs $Ss_{zero}ET_{ssn}$, the evapotranspiration flux strongly reduces during winter time, leading to higher groudwater levels and head levels compared to model runs $Ss_{zero}ET_{on}$.

Furthermore, table 4.4 shows that, for the dry and intermediate year, implementing the basic evapotranspiration feedback leads to a decrease in lowest groundwater table and heads of 12% to 48%. Thus, the maximum groundwater and head depth decreases. However, under wet circumstances, the implementation of the basic evapotranspiration feedback leads to an increase in lowest groundwater table and head of 54% to 108%, also due to the high evapotranspiration rate in winter. This will be further discussed in chapter 5.

Table 4.4 also shows that the lowest groundwater depth and the depth of the lowest head is decreasing for model runs with the seasonal evapotranspiration feedback compared to model runs without an evapotranspiration feedback. This effect is the smallest for a wet year, in which the decrease is only 0.08% and the highest for the dry year, in which the decrease is 43% to 49%. However, these percentage differences do not differ that much from model runs with the basic evapotranspiration feedback, suggesting that implementing a seasonal evapotranspiration feedback over a basic evapotranspiration feedback, does not make much difference for the lowest groundwater levels and heads. Nevertheless, during winter time, the groundwater tables and heads in the runs with a seasonal evapotranspiration do differ from the groundwater tables and heads in the runs with the basic evapotranspiration feedback.

4.3.2 The influence of an evapotranspiration feedback on the outgoing fluxes

Implementing an evapotranspiration feedback also affects the fluxes from the glyde layer to the sand layer. In figure 4.9 the change in average flow from the glyde towards the sand layer is given for a dry year (figure 4.9a), an intermediate year (figure 4.9b) and a wet year (figure 4.9c). Note that the average is calculated as a median and note that the data is not normally distributed, so the standard deviations should be interpreted with caution. In appendix E.2 the exact values of the medians are given.



(a) dry year *(b) intermediate year* *(c) wet year*

Figure 4.9: Barplots showing the average flow from the glyde towards the sand layer for model runs without the evapotranspiration feedback implemented ($Ss_{zero}ET_{off}$), with the basic evapotranspiration feedback implemented ($Ss_{zero}ET_{on}$) and with the seasonal evapotranspiration feedback implemented ($Ss_{zero}ET_{ssn}$), for a dry, an intermediate and a wet year. In each barplot, the average over a whole year and the averages over only the summer and the winter months are given.

The figure shows that the outgoing flux in model simulations with a seasonal evapotranspiration feedback almost always is higher than model simulations without an evapotranspiration feedback implemented ($Ss_{zero}ET_{off}$). The increase in yearly average outgoing flux between model run $Ss_{zero}ET_{off}$ and $Ss_{zero}ET_{ssn}$ is most pronounced during a dry year with a difference of 7 m^3d^{-1}. During an intermediate year, the difference is already less pronounced, namely 3 m^3d^{-1}. During a wet year, the yearly average flux is even slightly lower for model run $Ss_{zero}ET_{ssn}$, compared to model run $Ss_{zero}ET_{off}$, namely 1 m^3d^{-1}. Thus, implementing a seasonal evapotranspiration feedback leads to a higher outgoing flux compared to model runs without and evapotranspiration feedback.

The figure also shows that the outgoing flux averaged over a year in model simulations with a seasonal evapotranspiration feedback ($Ss_{zero}ET_{ssn}$) always is 8 or 9 m^3d^{-1} higher than model simulations with a basic evapotranspiration feedback ($Ss_{zero}ET_{on}$). Evaluating for seasonal effects, the figure also shows this difference is most pronounced during winter, namely between 4 to 13 m^3d^{-1} higher for $Ss_{zero}ET_{ssn}$. The differences in the summer months are only 1 to 2 m^3d^{-1}. Thus, the constant maximum evapotranspiration leads to a lower averaged outgoing flux during winter. This is also reflected in the yearly averaged outgoing flux.

4.4 Combined effects of implementing both peat volume change and an evapotranspiration feedback

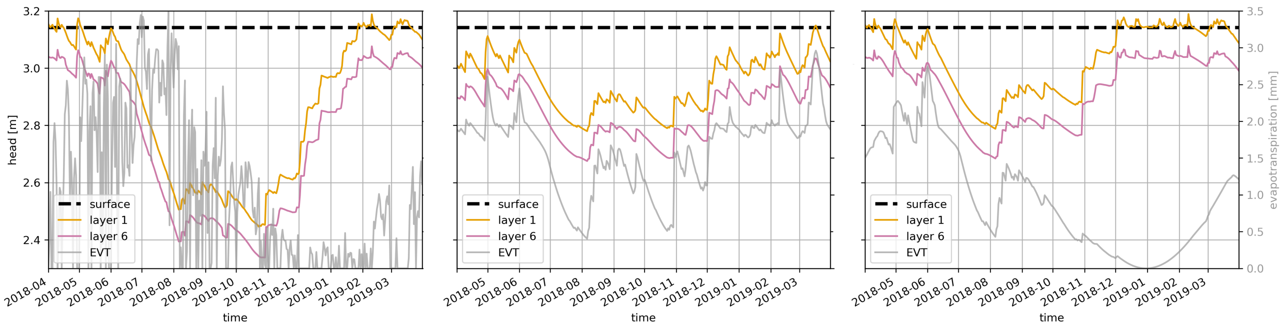
To evaluate for the effects of implementing both peat volume change and an evapotranspiration feedback, in figure 4.10 a comparison is made between $Ss_{zero}ET_{off}$ and $Ss_{med}ET_{off}$, between $Ss_{zero}ET_{on}$ and $Ss_{med}ET_{on}$, and between $Ss_{zero}ET_{ssn}$ and $Ss_{med}ET_{ssn}$. Furthermore, in table 4.5 the lowest water tables, the differences between surface level and lowest water table and a percentage difference is given for the dry year. In this chapter, only the figures for the dry year will be discussed, as in the previous sections the most pronounced effects were found for the dry year. In appendix C, the same figures with corresponding tables for the intermediate and wet year can be found.

A comparison between figures 4.10a and 4.10d shows a big increase in minimum groundwater levels and head levels, namely for the groundwater level (L1) an increase of 2.84-2.45 = 0.39m and for the head level in the sand layer (L6) an increase of 2.79-2.34 = 0.45m. A comparison between figures 4.10b and 4.10e shows a much smaller increase in minimum groundwater level and head levels, namely for the groundwater level an increase of 0.06m and for the head level an increase of 0.10m. Thus, in this study, adding a specific storage to a model in which the basic evapotranspiration feedback already is included, has less effect on the minimum groundwater levels and head levels then adding a specific storage to a model in which the basic evapotranspiration feedback is not yet included. However, in figure 4.10e is visible that adding the storage term to a model in which the basic evapotranspiration feedback is included (4.10b), does impact the general yearly trend of the heads. Namely, the heads become more stable throughout the whole year. As a consequence, when a specific storage term is implemented, the heads seem to recover slower from a low level compared to when no specific storage is implemented. This is visible in figure 4.10e in which the levels at the end of the hydrological year are the lowest at the end of the year, compared to the levels at the end of the hydrological year in figures 4.10a, 4.10b and 4.10d.

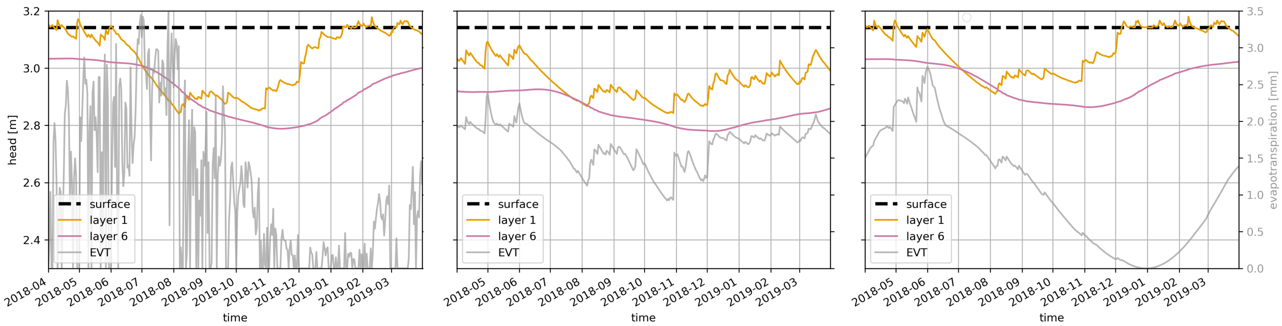
Furthermore, a comparison between figures 4.10a and 4.10b shows a big increase in minimum groundwater levels and head levels, namely of 0.33 and 0.34m for respectively L1 and L6, while a comparison between figures 4.10d and 4.10e shows almost no change in minimum groundwater levels and head levels. Thus, in this study, adding a basic evapotranspiration feedback to a model in which already a specific storage term is implemented, has almost no impact on the lowest groundwater levels and head levels. A small change in the general trend is visible, as head levels seem to be more stable throughout the year.

A comparison between figures 4.10a and 4.10c shows a big increase in lowest groundwater levels and heads. Similar to the comparison of 4.10a and 4.10b, the lowest groundwater level increases with 2.79-2.45 = 0.34m and the lowest head level of the sand layer also increases with 2.68 - 2.34 = 0.34m. Thus, implementing a seasonal varying evapotranspiration feedback over the basic evapotranspiration feedback does not directly affect the lowest groundwater levels and heads. However, due to the decrease in evapotranspiration during the winter months in figure 4.10c, groundwater levels and heads can recover faster then the groundwater levels and heads in fig 4.10b.

A comparison between figures 4.10d and 4.10f shows that, when adding the seasonal evapotranspiration feedback into a model in which a specific storage term is already included, the minimum groundwater levels and head levels only show a small increase. In this case, the groundwater level in layer 1 increases with 2.91-2.84 = 0.07m and also the head in the sand layer increases with 2.86-2.79 = 0.07m.



(a) dry year, $Ss_{zero}ET_{off}$ *(b) dry year, $Ss_{zero}ET_{on}$* *(c) dry year, $Ss_{zero}ET_{ssn}$*



(d) dry year, $Ss_{med}ET_{off}$ *(e) dry year, $Ss_{med}ET_{on}$* *(f) dry year, $Ss_{med}ET_{ssn}$*

Figure 4.10: Modelled heads of model simulations with no, a basic, or a seasonal evapotranspiration feedback and with no or a medium specific storage, given for a dry year.

Table 4.5: For layer 1 and 6 is given: the water table depth (WTD), the difference between surface level and the water table depth and a percentage difference calculated as follows: percentage difference $= \frac{ET_{on/ssn} - ET_{off}}{ET_{off}} \cdot 100\%$

	dry year					
	lowest WTD $[m]$		**surface level − lowest WTD** $[m]$		**percentage diff.** $[-]$	
	L1	**L6**	**L1**	**L6**	**L1**	**L6**
$Ss_{zero}ET_{off}$ (4.10a)	2.45	2.34	0.69	0.80	-	-
$Ss_{zero}ET_{on}$ (4.10b)	2.78	2.68	0.36	0.46	48%	43%
$Ss_{zero}ET_{ssn}$ (4.10c)	2.79	2.68	0.35	0.46	49%	43%
$Ss_{med}ET_{off}$ (4.10d)	2.84	2.79	0.30	0.35	57%	56%
$Ss_{med}ET_{on}$ (4.10e)	2.84	2.78	0.30	0.36	57%	55%
$Ss_{med}ET_{ssn}$ (4.10f)	2.91	2.86	0.23	0.28	67%	65%

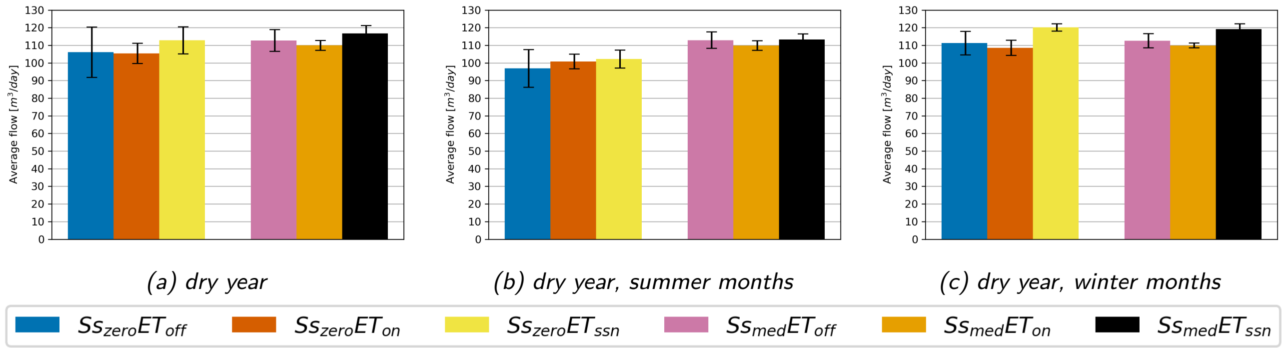
Thus, implementing a specific storage term has more impact on the lowest heads than implementing an evapotranspiration feedback. This is also visible in the percentage differences given in table 4.5. Implementing a specific storage term reduces the lowest groundwater table with 57% and the lowest head in the sand soil with 56%, while implementing an evapotranspiration feedback reduces the lowest groundwater table with 58% and the lowest head in the sand soil with 43%. Implementing both a specific storage term and an evapotranspiration feedback reduces the lowest groundwater table with 67% and the lowest head in the sand soil with 65%. Thus, the implementation of both feedbacks does lead to a further decrease in lowest groundwater tables and heads, but that decrease is less than the sum of the influence of accounting for peat volume change and the seasonal evapotranspiration feedback separately.

In figure 4.11 are the daily average (median) outgoing flows from the glyde towards the sand layer visible, with averages taken over a whole dry year, over only the summer months of the dry year and over only the winter months of the dry year. In appendix E.3, the exact numbers of the barplots are given.

The first thing that stands out from this figure is that model runs with Ss_{med} have a higher outgoing flux then model runs with Ss_{zero} for the whole dry year and the summer months of the dry year. The highest difference is found during the summer months of the dry year, namely an increase of 16 m^3d^{-1} when implementing a medium specific storage.

Furthermore, when comparing ET_{off}, ET_{on} and ET_{ssn}, it is visible that the seasonal evapotranspiration feedback almost always leads to higher outgoing fluxes than the basic evapotranspiration feedback and no evapotranspiration feedback. This difference is most pronounced during the winter months, and can be explained by the decrease in maximum evapotranspiration rate in those simulations.

Also, what can be seen is that the increase in outgoing flux when implementing a seasonal evapotranspiration feedback, for a model simulation in which the medium specific storage is already taken into account, is smaller than for model runs in which no storage term is included yet. Adding both a specific storage and an evapotranspiration feedback however always to the highest outgoing fluxes over the whole year.



(a) dry year *(b) dry year, summer months* *(c) dry year, winter months*

Figure 4.11: Barplots showing the average flow from the glyde towards the sand layer for all model runs, for a dry year. The average is taken over the whole year and over the summer and winter months separately.

5 | Discussion

The aim of this study was to implement peat-specific storage behaviour and a peat-specific evaporation feedback of an undisturbed raised bog in a conceptual groundwater model and determine the effects of this implementation on the modelled water balance. In this section, the results presented in chapter 4 will be discussed. First, some assumptions and simplifications regarding the model that was build will be discussed. Second, some notes on the methods of evaluating effects are placed. Then, the observed effects of the implementation of peat volume change and an evapotranspiration feedback are discussed.

5.1 Capturing peatland processes in groundwater models

To develop a conceptual groundwater model of a raised bog system, simplifications were made. In order to answer the second research question -*To what extent is a simple, conceptual model capable of simulating the behaviour of an undisturbed raised bog?*- here the possible consequences of those simplifications will be discussed in more detail.

During the model verification, it was observed that the conductance of the ditches has almost no influence on the modelled heads. This is visible in figure 4.2, where a conductance of 5 m^2d^{-1} resulted in the same modelled heads as a conductance of 1000 m^2d^{-1}. This might be due to the fact that the ditches are only draining the model layer that resembles the underlying sand layer, layer 6. The only way for water in the upper four peat layers to reach the ditches is via this glyde layer. Though, the resistance of the glyde layer is high: the K_{sat} is only 0.0001 md^{-1} and the layer as a thickness of 0.1 m, resulting in a resistance of $0.1/0.0001 = 1000d$. Therefore, the hydrological contact between the ditches and the peat system is limited, meaning not much water flows via the glyde layer, trough the sand layer and to the ditches. This results in simulated heads to be insensitive for the parameter $C_{ditches}$, due to the glyde layer.

A second observation that was done, was that the flux towards the environment, thus the flux leaving the bog system through the glyde layer, towards the ditches, only showed small differences between model runs with and without peat volume change implemented and between model runs with and without an evapotranspiration feedback implemented. Also this observation might be due to the high resistance of the glyde layer, as this limits the outgoing flux. Thus, in this study where a raised bog system with a glyde layer at the base is simulated, the flux to the environment is not very sensitive for an increase in water storage in the soil, when accounting for peat volume change or an evapotranspiration feedback. The increase in amount of water in the peat soil is most likely largely removed from the system by the drains. This hypothesis is already explored by visualising how much water is leaving the system via the drains for three different model runs, see appendix F.1. Those figures show an increase in outflow via the drains, when peat volume change of an evapotranspiration feedback is implemented.

However, it should be noted that, in reality, the resistance of such a glyde layer can be hard to determine and a glyde layer is not always present at the base of a raised bog system (Sevink et al., 2014). In a situation in which the resistance of such a glyde layer is lower, or the layer is not even present, the hydrological contact between the ditches and the peat system might increase, resulting in the simulated heads to become more sensitive for the parameter $C_{ditches}$. Also, in such a situation, the flux leaving the bog system might increase, as the flux through the glyde layer increases. A sensitivity analysis of the resistance of the glyde layer is necessary to determine the influence of the presence of this glyde layer on the modelled heads and the outgoing fluxes.

Furthermore, the *General Head Boundary package* was used at the sides of the sand layer, to simulate ditches. However, this package was used over the entire first and last column. Thereby, the ditches reach all the way to the bottom of the sand layer, having a depth of 1m and having the width of a model cell, which is 25m. Thus, ambient groundwater levels are not represented. Also, as the head of the ditches may be higher then ambient groundwater levels would be, what is now interpreted as the flow to the environment may be underestimated. In future research, efforts should be done to implement ambient groundwater levels, to get a better estimation of the groundwater flow to the environment. This can still be done using the *General Head Boundary package*. This could be done by creating shallower ditches and, underneath the ditches, implement a second General Head Boundary, representing flow to the environment. However, is can also be argued that representing ditches is not necessary at all, as surface runoff can be captured by the implemented drains on top of the surface.

In the situation that is modelled in this study, implementing ambient groundwater levels instead of ditches may not make that much difference, as the glyde layer still acts as a resistance layer, preventing water to flow out of the bog system. However, especially in situations in which the glyde layer has a lower resistance, or is not even present, representing accurate ambient groundwater levels is more important to estimate the flow towards the environment.

It should also be noted that the raised bog system modelled in this study is an undisturbed system. However, most raised bog systems in the Netherlands are disturbed systems, meaning they are excavated (van Beek et al., 2015; Andersen et al., 2017). The water tables in those systems often are too low for the characteristic vegetation types, like peatmosses, to survive (Schouwenaars, 1993). As a consequence, the production and accumulation of peat can stop (Waddington et al., 2015), leading to a loss in the hydrologically positive effects the peat may have on the environment. Furthermore, these low water tables can result in the growth of other vegetation types of which the evapotranspiration rate is much higher under dry circumstances compared to the evapotranspiration rate of peatmosses. In the Netherlands a vegetation type that often occurs in disturbed peatlands is moor-grass. The extensive growth of moor-grass will lead to even lower groundwater tables (Schouwenaars, 1993). When putting this model study in the perspective of a Dutch raised bog area, attention to the characteristics of a disturbed raised bog system that differ from the characteristics of an undisturbed raised bog system should be raised.

5.2 Choosing weather scenario's

The weather scenario's used in this study show precipitation sums that are relatively low compared to the long-term averages measured at the KNMI-station in Eindhoven, which is around 775 mm yr^{-1} (KNMI, 2023a). For this study, most important was that the years were dry, intermediate or wet in terms of precipitation compared to each other. However, in further research, more attention may be raised for choosing weather scenario's, in order to also evaluate for more extreme years. Especially for the intermediate and the wet years, years with more precipitation may be chosen.

5.3 Effects of implementing peat volume change

The third research question was: *How can **peat volume change** be parameterized and incorporated into MODFLOW and how does this affect model simulations?* The first part of this question was already answered in chapter 3, where is explained how peat volume change is implemented in the groundwater model and in section 4.2 a quantitative description of the effects is given. In this section of the discussion, an interpretation of these results will be given.

The first observation when implementing the peat volume change via the specific storage, was that a higher specific storage leads to a decrease in the maximum depth of the modelled groundwater table and heads. Thus, a higher specific storage has a stabilizing effect on the groundwater table and the heads. This can be explained by the fact that a higher specific storage, leads to a higher volume in the soil to store water. Then, with constant evapotranspiration, the decrease in groundwater level and heads will be lower in a situation with a higher specific storage, compared to a situation with a lower specific storage.

The second effect that is observed, is the influence of the specific storage on the timing at which the lowest heads are reached in the soil. During a dry year, and with a high specific storage, there is a very pronounced delay in timing at which the phreatic level and the heads in the underlaying sand soil reach their lowest level, visible in figure 4.6a. This effect is also visible for the intermediate year in figure 4.6b, however less pronounced. For the wet year, no delay is visible (figure 4.6c), which might be due to the lack of groundwater dynamics, as the soil is under almost saturated conditions throughout time. The delay may be explained by the fact that water from the upper peat layers travels downward, towards the underlying sand soil. However, due to the dry circumstances, this water flowing out of the upper peat layers is not repleted. In fact, water from the upper layers is evaporated, while water from deeper layers is not. Also, the hydraulic conductivity of the peat soil reduces with depth, leading to water flowing faster downward in the top layers, compared to the flow rates in the deeper peat layers. Therefore, the underlying sand soil stays saturated for a longer amount of time, compared to the upper peat layers.

The inverse effect is also present: the heads at depth respond slower to recharge then shallower groundwater heads. This observation indicates the importance of implementing accurate peat volume change for both the peat soil itself, as well as the importance for the heads in the environment (in this study represented by the underlying sand soil), especially under dry circumstances. When peat volume change is underestimated, and water is extracted from deeper layers, the time it takes for the heads at depth and the heads in the environment to recover from this water extraction may also be underestimated.

Also observed was the increase in the flux from the glyde layer to the sand layer, when accounting for peat volume change. In figure 4.7 is visible that the higher the implemented specific storage, the higher the outgoing flux. This increase seems relatively small, as in the most pronounced case the increase is only 21 m^3d^{-1}. However, it should be noted that this small change most likely is caused by the thickness and the resistance of the peat layers and the glyde layer. The resistance is calculated as the thickness divided by the hydraulic conductivity. When the peat layers are thinner, the resistance will decrease and outgoing flux will be higher. Furthermore, in this study, a relatively high resistance of 1000 days is assumed. Estimating the resistance of the glyde layer accurately is difficult (Nijp et al., 2022) and in some cases, the glyde layer may not even be present. Thus, this 21 m^3d^{-1} probably not only depends on the height of the specific storage, but is also influenced by the landscape setting, e.g. the resistance and the presence of the glyde layer. A sensitivity analysis is needed to determine the influence of the landscape setting on the outgoing flux.

Both the influence of an increase in specific storage on the modelled heads and the modelled fluxes are most pronounced during a dry year, suggesting this self-regulating process of the peat mainly becomes active under dry circumstances. In Waddington et al. (2015) it was already suggested that a surface adjustment through peat deformation, in this model implemented via the specific storage, can help to maintain high water tables during dry summer months. The results in this study as described in sections 4.2.1 and 4.2.2 support this suggestion. Underestimating the storativity of raised bogs, makes them appear more vulnearble to droughts then they are, and neglects the buffering effect the peat has on its surroundings. The latter is visible in the increase in the delay, as described in this section.

5.4 Effects of implementing the evapotranspiration feedback

The fourth research question was: *How can a **peatland specific evapotranspiration feedback** be parameterized and incorporated into MODFLOW and how does this affect model simulations?* In chapter 3 is explained how peatland specific evapotranspiration can be parameterized. In short, this was done by using the evapotranspiration package in two different ways: (1) by assuming the maximum evapotranspiration was constant throughout the year and (2) by assuming the maximum evapotranspiration has a seasonal cycle, simplified via a sine function. In both methods, the evapotranspiration did depend on the groundwater heads, but not on the *potential evaporation*. Instead of potential evaporation, a varying maximum evapotranspiration for peatland from Lafleur et al. (2005) was used.

Therefore, when looking at the effects of implementing the seasonal evapotranspiration feedback (ET_{ssn}), compared to model runs without an evapotranspiration feedback (ET_{off}) it should be noted that actually a combined effect is evaluated. Namely the effect of both implementing the evapotranspiration package and the effect of replacing seasonal varying potential evapotranspiration by a sine function for varying maximum evapotranspiration. However based on measurements in Canada, the latter does not take actual solar radiation, wind speed, air pressure and daily mean temperature into account. In further research, this should be taken into account by using the potential evapotranspiration and a seasonal correction factor for the canopy cover, instead of only a seasonal varying maximum evapotranspiration. This comment should be kept in mind when reading further trough the discussion.

In figure 4.8, during the dry year, is visible that implementing both a basic or a seasonal evapotranspiration feedback ($Ss_{zero}ET_{on}$ and $Ss_{zero}ET_{ssn}$) leads to higher groundwater tables and heads from August until December, compared to when no evapotranspiration feedback is implemented ($Ss_{zero}ET_{zero}$). This is explained by the fact that in the simulations with an evapotranspiration feedback, the evapotranspiration reduces with increasing groundwater depth. Under meteorological dry circumstances, the groundwater table and the heads lower, and the implementation of the evapotranspiration feedback causes then evapotranspiration also to reduce.

In figure 4.8 also is visible that when implementing the basic evapotranspiration feedback ($Ss_{zero}ET_{on}$), the evapotranspiration flux stays higher during the winter months and the beginning of spring (beginning of december to end of march), compared to the evapotranspiration flux in the winter months of simulations without an evapotranspiration feedback implemented ($Ss_{zero}ET_{off}$). This leads to groundwater tables and heads that are lower during winter and the beginning of spring, compared to model runs without an evapotranspiration feedback implemented. This reflects the limitations of implementing only a constant maximum evapotranspiration flux, as is done when implementing the basic evapotranspiration feedback. A negative feedback loop occurs in which more rain leads to higher heads, leading to more evapotranspiration with a maximum evapotranspiration rate that stays high, leading to lower heads. This is a pattern that pursues.

This pattern can be changed, when implementing a sine function for the maximum evapotranspiration rate, as is done in model runs with the seasonal evapotranspiration feedback implemented ($Ss_{zero}ET_{ssn}$). In those runs, the maximum evapotranspiration rate reduces during the winter months, leading to an increase in heads that is no longer inhibited by a maximum evapotranspiration rate that is too high. Therefore, the heads can increase towards the levels at the start of the summer.

When comparing the model runs with the basic evapotranspiration feedback implemented in table 4.4 ($Ss_{zero}ET_{on}$) and model runs with the seasonal evapotranspiration feedback implemented ($Ss_{zero}ET_{ssn}$) is also visible that the lowest head levels almost not change. Thus, in summary, the model runs with a basic evapotranspiration feedback implemented seem to be quite capable of simulating the dry periods, but lead to heads that are too low during more wet periods. In the case in which there are consecutive dry years, this effect of having too low heads during wet periods may become cumulative: since the heads cannot recover to their levels at the start of the summer, the heads will become increasingly low.

The fact that implementing only a basic evapotranspiration feedback leads to heads that are too low during wet periods is also reflected in the fluxes from the glyde towards the sand layer. Figure 4.9 and table E.2 show that model runs with both no evapotranspiration feedback or a feedback with a varying maximum evapotranspiration rate almost always have higher fluxes towards the environment, compared to model runs with a constant maximum evapotranspiration rate. Also this is due to the fact that the evapotranspiration of the model runs with a constant maximum evapotranspiration rate have an evapotranspiration flux that is too high during wet periods.

Just as with the implementation of the peat volume change, the implementation of the seasonal evapotranspiration feedback has most effects in the dry year, suggesting this feedback becomes increasingly important under dry circumstances.

5.5 Combined effects of implementing both peat volume change and an evapotranspiration feedback

From figure 4.10 and from table 4.5 it is apparent that implementing a specific storage into a model in which no specific storage and no evapotranspiration feedback is implemented, has more effect on the lowest groundwater tables and heads than implementing an evapotranspiration feedback. Also, implementing an evapotranspiration feedback into a model in which already a specific storage term is implemented, does not affect the lowest groundwater tables and heads that much. Thus, implementing an evapotranspiration feedback has less influence on the lowest groundwater tables and heads, compared to implementing a specific storage. However, it should be noted that the effect of the specific storage is also determined by the height of the specific storage term. In figure 4.10 a specific storage term of 0.125 m^{-1} (Ss_{med}) is used, while when using a lower specific storage term, for example of 0.02 m^{-1} (Ss_{low}), the difference between the implementation of the evapotranspiration feedback and the specific storage might be less pronounced. Effects on the modelled heads when implementing a low specific storage term are visualised in appendix A.1b. As storage terms can vary between bog systems, it is always important to account for an evapotranspiration feedback.

6 | Conclusion

This study focused on building a conceptual, 3D groundwater model of a raised bog system and determine the effects of implementing peat volume change and an evapotranspiration-water table feedback on the modelled heads in the peat system and the underlying sand soil, and on the fluxes leaving the bog system towards the underlying sand soil. This section will provide answers to the research questions, then some general remarks are done and lastly, some recommendations will be given.

Answers to the research questions
The first research question was: *How does peat volume change and and evapotranspiration-water table feedback influence the water system of an undisturbed raised bog?* From a literature study it can be concluded that due to peat volume change, the peat system is capable of maintaining groundwater tables relatively close to the surface. Furthermore, it can be concluded that due to the evapotranspiration-water table feedback, evaporative losses are reduced when the groundwater depth increases.

The second research question was: *To what extent is a simple, conceptual model capable of simulating the behaviour of an undisturbed raised bog?* The model that was build in this study is capable of simulating shallow water table dynamics of an undisturbed raised bog, however the model outcome seems to be insensitive for the modelled ditches. This is probably due to the high, but not unrealistic, resistance of the glyde layer as this limits the hydrological contact between the peat system and the ditches. A sensitivity analysis is necessary to determine the effects of the resistance of the glyde layer on the influence the ditches have on the modelled heads.

Furthermore, implementing an ambient groundwater level over a ditch level in the *General Head Boundary package*, is recommended. Drainage by ditches can also be captured by the drains that lay on top of the surface. An ambient groundwater level will then provide more accurate information on the fluxes leaving the bog system via the soil, towards the environment. This will likely become increasingly important when the glyde layer has a lower restistance or is absent.

The third research question was: *How can **peat volume change** be parameterized and incorporated into MODFLOW and how does this affect model simulations?* Peat volume change can be paramaterized using the specific storage in the Specific Storage package of iMOD Python. In this study, implementing a specific storage stabilizes groundwater tables and heads. Furthermore, a higher implemented specific storage, results in a delay in timing at which the lower layers reach their lowest groundwater levels and heads, compared to the timing at which the upper layers reach their lowest levels. Also, a higher specific storage leads to an increase in the flux leaving the bog system, towards the underlying soil. Ignoring or underestimating peat volume change makes the bog system appear more vulnerable to drought than in reality is the case and also the unique buffering effect the peat may have on its surroundings during dry periods is then underestimated.

The fourth research question was: *How can **an evapotranspiration feedback** be parameterized and incorporated into MODFLOW and how does this affect model simulations?* A feedback between evapotranspiration and the water table can be implemented using the *Evapotranspiration package* from MODFLOW. A constant maximum evapotranspiration may lead to an underestimation of the modelled heads and outgoing fluxes during winter time. A seasonally varying maximum evapotranspiration is needed to accurately model heads and outgoing fluxes throughout the year. During dry periods, implementing an evapotranspiration feedback with a seasonally varying maximum evapotranspiration leads to higher and more stabilized groundwater tables. For further improvement, a potential evapotranspiration corrected for the canopy cover should be implemented over a seasonally varying maximum evapotranspiration.

General remarks
In general, it can be concluded that both the implementation of a specific storage and a seasonal evapotranspiration feedback is important, as it leads to more water storage in the bog system. Implementing both hydrological processes results in the highest water storage, however not as much as the sum of both processes separately.

What also can be concluded is that all the observed effects, both of the specific storage and the evapotranspiration, are most pronounced during dry periods. From this it can be concluded that the hydrological processes become increasingly important when the bog system experiences drought.

Lastly, a general conclusion that needs to be emphasized, is that the results of this study apply to the currently simulated field situation: an undisturbed raised bog with a glyde layer at the base. However, the field situation can differ. For example, the glyde layer may be absent or differs in depth throughout space. This should be accounted for, when investigating the effects of the implementation of peat volume change and an evapotranspiration feedback. Also, in this study was assumed the raised bog was vegetated with Sphagnhum peatmosses. However, when this model study is put in the perspective of a *disturbed* raised bog system in the Netherlands, attention should be raised to the fact that those peatmosses are almost completely outcompeted by moor-grass. This moor-grass has much higher evapotranspiration rates, for which the model should account.

Recommendations
When continuing on this research, the following recommendations are made:

- A sensitivity analysis on the dependence of model results on differences between landscape settings in which raised bogs occur is recommended. In such a sensitivity analysis, special interest should be raised to the effects of the glyder layer on the model results.
- Improvements in the seasonal evapotranspiration feedback can be made. The maximum evapotranspration rate that is implemented in the *Evapotranspiration package* from MODFLOW should be replaced by the potential evapotranspiration, corrected by a factor for the vegetation type, corrected by a factor for the seasonal variation in canopy cover.
- The *General Head boundary package* with which ditches are simulated can better be used to simulate ambient groundwater levels, in order to more accurately simulate groundwater flow to the environment. As the drains are capable of simulation surface runoff, the ditches may be neglected when implementing ambient groundwater levels.

7 | Acknowledgements

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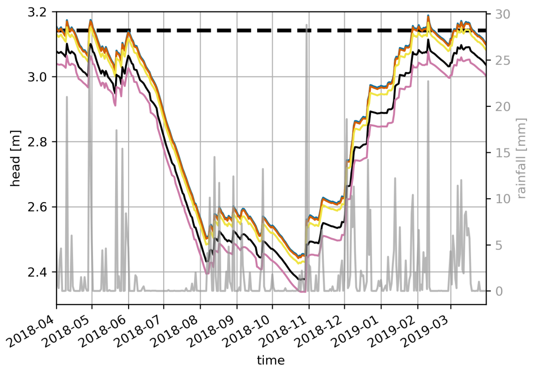
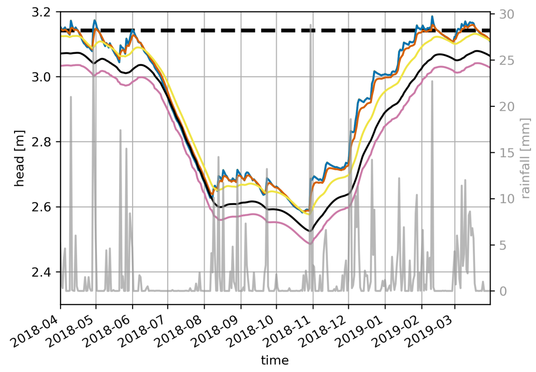
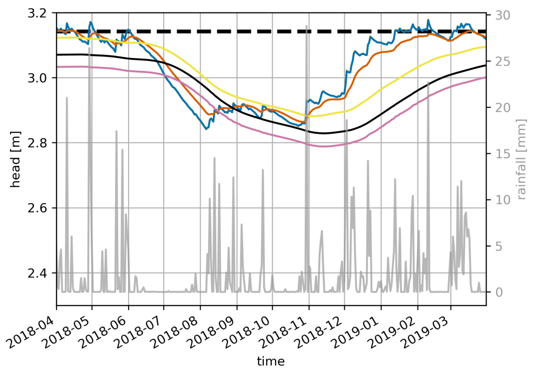
A | Groundwater Depth of Simulations ET_{off}



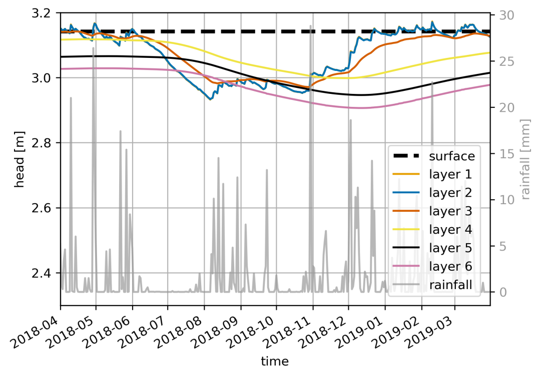
(a) $Ss_{zero}ET_{zero}$



(b) $Ss_{low}ET_{zero}$

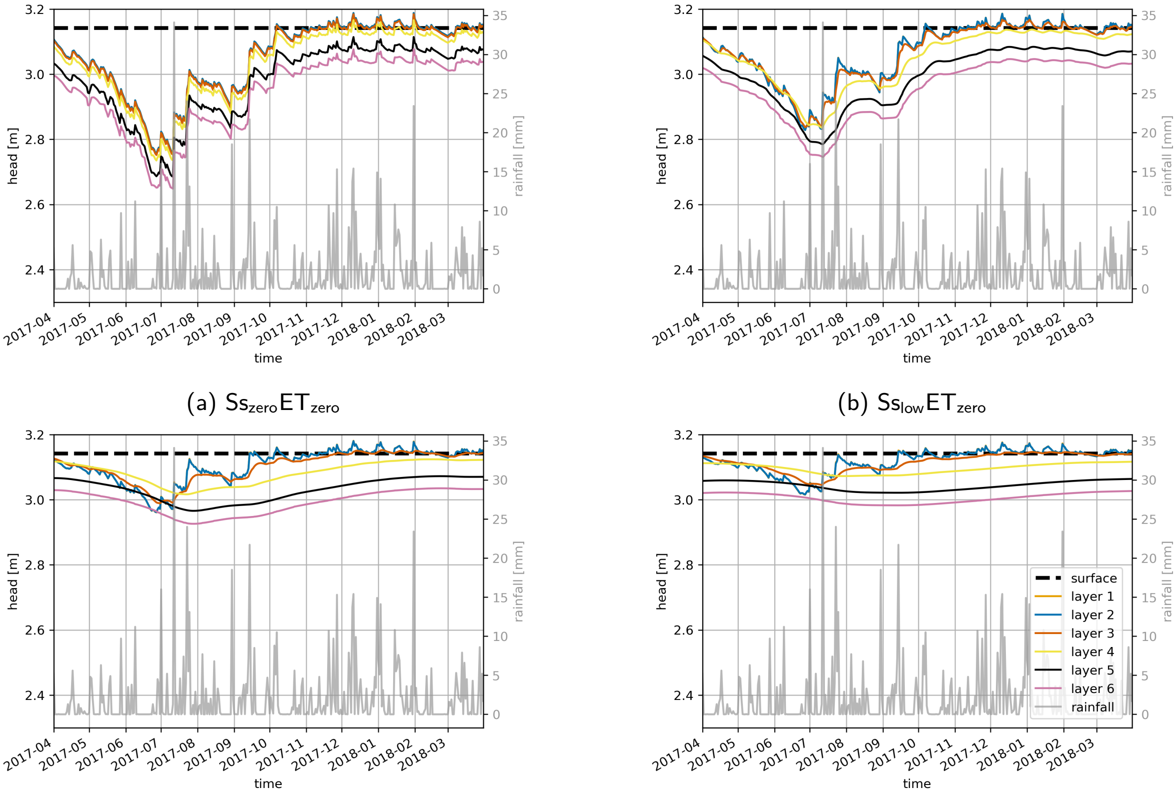


(c) $Ss_{med}ET_{zero}$



(d) $Ss_{high}ET_{zero}$

Figure A.1: Modelled groundwater heads for a dry year, different specific storages and with no evapotranspiration feedback implemented. For the exact values of the storage terms, see table 3.2.



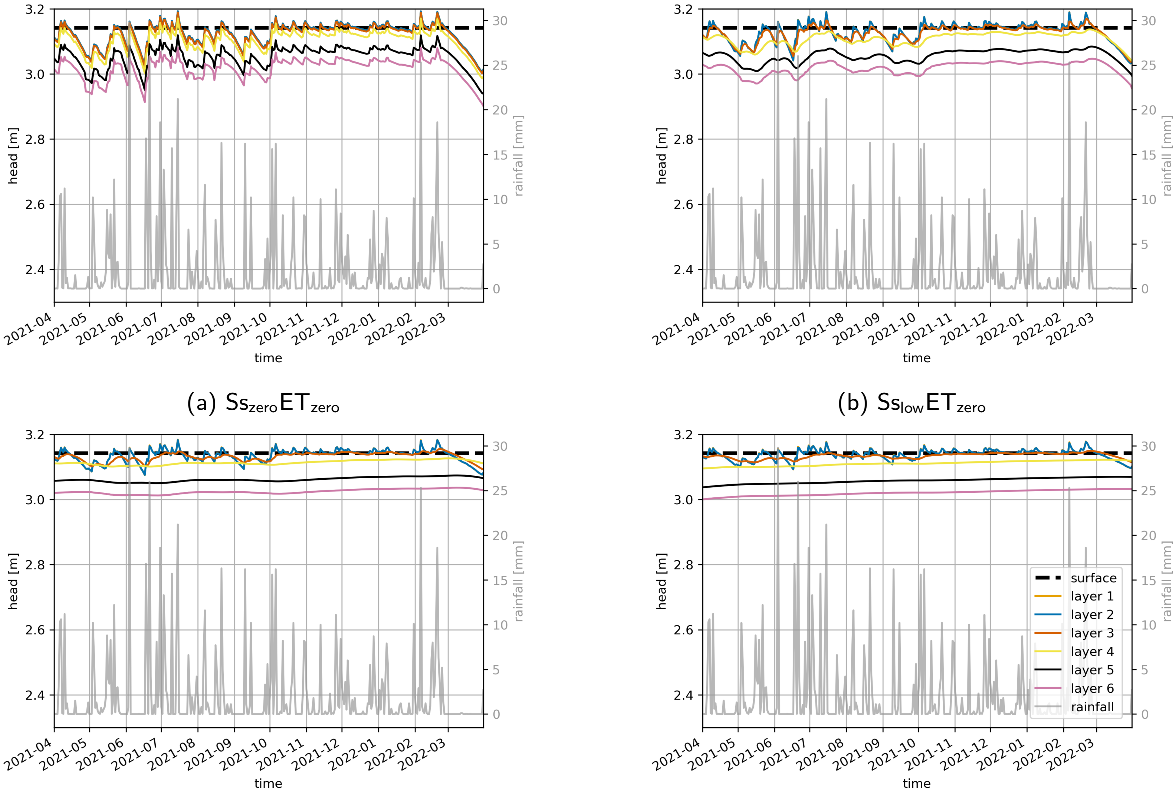
(a) $Ss_{zero}ET_{zero}$

(b) $Ss_{low}ET_{zero}$

(c) $Ss_{med}ET_{zero}$

(d) $Ss_{high}ET_{zero}$

Figure A.2: Modelled groundwater heads for an intermediate year, different specific storages and with no evapotranspiration feedback implemented. For the exact values of the storage terms, see table 3.2.



(a) $Ss_{zero}ET_{zero}$

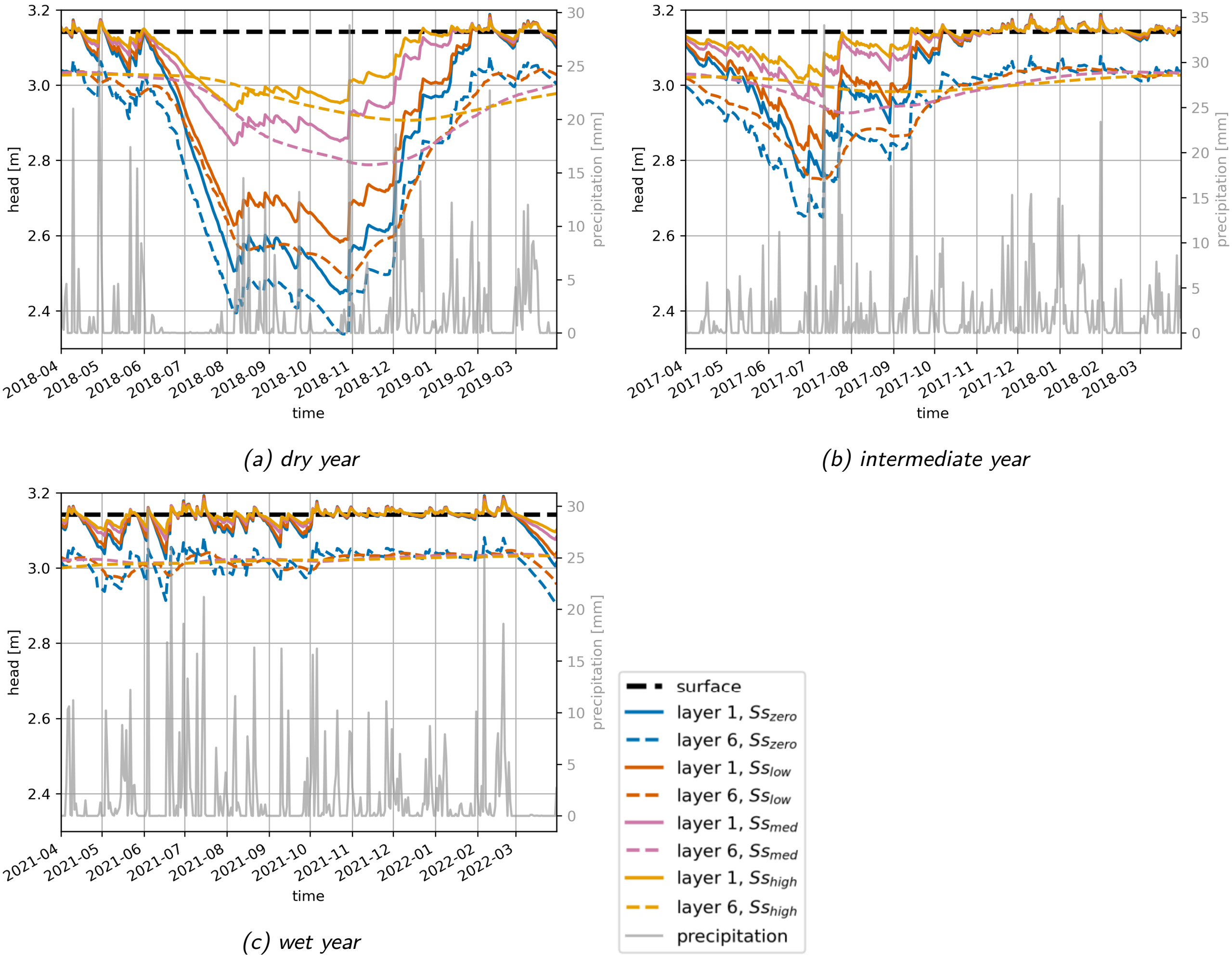
(b) $Ss_{low}ET_{zero}$

(c) $Ss_{med}ET_{zero}$

(d) $Ss_{high}ET_{zero}$

Figure A.3: Modelled groundwater heads for a wet year, different specific storages and with no evapotranspiration feedback implemented. For the exact values of the storage terms, see table 3.2.

B | Delay



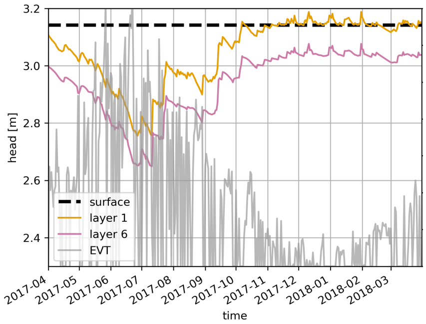
(a) dry year

(b) intermediate year

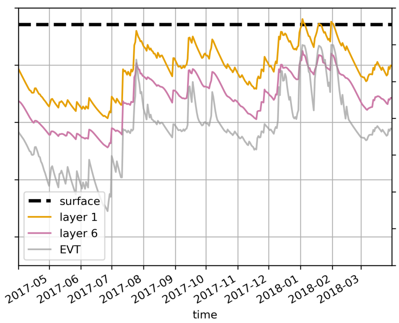
(c) wet year

Figure B.1: Delay in lowest groundwater tables (layer 1) and heads (layer 6) for a dry, intermediate and wet year, given for all specific storage scenario's.

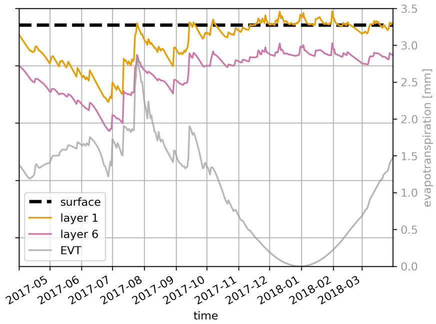
C | Combined Effects on modelled heads



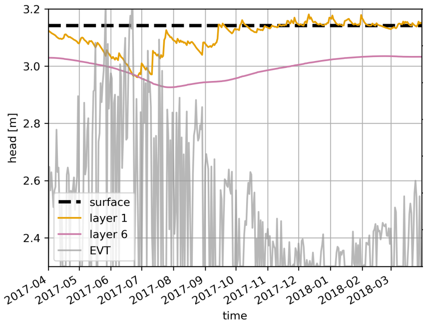
(a) *Intermediate year, $Ss_{zero}ET_{off}$*



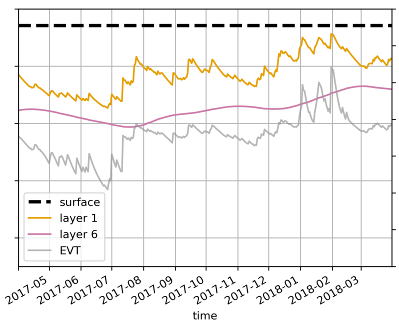
(b) *Intermediate year, $Ss_{zero}ET_{on}$*



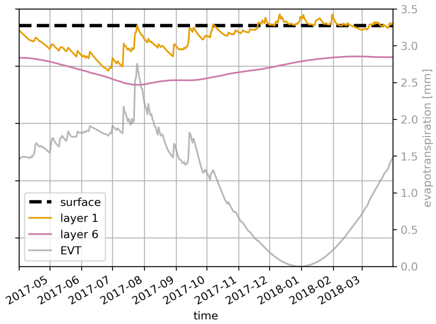
(c) *Intermediate year, $Ss_{zero}ET_{ssn}$*



(d) *Intermediate year, $Ss_{med}ET_{off}$*



(e) *Intermediate year, $Ss_{med}ET_{on}$*

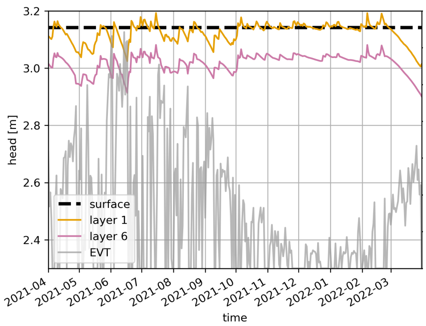


(f) *Intermediate year, $Ss_{med}ET_{ssn}$*

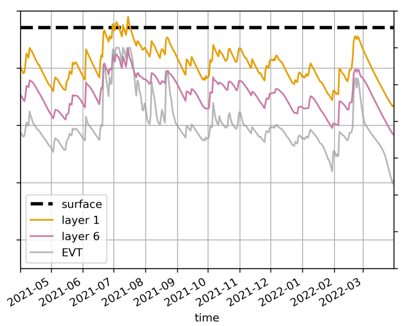
Figure C.1: Modelled heads of model simulations with no, a basic, or a seasonal evapotranspiration feedback and with no or a medium specific storage, given for an intermediate year

Table C.1: For layer 1 and 6 is given: the water table depth (WTD), the difference between surface level and the water table depth and a percentage difference calculated as follows: percentage difference $= \frac{ET_{on/ssn} - ET_{off}}{ET_{off}} \cdot 100\%$

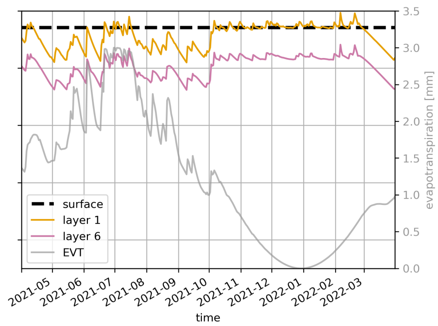
	intermediate year					
	lowest head $[m]$		**surface level − lowest head** $[m]$		**percentage diff.** $[-]$	
	L1	**L6**	**L1**	**L6**	**L1**	**L6**
$Ss_{zero}ET_{off}$ (C.1a)	2.76	2.65	0.38	0.49	-	-
$Ss_{zero}ET_{on}$ (C.1b)	2.81	2.71	0.33	0.43	52%	46%
$Ss_{zero}ET_{ssn}$ (C.1c)	2.87	2.77	0.27	0.37	61%	54%
$Ss_{med}ET_{off}$ (C.1d)	2.96	2.93	0.18	0.21	74%	74%
$Ss_{med}ET_{on}$ (C.1e)	2.85	2.79	0.29	0.35	58%	56%
$Ss_{med}ET_{ssn}$ (C.1f)	2.98	2.93	0.16	0.21	77%	74%



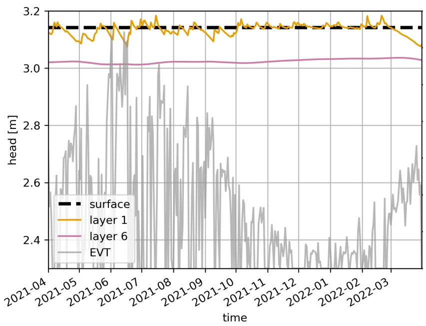
(a) Wet year, $Ss_{zero}ET_{off}$



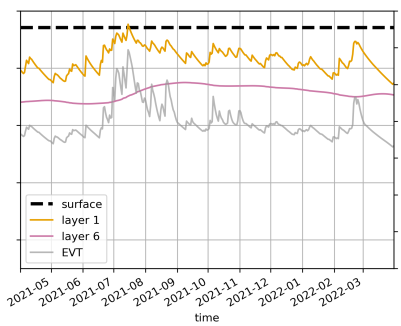
(b) Wet year, $Ss_{zero}ET_{on}$



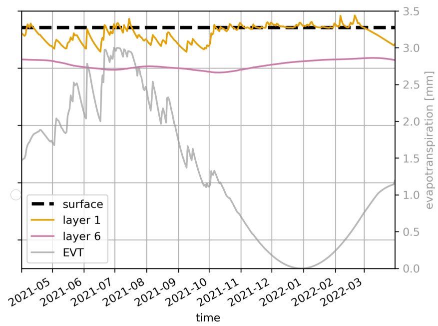
(c) Wet year, $Ss_{zero}ET_{ssn}$



(d) Wet year, $Ss_{med}ET_{off}$



(e) Wet year, $Ss_{med}ET_{on}$



(f) Wet year, $Ss_{med}ET_{ssn}$

Figure C.2: Modelled heads of model simulations with no, a basic, or a seasonal evapotranspiration feedback and with no or a medium specific storage, given for a wet year.

Table C.2: For layer 1 and 6 is given: the water table depth (WTD), the difference between surface level and the water table depth and a percentage difference calculated as follows: percentage difference $= \frac{ET_{on/ssn} - ET_{off}}{ET_{off}} \cdot 100\%$

	wet year					
	lowest head $[m]$		**surface level − lowest head** $[m]$		**percentage diff.** $[-]$	
	L1	**L6**	**L1**	**L6**	**L1**	**L6**
$Ss_{zero}ET_{off}$ (C.2a)	3.01	2.90	0.13	0.24	-	-
$Ss_{zero}ET_{on}$ (C.2b)	2.87	2.77	0.27	0.37	61%	54%
$Ss_{zero}ET_{ssn}$ (C.2c)	3.02	2.92	0.12	0.22	83%	73%
$Ss_{med}ET_{off}$ (C.2d)	3.07	3.01	0.07	0.13	90%	84%
$Ss_{med}ET_{on}$ (C.2e)	2.94	2.88	0.20	0.26	71%	68%
$Ss_{med}ET_{ssn}$ (C.2f)	3.06	2.98	0.08	0.16	88%	80%

D | Combined Effects on outgoing fluxes

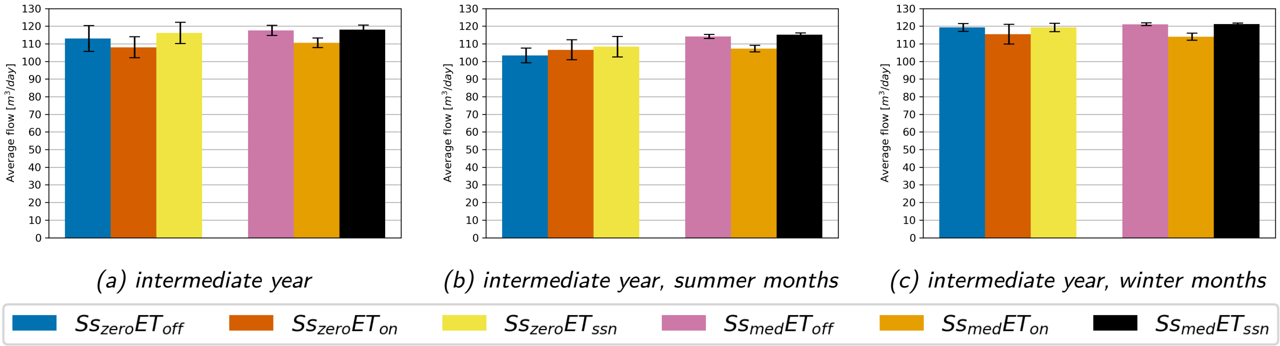


Figure D.1: Barplots showing the average flow from the glyde towards the sand layer for all model runs, for an intermediate year. The average is taken over the whole year and over the summer and winter months separately.

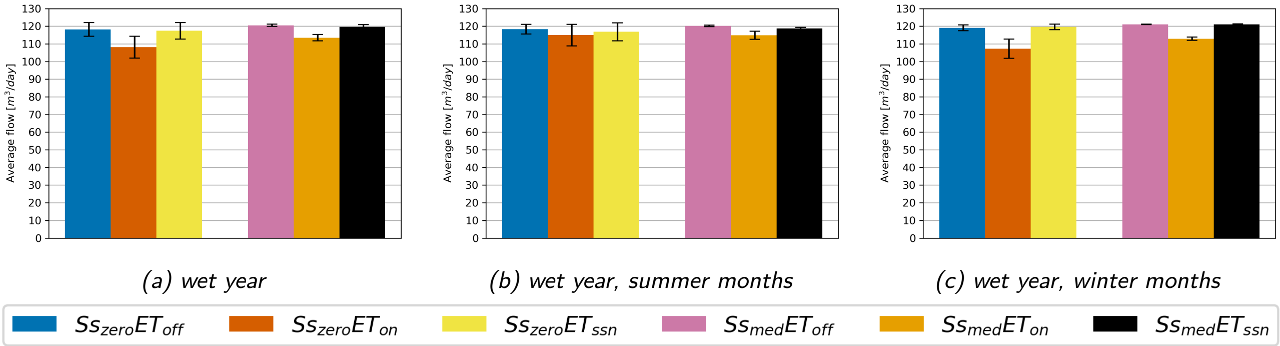


Figure D.2: Barplots showing the average flow from the glyde towards the sand layer for all model runs, for a wet year. The average is taken over the whole year and over the summer and winter months separately.

E | Complementary Barplot Data

Table E.1: Complementary to figure 4.7: The exact numbers of the average (median) outflow from the glyde towards the sand layer for model runs $Ss_{zero}ET_{off}$, $Ss_{low}ET_{off}$, $Ss_{medium}ET_{off}$ and $Ss_{high}ET_{off}$, for a dry, an intermediate and a wet year. Per year, the average is taken over the whole year and over the summer and winter months separately.

	dry year median flow $[m^3d^{-1}]$			**intermediate year median flow** $[m^3d^{-1}]$			**wet year median flow** $[m^3d^{-1}]$		
	year	**summer**	**winter**	**year**	**summer**	**winter**	**year**	**summer**	**winter**
$Ss_{zero}ET_{off}$	106	97	111	113	103	119	118	118	119
$Ss_{low}ET_{off}$	110	100	113	116	107	121	120	119	121
$Ss_{med}ET_{off}$	113	113	113	118	114	121	120	120	121
$Ss_{high}ET_{off}$	116	118	114	119	117	120	120	120	121

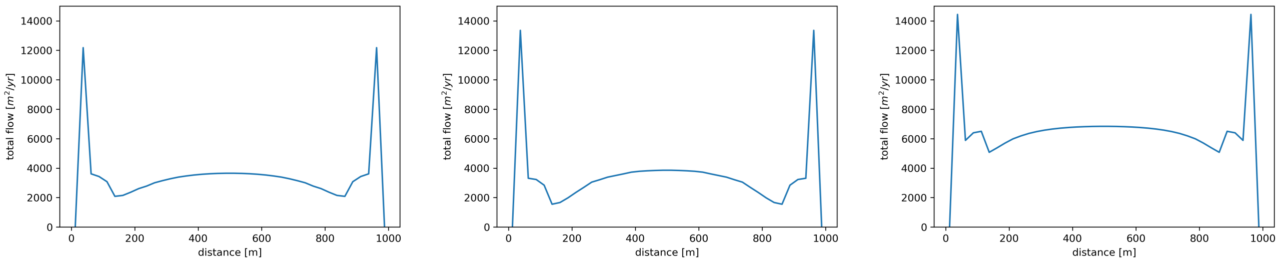
Table E.2: Complementary to figure 4.9: The exact numbers of the average (median) outflow from the glyde towards the sand layer for model runs $Ss_{zero}ET_{off}$, $Ss_{zero}ET_{on}$ and $Ss_{zero}ET_{ssn}$, for a dry, an intermediate and a wet year. Per year, the average is taken over the whole year and over the summer and winter months separately.

	dry year median flow $[m^3d^{-1}]$			**intermediate year median flow** $[m^3d^{-1}]$			**wet year median flow** $[m^3d^{-1}]$		
	year	**summer**	**winter**	**year**	**summer**	**winter**	**year**	**summer**	**winter**
$Ss_{zero}ET_{off}$	106	97	111	113	103	119	118	118	119
$Ss_{zero}ET_{on}$	105	101	109	108	107	115	108	115	107
$Ss_{zero}ET_{ssn}$	113	102	120	116	108	119	117	117	120

Table E.3: Complementary to figure 4.11: The exact numbers of the average (median) outflow from the glyde towards the sand layer for all model runs, for a dry year. The average is taken over the whole year and over the summer and winter months separately.

	dry year median flow $[m^3d^{-1}]$					
	year (4.11a)		**summer** (4.11b)		**winter** (4.11c)	
	Ss_{zero}	**Ss_{med}**	**Ss_{zero}**	**Ss_{med}**	**Ss_{zero}**	**Ss_{med}**
ET_{off}	106	113	97	113	111	113
ET_{on}	105	110	101	110	109	110
ET_{ssn}	113	117	102	113	120	119

F | Outflow by drains



(a) $Ss_{zero}ET_{off}$ (b) $Ss_{med}ET_{off}$ (c) $Ss_{zero}ET_{ssn}$

Figure F.1: Outflow by the drains, given for three different model simulations. On the y-axis the outflow is given, on the x-axis the cross-sectional distance of the model is given.

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