Master's Thesis – Master Water Science and Management

Subirrigation as a drought adaptation measure for the Deurnsche Peel nature area

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Summary

Recent climate change has increased the occurrence of prolonged drought events in the Netherlands, which stresses the need for more efficient and sustainable water management for the coming years. Furthermore, vulnerable nature areas in the Netherlands, such as the Natura 2000 (N2000) Deurnsche Peel, experience more drought damages in recent years. A promising drought adaptation measure explored in this study, is applying subirrigation on agricultural land plots surrounding vulnerable nature areas. In theory, the added water via subirrigation, can increase groundwater levels and create a hydrological counter pressure around nature areas, in order to reduce water losses from the nature area. The Dutch waterboard Aa en Maas is interested in implementing subirrigation and two subirrigation pilot projects are planned in the 500 meter hydrological protection zone (HPZ) around the Deurnsche Peel. The presented study here serves as a reconnaissance study to explore the effects and implications of implementing subirrigation in the HPZ. The aim of this study is to determine the effects of subirrigation on agricultural practices and groundwater levels in the N2000 Deurnsche Peel and analyse the implications for water management and policy of the waterboard Aa en Maas.

The regional groundwater model of the waterboard Aa en Maas was used in combination with a recently developed module to simulate subirrigation and the WOFOST crop development model. Multiple model scenarios were created which allowed for a sensitivity analysis of different parameterisation on the effects of subirrigation on agriculture, nature area and the water system. Scenarios were set up with variation in: the scale of implementation, the type of irrigation, subsurface resistance, timing, maximum control well water level, drain depth, crop type and subirrigation water supply limit. The research area included the N2000 Deurnsche Peel nature area and a zone of roughly 500 meter around the Deurnsche Peel, which represented the HPZ. The effects of subirrigation were analysed based on groundwater levels, crop yields, groundwater fluxes and the regional water balance.

Subirrigation was able to raise groundwater levels on both pilot land plots to desired levels (40-90 cm BGL) and therefore produced equal or higher crop yields (grass) in comparison with applying sprinkling irrigation. However, results also showed that limiting the water supply or infiltration capacity, resulted in lower crop yields in comparison with sprinkling irrigation. Moreover, the presence of hydraulic resistance in the subsurface below the drains was found to be crucial for maintaining sufficient groundwater levels for crop development. Furthermore, the added infiltration via subirrigation increased groundwater levels in the HPZ and nature area creating a hydrological counter pressure, which decreased percolation from the Deurnsche Peel nature area. Moreover, large scale application of subirrigation can supplement the regional groundwater budget in order to make regions more drought resistant.

Applying subirrigation required large amounts of water which decreases water availability for downstream areas. This can be harmful for downstreams stream ecology and agricultural practices. Therefore, regulations, temporal abstraction bans and user instructions regarding subirrigation are necessary to ensure proper functioning of subirrigation systems and minimise potential negative impacts.

Overall, subirrigation has proven to be a suitable alternative for sprinkling irrigation and is expected to reduce drought damages in the Deurnsche Peel nature area. The approach of using a groundwater model in combination with an unsaturated zone module and crop development model, was useful for analysing the effects of subirrigation. For future research, results from this study could be compared with actual measurements from both pilot projects, to validate and improve the used subirrigation module. Furthermore, it would be interesting for the waterboard to study the feasibility of subirrigation in other potential locations in their service area, based on the success criteria found in this study.

Samenvatting (in Dutch)

Met de huidige klimaatveranderingen is de intensiviteit en het aantal droge zomers in de laatste jaren toegenomen in Nederland. Aa en Maas heeft als waterschap de taak om droogteschade in kwetsbare natuurgebieden te beperken. Een van deze natuurgebieden is het Natura 2000 gebied Deurnsche Peel. In 2017 is project Leegveld gestart om grondwaterstanden en de waterbeschikbaarheid in de Deurnsche Peel te verhogen en op peil te houden. Een van de mogelijke vernattingsmaatregelen is het toepassen van regelbare drainage met subinfiltratie op landbouwpercelen in de attentiezone rondom de Deurnsche Peel. Door middel van regelbare drainage met subinfiltratie kunnen grondwaterstanden in desbetreffende percelen gestuurd worden en wordt de regionale grondwatervoorraad aangevuld met subinfiltratiewater. De verwachting is dat subinfiltratie en de mogelijke afname van beregeningsonttrekkingen in de attentiezone kan zorgen voor een hydrologische tegendruk, waardoor wegzijging uit het te beschermen natuurgebied verminderd wordt.

Het waterschap gaat twee pilotprojecten met subinfiltratie uitvoeren in de attentiezone rondom de Deurnsche Peel, waarbij dit onderzoek dient als verkenningsstudie om vooraf inzicht te krijgen in de effecten van subinfiltratie voor de landbouw en natuur in en rondom de Deurnsche Peel. Verder is het belangrijk om de watervraag van eventuele grootschalige toepassing van subinfiltratie in de attentiezone in kaart te brengen en de opgedane kennis te vertalen naar eerste beleidsadviezen rondom het toepassen van subinfiltratie binnen het beheergebied van Aa en Maas. De volgende vragen worden beantwoord tijdens dit onderzoek:

1) Wat zijn de effecten van subinfiltratie in de pilotpercelen onder verschillende parameters voor landbouw, N2000 Deurnsche Peel en het watersysteem?
2) Wat zijn de effecten van grootschalige subinfiltratie en mogelijke afname van beregening op de N2000 Deurnsche Peel en het watersysteem?
3) Wat zijn aanbevelingen aan het waterschap met betrekking tot beleidsvorming over de implementatie en waterverdeling ten behoeve van subinfiltratie?

Modelberekeningen zijn uitgevoerd met het grondwatermodel van Aa en Maas, waarbij gebruik gemaakt is van een binnen Lumbricus recent ontwikkelde MetaSWAP module waarmee subinfiltratie gesimuleerd kan worden. Berekeningen zijn gedaan over een tijdsperiode van 2015 t/m 2019 met een celgrootte van 25 bij 25 meter. Allereerst is er gerekend aan enkel de twee pilotpercelen, waarbij gevarieerd is met de volgende parameters: type irrigatie, bodemweerstand, periode van subinfiltratie, maximaal sturingspeil, draindiepteligging, gewastype en het wateraanvoerlimiet. Daarnaast zijn de regionale effecten van subinfiltratie bepaald door subinfiltratie grootschalig, op meerdere potentiële percelen, toe te passen. De effecten van subinfiltratie zijn geanalyseerd op basis van grondwaterstanden, gewasopbrengsten, wegzijging/kwel en regionale waterbalansen.

Effecten van subinfiltratie op de landbouw, natuur en het waterschap

Met subinfiltratie op de pilotpercelen konden gewenste grondwaterstanden tussen 40 en 90 cm -mv gerealiseerd en vastgehouden worden over de jaren 2016-2019. Gewasopbrengsten bleven gelijk of vielen hoger uit in vergelijking met het toepassen van beregening. Gemiddeld vond er op beide pilotpercelen met gras in het groeiseizoen (april t/m september) 795 mm aan subinfiltratie plaats. Maximaal berekende infiltratiehoeveelheden lagen tussen de 6 en 7 mm/dag, wat neerkomt op 24 l/s voor beide percelen opgeteld. Subinfiltratie zorgde echter niet onder alle omstandigheden/scenario’s voor gewenste grondwaterstanden en gewasopbrengsten. Zo vielen gewasopbrengsten lager uit bij een hogere bodemdoorlaatbaarheid, beperkte wateraanvoer of lager sturingspeil (80 cm -mv i.p.v. 50 cm -mv). Ten opzichte van een situatie zonder beregening was de gewasopbrengst voor deze scenario’s nog wel een stuk hoger. Ten slotte bleek het toepassen van subinfiltratie tijdens het voorseizoen (winter) voor de gewasopbrengsten weinig extra voordeel op te leveren.

Ook voor de Deurnsche Peel kan subinfiltratie, vooral bij grootschalige toepassing, gunstig zijn door de verhoogde grondwaterstanden. Subinfiltratie in de attentiezone zorgde voor een hydrologische tegendruk waardoor wegzijging in het natuurgebied verminderd werd. Ook leidt subinfiltratie tot een afname van beregening in de attentiezone.

Op dit moment wordt er in normale jaren ongeveer 330 l/s ingelaten in het gebied. In droge jaren kan dit worden verhoogd naar ongeveer 520 l/s. Dit water wordt deels ingelaten om de peilen in de attentiezone op peil te houden en deels om benedenstroomse beken watervoerend te houden. De watervraag voor subinfiltratie in de attentiezone rondom de Deurnsche Peel is groot in vergelijking met de totale hoeveelheid water dat ingelaten wordt. Voor het jaar 2017 zou er volgens modelberekeningen gemiddeld 94 l/s nodig zijn voor grootschalige subinfiltratie in de attentiezone. In droge jaren neemt de water vraag toe naar gemiddeld 112 l/s. Het grootschalig toepassen van subinfiltratie in de attentiezone vermindert de waterbeschikbaarheid benedenstrooms waardoor er eerder waterschaarste en ecologische schade benedenstrooms kan optreden.

Beleidsadviezen en -overwegingen voor subinfiltratie

Subinfiltratie biedt kans als maatregel om grondwaterstanden aan te vullen en/of als vervanging van beregening en zo gebieden meer klimaatrobuust te maken. Modelberekeningen bevestigen dat subinfiltratie, vooral in de buitenste zones, positief kan zijn voor de waterbeschikbaarheid in het nabijgelegen natuurgebied Deurnsche Peel en dus als ondersteunende maatregel kan dienen in de attentiezone.

Om subinfiltratie in het beheergebied van Aa en Maas in goede banen te leiden en eventuele negatieve effecten te minimaliseren, zijn er inzichten, regels, verboden en voorschriften nodig. Zo wordt het bijvoorbeeld aangeraden om onttrekkingsverboden ook te laten gelden voor subinfiltratie om waterschaarste benedenstrooms te beperken. Echter het advies is om deze maatregel zo laat mogelijk toe te passen, om zo de positieve effecten van subinfiltratie op grondwaterstanden en wegzijging zo lang mogelijk in stand te houden. Verder is kennisoverdracht en communicatie tussen de agrariër en het waterschap belangrijk voor het functioneren van subinfiltratie binnen het beheergebied van Aa en Maas. Het opstellen van gebruiksvoorschriften kan hierbij nuttig zijn, waarin bijvoorbeeld duidelijk beschreven staat welk drainageniveau geacht wordt om gevoerd te worden buiten het groeiseizoen.

Conclusie en aanbevelingen

Over het algemeen kan worden geconcludeerd dat subinfiltratie een goed alternatief kan zijn voor beregening om zo gebieden klimaatrobuuster in te richten en eventueel droogteschade in nabijgelegen natuurgebieden te verminderen. Daarnaast is er met dit onderzoek meer inzicht verkregen in de (regionale) effecten van subinfiltratie op het watersysteem en zijn eerste adviezen voor het nog te vormen subinfiltratiebeleid opgesteld.

Als vervolg op dit onderzoek is het interessant om de bevindingen te vergelijken met metingen en monitoring van beide subinfiltratie pilotprojecten in de attentiezone rondom de Deurnsche Peel. Zo kan de gebruikte module gevalideerd en waar nodig verbeterd worden. Daarnaast kan op basis van de geïdentificeerde slagingscriteria voor subinfiltratie eventueel een kansenkaart gemaakt worden voor het beheergebied van Aa en Maas.

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List of Abbreviations

BGL	Below Ground Level
GHG	Average of the highest groundwater levels (Gemiddeld Hoog Grondwater in Dutch)
GLG	Average of the lowest groundwater levels (Gemiddeld Laag Grondwater in Dutch)
HPZ	Hydrological Protection Zone
KAD	Klimaat Adaptieve Drainage
KNMI	Koninklijk Nederlands Meteorologisch Instituut
N2000	Natura 2000
NAP	Amsterdam Ordnance Datum (Normaal Amsterdams Peil in Dutch)
RCP	Representative Concentration Pathways

1. Introduction

Increased emission of greenhouse gasses during the past 50 years, have resulted in climate change worldwide. Both the year 2003 and 2018 were extremely dry years in central Europe with extreme heat waves causing extensive summer droughts. If no mitigation measures will be taken, as projected with Representative Concentration Pathways (RCP) 6.0 and 8.5, the occurrence of such events is expected to increase significantly in the 21st century (Christidis et al., 2015). Changes in temperature, precipitation, evaporation and weather extremes also effect the Dutch climate, as longer periods of droughts are increasingly common in recent years. In 2014, four climate scenarios were developed by the Royal Netherlands Meteorological Institute (KNMI), which describe the expected Dutch climate conditions in the coming century (KNMI, 2014). Both the average annual temperature and the annual mean precipitation are expected to increase in the Netherlands, whilst summers are expected to become drier. Furthermore, potential evaporation is projected to increase strongly in summer months because of the higher temperatures and increased solar radiation. Overall, climate change effects on temperature, precipitation and evaporation can, under extreme conditions, increase the occurrence of prolonged droughts in the Netherlands for this century.

The summer of 2018 was exceptionally dry, with an average precipitation deficit of 306 mm in the Netherlands (Sluijter et al., 2018). The effects of the drought in 2018 were widespread and impacted multiple water demand sectors such as agriculture, households, industry and natural ecosystems. Total economic damages were estimated between 0.5 and 2 billion euros according to the Dutch Ministry of Infrastructure and Water Management (van Hussen et al., 2019). The highest economic damages were in the agricultural sector followed by shipping, water management authorities and drinking water supply. The estimation of economic damages only partly portrays the total damages of the 2018 drought, as damages in follow-up years are not accounted for and damage to nature is unquantifiable. The effects of the drought on groundwater levels were persistent after the year 2018, especially in the higher sandy areas of the Netherlands (van den Eertwegh et al., 2019). This is mainly because groundwater systems react relatively slow and recharge in these areas is small because of the absence of major rivers.

The economic damages of droughts to nature are difficult to quantify, mainly because nature's water demand is hard to quantify. In a recent exploratory study on the water demand of nature in the Dutch province of Noord-Brabant, the total water demand is estimated between 50-60 billion litres water per year (Stuurman et al., 2020). This water is needed to maintain groundwater dependent nature areas such as peat areas, brooks, and heath lands. One of such a nature area within the district of the waterboard Aa en Maas is the Deurnsche Peel nature area. Characteristic for the Deurnsche Peel is the presence of ombrotrophic bog, a type of peat which is scarce in the Netherlands. Since this type of peat provides a home for rare flora and fauna, the Deurnsche Peel together with neighbouring nature areas Mariapeel, Grauwveen and Grote Peel are designated as Natura 2000 (N2000) areas since 2004. A sufficient water quantity and quality is essential for the conservation of biodiversity in these nature areas. Furthermore, low groundwater levels will induce peat decomposition, which is a source of CO_2 emissions in the Netherlands (van den Akker et al., 2008). That's why sustainable water management is key in and around these nature areas.

Waterboard Aa en Maas designated the Deurnsche Peel as one of their attention areas to focus on in recent and coming years. To minimise further biodiversity loss, peat oxidation and damages by future droughts in the Deurnsche Peel, the responsible waterboard Aa en Maas has started the project Leegveld in 2017. This project includes a hydrological protection zone (HPZ) of roughly 500 meter around the nature area, westwards of the Deurnsche Peel. Water practices in the HPZ are restricted to maintain the groundwater levels in the adjacent nature area. Because this zone mainly consists of agricultural lands, the high demand for irrigation water is in conflict with the functioning of the ombrotrophic bogs. Furthermore, with the increasing occurrence and intensity of droughts in the Netherlands, the demand for water in the HPZ will increase in the future. As regulated by the Dutch Verdringingsreeks, N2000 nature areas such as the Deurnsche Peel, have priority over agricultural lands regarding water allocation during water scarcity. To ensure water availability for both nature and agriculture, measures are needed which elevate the groundwater levels in the HPZ to create counter pressure for minimising water losses from the nature area. One of the proposed measures by the waterboard is implementation of subirrigation in combination with controlled drainage in the hydrological protection zone. By doing so, groundwater abstractions are reduced which decreases water stress in N2000 Deurnsche Peel. On top of that, subirrigation is expected to create a water buffer to mitigate water scarcity in the area.

Subirrigation is relatively uncommon in the Netherlands despite the growing interest (Verbiesen, 2020). Studies have been done on the effects of subirrigation on soil moisture content and crop development, which show that subirrigation can increase groundwater levels and soil moisture content, which optimises crop evapotranspiration (Bartholomeus et al., 2018). Another innovative technique in agriculture also aiming at maintaining sufficient groundwater levels, is Climate Adaptive Drainage or “Klimaat Adaptieve Drainage” (KAD) in Dutch (van den Eertwegh et al., 2013). This technique is similar to controlled drainage except that a KAD system can be remotely controlled and combined with weather forecasts to maintain optimal groundwater levels and limit drainage when downstream peak discharges are expected. Whilst KAD is a suitable system for water conservation, the system is not designed for supplying water to crops, which is the case for subirrigation systems. Other studies have focussed on more chemical soil and water interactions when implementing subirrigation (Bonaiti & Borin, 2010; Tsigoida & Argyrokastritis, 2020). Furthermore, a recent study on the implementation of subirrigation has shown that treated wastewater from wastewater treatment plants in the Netherlands can satisfy a significant amount of agricultural water demand at a national scale (Narain-Ford et al., 2021). The soil purifies the treated wastewater via infiltration and contaminants are filtered by sorption and (bio)transformation processes (Narain-Ford et al., 2020).

1.1 Study aim

The (regional) effects of subirrigation on neighbouring nature area are not yet studied in the Netherlands. Furthermore, the waterboard Aa en Maas seeks to gain insight in how subirrigation affects agricultural practices in the HPZ, water availability in the Deurnsche Peel nature area and what it means for future water management and policy regarding subirrigation. Therefore, the aim of this study is to determine the effects of subirrigation on agricultural practices and groundwater levels in the N2000 Deurnsche Peel and analyse the implications for water management and policy of the waterboard Aa en Maas. This study is part of the pilot *“Sub-irrigatie in beschermingszone N2000 Deurnsche Peel”* associated with the project Leegveld, where subirrigation systems will be installed at two agricultural land plots. The hypothesis of this research is that subirrigation causes counter pressure and lowers groundwater abstraction in the hydrological protection zone, which reduces water losses from the N2000 Deurnsche Peel nature area.

This study focusses solely on the (larger scale) quantitative effects of subirrigation as no chemical analysis is performed and the goal is not to optimise the subirrigation system design. Furthermore, subirrigation mentioned in this study is always applied in combination with controlled drainage.

1.2 Research questions

The following research questions were answered during this study:

Main questions:

1) What are the effects of pilot-scale subirrigation under different parameterisation on agriculture, the N2000 Deurnsche Peel and the water system?
2) What are the effects of larger scale implementation of subirrigation and the subsequent decrease of groundwater abstraction, on the N2000 Deurnsche Peel and the water system?
3) What are the recommendations for the waterboard regarding policy on implementation and water allocation concerning subirrigation?

Sub questions under main question 1 :

a) Is only subirrigation itself sufficient during droughts or is additional sprinkling irrigation needed?
b) How does a higher hydraulic resistance in the subsurface affect the local groundwater levels and subirrigation water demand?
c) What is the effect of inactivity during winter and an earlier stop of subirrigation water supply on crop development and nature?
d) What is the effect of the maximum water level in the subirrigation control well on crop development of grass and corn and how does the control well water level affect nature and the water system?
e) What is the effect of a subirrigation water supply limit on crop development?
f) What is the effect of the drain depth in the subirrigation system on agriculture and nature?

Sub questions under main question 2 :

a) How are groundwater levels and hydraulic heads in the Hydrological Protection Zone and N2000 Deurnsche Peel influenced by larger scale subirrigation?
b) How much water is needed for subirrigation in the Hydrological Protection Zone and could the system meet this water demand?

Sub questions under main question 3 :

a) Under what conditions should the waterboard stimulate subirrigation and where/when should it be prevented?
b) Should water abstractions for subirrigation be liable to abstraction bans, if they are enacted?
c) Are regulations regarding the inlet and outlet of water and setting of the drainage level during wet periods needed?
d) Should water allocation prioritise subirrigation over sprinkling irrigation based on the Dutch priority ranking when water is scarce?

2. Background

2.1 Definition of a drought

Droughts are a naturally occurring phenomenon and have affected humans for decades, especially in arid regions. Examples are the extensive drought known as the “Dust Bowl” in the 1930’s and the major 1976 European drought (Fink et al., 2004; Schubert et al., 2004). Although droughts are naturally occurring events, their occurrence and severity is expected to increase under the current human-induced climate change (IPCC, 2018; Spinoni et al., 2018). This is also true for the Netherlands as it is expected that climate change increases the occurrence and severity of droughts in the Netherlands (KNMI, 2014).

There are four types of droughts to be distinguished (Dingman, 2015; Van Loon, 2015), propagating into one another in successive order (Wang et al., 2016). Firstly, the lack of sufficient precipitation over a longer period of time is classified as a meteorological drought. Below average precipitation values often coincide with high temperatures, low air humidity, high winds and high solar radiation, which result in excessive evapotranspiration losses. Over a longer period of time, a meteorological drought can propagate into an agricultural or soil moisture drought, which impacts crop development as soil moisture in the root zone is limited. When meteorological and agricultural droughts occur on a bigger time and spatial scale, the drought can propagate into a hydrological drought, characterised by below average surface and subsurface/groundwater levels. Finally, the impacts of all aforementioned drought types can result in a socio-economic drought when water resource systems fail or the health of the population is affected. The above mentioned drought types propagate into each other in the following order: meteorological, agricultural, hydrological and socio-economic drought (Dingman, 2015). Similarly, the time it takes to recover when precipitation returns to normal values follows the same sequence. The types of drought relevant for this study are the agricultural and hydrological drought.

2.2 Subirrigation as an efficient irrigation technique

For as long humans are growing crops for their food supply, irrigation has been needed to stimulate plant growth and optimise crop production. The green revolution in the late 1960’s increased the worldwide crop production in order to cope with the growing world population (Khush, 2001). Although the green revolution is especially known for the adoption of genetically improved crops combined with improvements in agrochemicals and agricultural mechanisation, developments in irrigation practices were also responsible for the intensification of agricultural practices. Due to improvements in irrigation, farmers were able to prolong the growing season an produce more and better yields. The intensification of agricultural practices in the Netherlands increased the stress on water resources, especially in more arid regions with low water availability, such as the higher elevated sandy areas. The increased water stress has driven the need for more efficient irrigation techniques.

An example of an efficient irrigation technique is subirrigation with controlled drainage. Firstly, controlled drainage is a system where the drainage level can be regulated in order to minimise drainage and conserve water in the field. Subirrigation applies when besides draining, water is also supplied via the drain system (Figure 1). Water is supplied from nearby surface water or local groundwater to a control well which regulates the irrigation water supply to the drains. This way groundwater levels can be set up and maintained at desired levels, depending on the crop type and capillary rise in the subsurface. Since water is supplied underground, evaporation and runoff losses are minimised which makes subirrigation a more efficient irrigation technique in comparison with sprinkling. Excess water to be discharged during wetter times or sowing practices, is discharged via a controlled drainage well into nearby surface water (Figure 1).

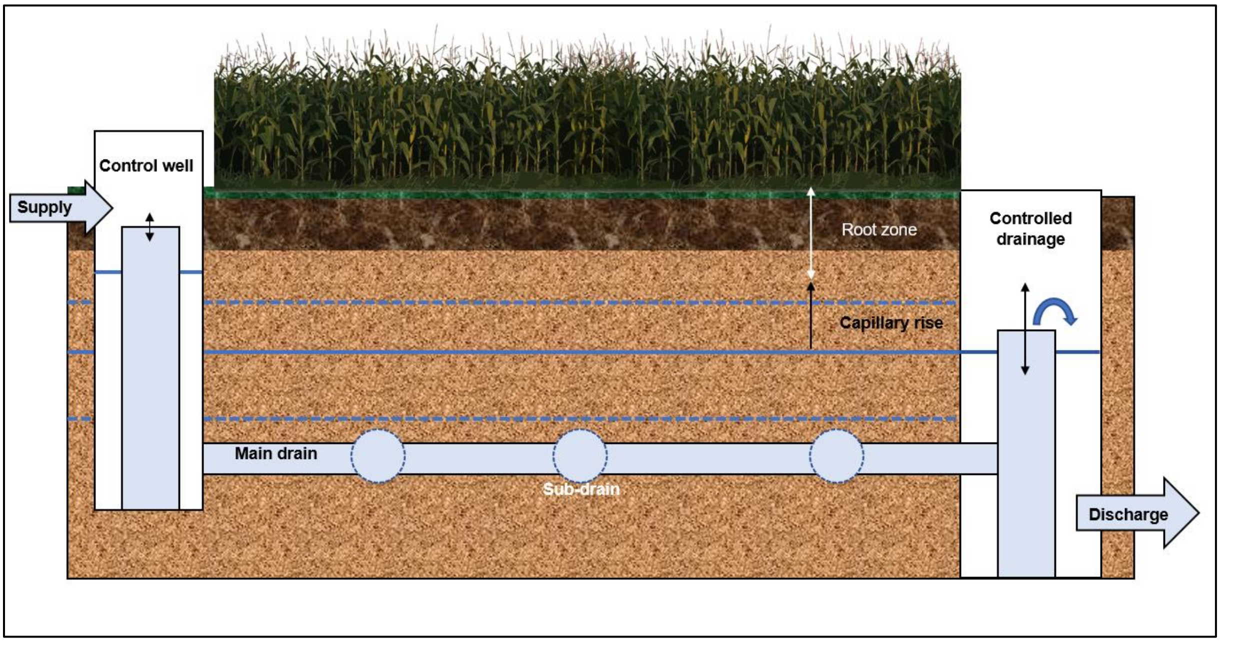


Figure 1, Schematic overview of a subirrigation system

An advantage of subirrigation besides the lower evaporation losses, is that once installed, water can be supplied continuously to the land plot and no more heavy machinery is required for irrigation. This reduces the amount of soil compaction. Disadvantages of a subirrigation system are the high initial investment costs and need for regular maintenance as the drains can silt up which diminishes system functioning. However, it can be argued that a subirrigation system, when functioning properly, will be profitable on the long term as crop yields are better, drought damages lower and less fuel costs are needed for distributing water compared with sprinkling irrigation.

3. Material and Methods

3.1 Study area

The study area is located in the south-eastern part of the province of Noord-Brabant and the service area of waterboard Aa en Maas (Figure 2). It describes the protected Deurnsche Peel nature area and the surrounding HPZ, which are in total 2700 hectares. Characteristic for the area are the remnants of an extensive raised bog area, "*Hoogveen*" in Dutch. These remnants, which the Deurnsche Peel is part of, are designated as N2000 areas because of the presence of rare flora and fauna. When the peat extraction started in 1870 the total area of raised bog significantly decreased as peat was excavated and used as fuel for house heating. For transporting all the excavated peat, the Deurnsche Peel canal was constructed, currently flowing through the N2000 Deurnsche Peel. The excavated areas where later on reoccupied with agriculture and urban area. Nowadays, the Deurnsche Peel nature area is positioned as an island in an agricultural area with specific hydrological demands. During winter and spring groundwater levels are preferred lower than natural conditions, to make the land practicable and prevent damages to agricultural land. During summer however, groundwater levels are most of the time insufficient for crop development and additional irrigation is needed. Most of the agricultural land is used for growing crops of which the majority are grass, corn and potatoes.

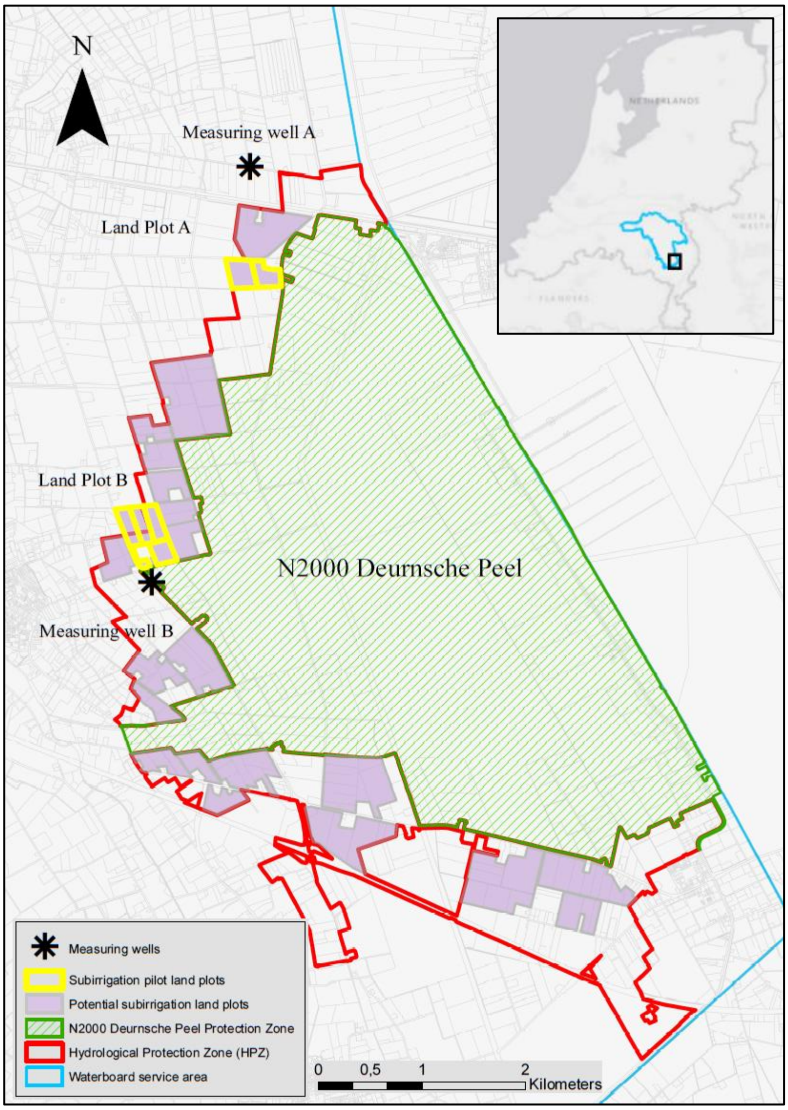


Figure 2, Overview of the study area

The two pilot land plots are located in the HPZ westwards of the N2000 Deurnsche Peel protection zone (Figure 2). The effects of subirrigation were modelled in detail for these two plots at first and later on, subirrigation was simulated on more land plots (potential land plots in Figure 2). The total areas for land plot A and B are 12.2 ha and 19.5 ha respectively. Both land plots are dedicated to growing fodder crops, mainly grass alternated with corn, to feed cattle on the dairy farms. Currently, the mean elevation of plot A is 30,1 meters above Amsterdam Ordnance Datum (NAP) and 29,2 meters above NAP at land plot B. The subsurface in the study area mainly consists of fine to coarse sand with occasional peat and loamy layers in the upper 2 meters (TNO, 2021).

Water in the Deurnsche Peel and the HPZ is distributed via canals, streams and ditches. The main water supply of the area is via the Deurne canal. The Deurne canal is fed by the Noordervaart, which in turn is fed by water from the Meuse river. The most important streams supplying water from the Deurne canal to the HPZ are the Vlier, the Oude Aa and the Soeloop. The network of small streams is managed by weirs and pumps and the area drains in westward direction. Adjacent to land plot A is the Vlier and adjacent to land plot B are the Peel loop and Hogedonkse loop. Stream water levels around both land plots can be maintained by the existing weirs and installation of a pump is planned for land plot B.

The regional hydrology is a result of the presence of the Peelrand fault and the subsequent elevation differences between the horst and graben (Stouthamer et al., 2015). The net regional groundwater flow direction is towards the graben located westwards of the study area. Groundwater flows thus from the Deurnsche Peel nature area westwards through the HPZ before reaching the Peelrand fault zone or seeping into local streams.

3.2 Research approach

This study is divided into 2 parts, as described in Figure 3 . Part 1 describes the modelling of both small and large scale implementation of subirrigation in the study area. Model results are then interpreted and evaluated with information on current water policy regarding subirrigation. Furthermore, it is discussed whether the current water distribution network is sufficient when subirrigation is implemented on a larger scale. These discussions lead to recommendations regarding both implementation and future policy on subirrigation for the waterboard Aa en Maas in part 2.

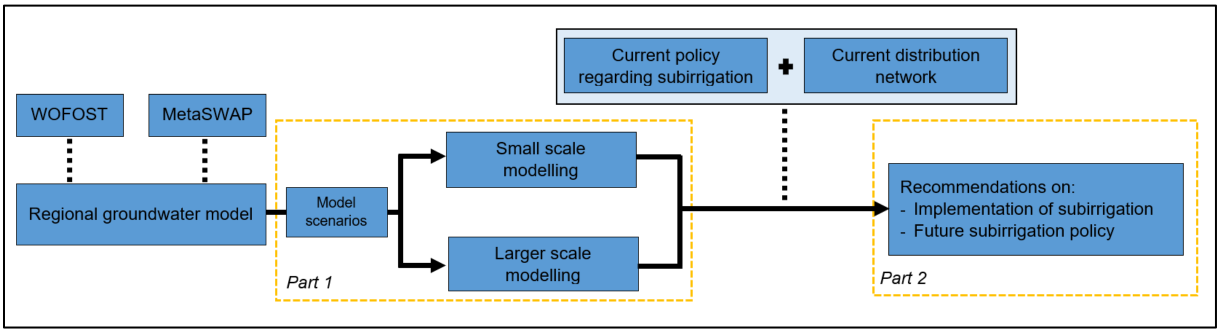


Figure 3, Workflow diagram describing the two parts of this study

3.3 Part 1: Subirrigation modelling

Groundwater modelling is a useful tool for making water management decisions in the service area of the waterboard Aa en Maas. Modelling is a relatively simple and effective method for understanding the effects of hydrological measures, such as subirrigation, on the hydrology of an area. Furthermore, different scenarios can be created to explore how a system responds under different conditions. That's why groundwater modelling is used in the first part of this study. Multiple model scenarios are set-up to vary between relevant model parameters and answer the different sub-questions.

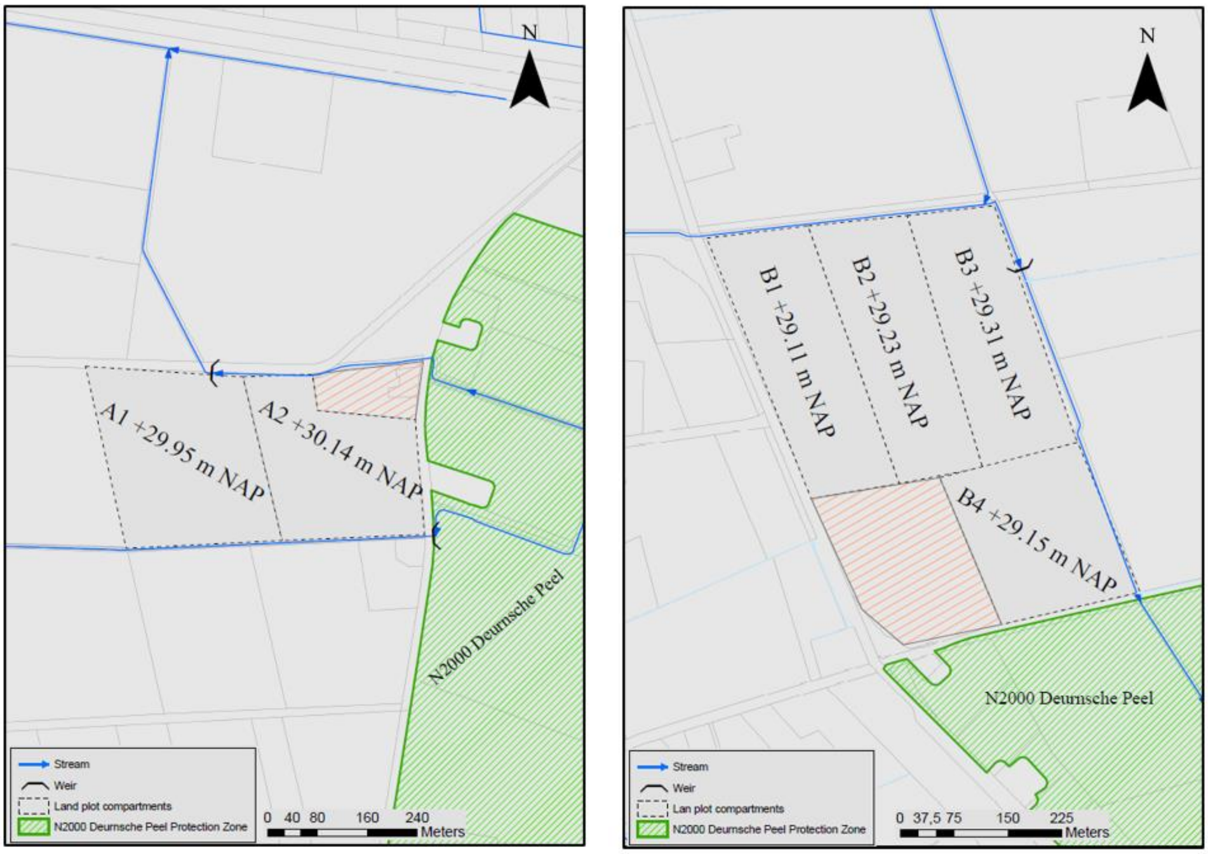
3.3.1 Model setup

To model the effects of subirrigation in this study, the regional hydrological groundwater model of the waterboard Aa en Maas is used in combination with the MetaSWAP (Soil-Water-Atmosphere-Plant) and WOFOST (WOrld FOod STudies) model. MetaSWAP is used to model soil-water interactions in the unsaturated zone in relation to atmospheric conditions and plants (Kroes et al., 2017), whilst WOFOST is used to simulate crop development (de Wit et al., 2020). Controlled drainage with subirrigation is simulated by using a MetaSWAP module recently developed within the Lumbricus program (Pouwels et al., n.d.). All models are combined and simulated in the iMOD software (Vermeulen et al., 2020).

The structure and hydraulic properties of the soil layers in the model are based on the BRO GeoTOP v1.4 subsurface model of the Geological Survey of the Netherlands (TNO, 2021) and consist of 19 layers with a total depth of 200 meters at the location of both land plots (Appendix A). To determine the effects of subirrigation in the study area, the model encompasses an area of 8 by 8 kilometres. As the focus in this study is more on the regional effects of subirrigation, a relatively low model resolution of 25 by 25 meters was chosen. Simulations covered a time period of 5 years from 01-01-2015 till 31-12-2019, whereby the first year (2015) is used as a run-up year. Since the hydrological response time in the study area is relatively short, a run up time of only one year was sufficient to ensure stable groundwater heads and soil moisture conditions.

All input data for the regional groundwater model, MetaSWAP and the WOFOST model was existing and provided by the waterboard Aa en Maas. However, since both pilot land plots are modelled in more detail, some input data needed verification and adaptation to simulate the current and future situation with subirrigation. Verified input data are: locations of sprinkling irrigation, current locations of drainage and water levels in neighbouring streams. The functioning of the model was validated by comparing modelled (current situation) groundwater levels with measured groundwater levels in the study area.

The design and conceptualisation of the subirrigation systems is based on the planned design of the two pilot land plots, as provided by the installation contractor. First of all, the ground levels were equalised on each land plot, for proper functioning of the system. Each land plot was subdivided into different compartments with a specific ground level and drainage depth, as illustrated in Figures 4a and 4b. The subirrigation supply pipes are positioned at 90 cm below ground level. The system is active all year round so that groundwater levels can be maintained between 40 and 90 centimetres below the surface level.



Left: Figure 4a, Subirrigation system design on land plot A with the different compartments (A1-A2) and specific ground levels; Right: Figure 4b, Subirrigation system design on land plot B with the different compartments (B1-B4) and specific ground levels

Part of the aim of this study is to determine the effects of subirrigation when it is applied on a larger scale in the study area. To do so, subirrigation was assigned to other potential land plots for larger scale modelling, as illustrated in Figure 2 . Selection of these potential land plots was done in consultation with associated waterboard hydrologists and policy officers. Input data for these plots is not validated and verified in the same detail as is done for the pilot land plots.

3.3.2 Model scenarios

The 18 scenario's created for this study represent different conditions, designs and strategies under which subirrigation can be implemented in the study area. Varying parameters are type of irrigation, subsurface resistance, timing, maximum control well water level, drain depth, crop type, scale of implementation and supply limit (Table 1). The subset of these model scenarios allowed for a sensitivity analysis on the effects of different parameterisation on agriculture, nature area and the water system.

Table 1, Model scenarios under different parameterisation

Scenario	Goal	Parameter	
1	Simulating current situation with sprinkling irrigation on a pilot land plot scale	Subirrigation	None
		Sprinkling irrigation	On both pilot land plots
		Subsurface	Based on GeoTOPv1.4
		Timing	N.A.
		Max control well level	N.A.
		Drain depth	N.A.
		Crop type	Grass
		Scale	Pilot land plots (small)
		Infiltration limit	N.A.
2	Simulating current situation without sprinkling irrigation on a pilot land plot scale	Sprinkling irrigation	Not on the two pilot land plots
		All other	As scenario 1
3	Effects of small scale (pilot land plots) implementation of subirrigation Used as reference for scenarios 4 to 14	Subirrigation	On the two pilot land plots
		Sprinkling irrigation	Not on the two pilot land plots
		Subsurface	Based on GeoTOPv1.4
		Timing	All year (Jan-Dec)
		Max control well level	50 cm below ground level
		Drain depth	As designed (90 cm BGL)
		Crop type	Grass
		Scale	Pilot land plots (small)
		Infiltration limit	No limit
1a: Is only subirrigation itself sufficient during droughts or is additional sprinkling irrigation needed?			
4	Effect of additional sprinkling irrigation on pilot land plots	Sprinkling irrigation	Additionally on pilot land plots
		All other	As scenario 3
1b: How does a higher hydraulic resistance in the subsurface affect the local groundwater levels and subirrigation water demand?			
5	Effect of higher hydraulic resistance in the subsurface	Subsurface	Increased resistance of layer 3
		All other	As scenario 3
6	Effect of higher hydraulic permeability in the subsurface	Subsurface	Increased horizontal permeability of layer 3 and 4
		All other	As scenario 3
1c: What is the effect of an earlier start and earlier stop of subirrigation water supply on crop development and nature?			
7	Effect of winter inactivity of the subirrigation system	Timing	Apr-Sep
		All other	As scenario 3
8	Effect of an earlier stop of subirrigation water supply	Timing	Jan-Jun
		All other	As scenario 3
1d: What is the effect of the maximum water level in the subirrigation control well on crop development of grass and corn and how does the control well water level affect nature and the water system?			
9	Effects of subirrigation control well level when growing grass	Crop type	Gras
		Max control well level	80 cm below ground level
10	Effects of subirrigation control well level when growing corn	Crop type	Corn
		Max control well level	50 cm below ground level
11	Effects of subirrigation control well level when growing corn	Crop type	Corn
		Max control well level	80 cm below ground level
1e: What is the effect of a subirrigation water supply limit on crop development?			
12	Effect of a subirrigation infiltration limit	Infiltration limit	2 mm/day
		All other	As scenario 3
1f: What is the effect of the drain depth in the subirrigation system on agriculture and nature?			
13	Effect of a shallower drain depth	Drain depth	60 cm below ground level
		All other	As scenario 3
14	Effect of a deeper drain depth	Drain depth	120 cm below ground level
		All other	As scenario 3
2: What are the effects of larger scale implementation of subirrigation and the subsequent decrease of groundwater abstraction, on the N2000 Deurnsche Peel and the water system?			
15	Effects of larger scale implementation of subirrigation	Scale	Multiple land plots (large)
		Max control well level	50 cm below ground level
		All other	As scenario 3
16	Effects of larger scale implementation of subirrigation	Scale	Multiple land plots (large)
		Max control well level	80 cm below ground level
		All other	As scenario 3
17	Simulating the current situation with sprinkling irrigation on selected subirrigation land plots	Subirrigation	None
		Scale	Multiple land plots (large)
		Sprinkling irrigation	On selected land plots
		All other	As scenario 1
18	Simulating the current situation without sprinkling irrigation on selected subirrigation land plots	Subirrigation	None
		Scale	Multiple land plots (large)
		Sprinkling irrigation	Not on selected land plots
		All other	As scenario 1

To correctly compare the effects of subirrigation with current irrigation strategies, scenarios 1 and 2 are created which describe the current situation with and without application of sprinkling irrigation. By comparing scenarios 1 and 2, the potential negative effects of groundwater abstraction for sprinkling irrigation can be determined. Scenario 3 serves as the baseline scenario for implementing subirrigation on the pilot land plots. Furthermore, scenarios 4 up to 14 are created to model the effects of subirrigation under different conditions, designs and strategies, as described in Table 1.

Specifically under scenario 5, a higher hydraulic resistance (5000 days) for the third aquifer layer is simulated. The third layer was chosen since this is the first layer beneath the subirrigation supply pipes. Moreover, for scenario 6 a higher hydraulic transmissivity was simulated as the horizontal permeability of layer 3 and 4 was increased (see Appendix A). Finally, under scenarios 15 and 16, subirrigation is implemented on multiple land plots additional to the two pilot land plots, to model the effects and demands for larger scale implementation of subirrigation in the HPZ. Scenarios 17 and 18 serve as reference for the aforementioned larger scale scenarios (15 and 16).

3.3.3 Model results analysis

First of all water balances are created for each pilot land plot by calculating term fluxes in and out over the whole depth (layer 1 to 19) for the current situation and under implementation of subirrigation. This is done to gain insight into the fate of the infiltrated water and understand the effects of subirrigation on the water system. Data is shown mostly for the year 2017 only, since this was a normal year in terms of rainfall. However, water balances for other years are included in the Appendix. Secondly, to determine the effects of subirrigation on both agriculture and nature, output data from the model is visualised and compared between relevant scenarios. For example the mean of the three highest and/or lowest groundwater levels, GHG and GLG in Dutch, was analysed for different scenarios. More specifically, for the effects of subirrigation on crop development, crop production output from the WOFOST model was analysed.

When subirrigation is modelled on a larger scale, again a water balance was set up, to determine subirrigation water demands in the study area. Water demands are compared with water inlet to the area based on a report by Folmer et al. (2020). Furthermore, data was analysed on vertical groundwater flow fluxes between the upper model layers (L1 and L4). Layer 1 and 4 were chosen as they provide insight into percolation or seepage of groundwater. Groundwater flow fluxes were used to verify the hypothesis that the created counter pressure minimises water losses from the nature area.

3.3.4 Subirrigation module

For modelling subirrigation a recently developed module is used (Pouwels et al., n.d.). During this study it was found that the calculated amount of infiltration was strongly limited when groundwater levels dropped below the drainage depth of the subirrigation pipes (Appendix B). A drain depth of 90 cm BGL, based on the intended design, resulted in an underestimation of the amount of infiltration for the intended baseline scenario (scenario 3). Still, due to time constraints, it was decided to remain with 90 cm BGL as the drain depth for all scenarios other than 13 and 14. A deeper drainage dept of 120 cm BGL, as simulated under scenario 14, resulted in unrestricted infiltration. Where necessary, results of scenario 14 (unrestricted infiltration) are used as reference instead of scenario 3 (restricted infiltration).

The control well water level calculated in the subirrigation module remains at its maximum (50 cm BGL or 80 cm BGL in this study) if no oxygen stress is impended and the pressure head threshold values for agricultural practices are not exceeded. Threshold values are based on crop- and soil type and were between -40 and -80 cm for grass and -60 and -100 cm for corn in this study. When oxygen stress occurs or the threshold values are exceeded the control well water level is temporarily lowered in the module.

3.4 Part 2: Subirrigation policy recommendations

The research under part 2 focusses on the interpretation of the results of part 1 and translating these findings into advice for the waterboard on policy regarding subirrigation. Issues and concerns regarding the policy on subirrigation were identified in conjunction with a waterboard policy officer and by analysing current policy documents.

4. Results

4.1 Comparison model results with measurements

Overall, modelled groundwater levels and hydraulic heads were comparable with measured data from both measuring wells (Figure 5). Some outliers in the measured timeseries, caused by nearby groundwater abstractions or measuring errors, are not registered in the modelled data. Furthermore, measured data show a faster response in the wetting curve whilst modelled heads are well in line with measurements when hydraulic heads drop (drying curve).

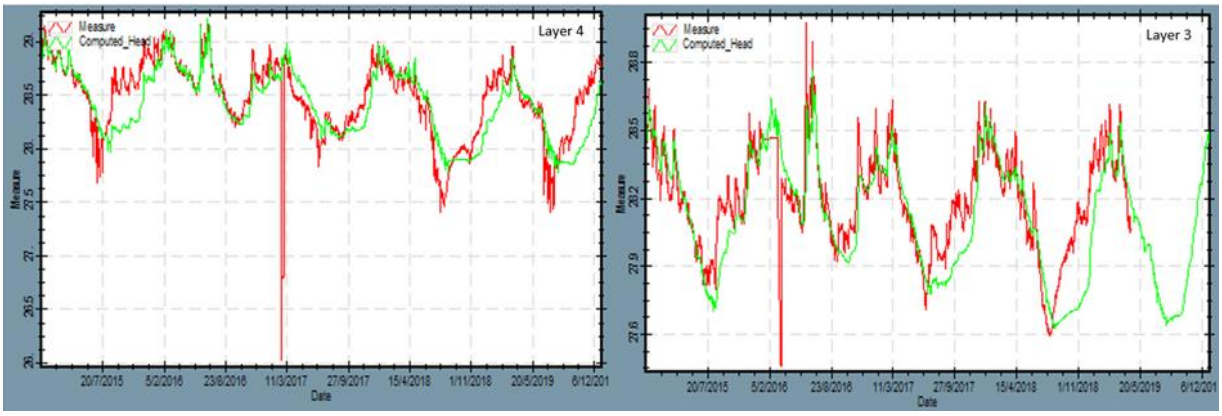


Figure 5: Comparison between modelled/computed hydraulic heads (green) and measured hydraulic heads (red). Left shows the comparison at measuring well A (layer 4) and right at measuring well B (layer 3); The location of both measuring wells is shown in Figure 2

4.2 Small scale subirrigation

4.2.1 Water balance

Figure 6 shows that implementing subirrigation has a significant impact on the water balance. First of all, 1357 mm and 940 mm of subirrigation was applied in 2017 on land plot A and B respectively. During only the growing season (April-September) on average 878 mm and 711 mm of subirrigation water was applied, whilst on average 117 mm and 98 mm was needed for sprinkling irrigation under the current situation. Subirrigation requires significantly more water in comparison with sprinkling irrigation, since a large share of the applied water supplements the groundwater budget. This is recognisable as an alternation of the net groundwater flux from -64 mm to -1438 mm at land plot A and +190 mm to -969 mm at land plot B (Figure 6). This outward (negative) groundwater flux increases local groundwater levels or is later on intercepted by local streams. Furthermore, structurally more subirrigation water is applied at land plot A, which is a result of the relatively low groundwater levels at land plot A, providing more room for infiltration.

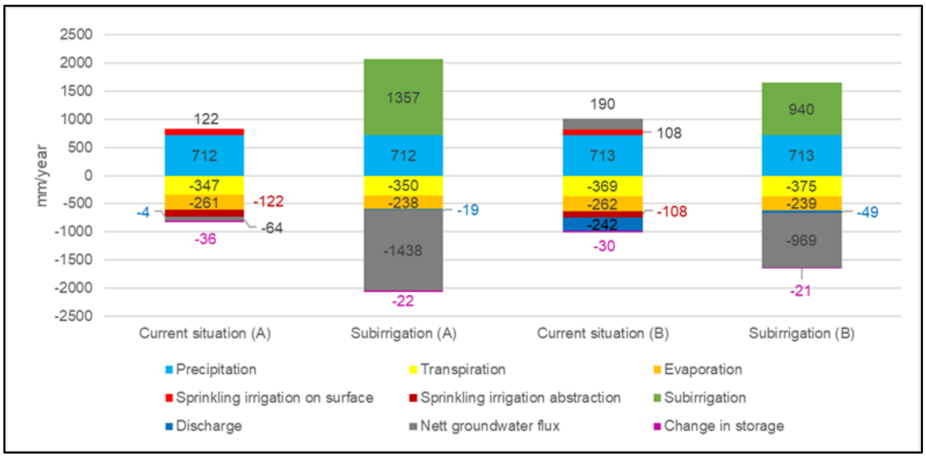


Figure 6, Water balances in mm for both land plots for the year 2017; Water balances for the years 2016, 2018 and 2019 are given in Appendix C

Interestingly the amount of discharge from land plots B decreases when subirrigation is applied (Figure 6). When subirrigation was applied, the subsequent removal of ditches and equalisation of the land plot surface led to a large reduction of discharge from land plot B. Results suggest that the controlled drainage from the subirrigation system at land plot B is more efficient in conserving water in comparison with conventional drainage by ditches. This was not true for land plot A since discharge in the existing ditches was already low due to the high ground level height and relatively low groundwater levels under the current situation. The application of subirrigation (scenario 3) at land plot A even led to a small increase of the discharge from 4 mm to 19 mm over the year 2017 (Figure 6).

The actual transpiration (Tact) of grass grown on both land plots, slightly increases when subirrigation is implemented (from 347 mm to 350 mm and from 369 mm to 375 mm, Figure 6). This indicates that subirrigation in this area is a sufficient technique to deliver water to the root zone in comparison with sprinkling irrigation. Moreover, evaporation losses are reduced by an average of 10% when applying subirrigation compared with sprinkling irrigation, which proves that subirrigation is a more efficient irrigation technique in terms of water losses.

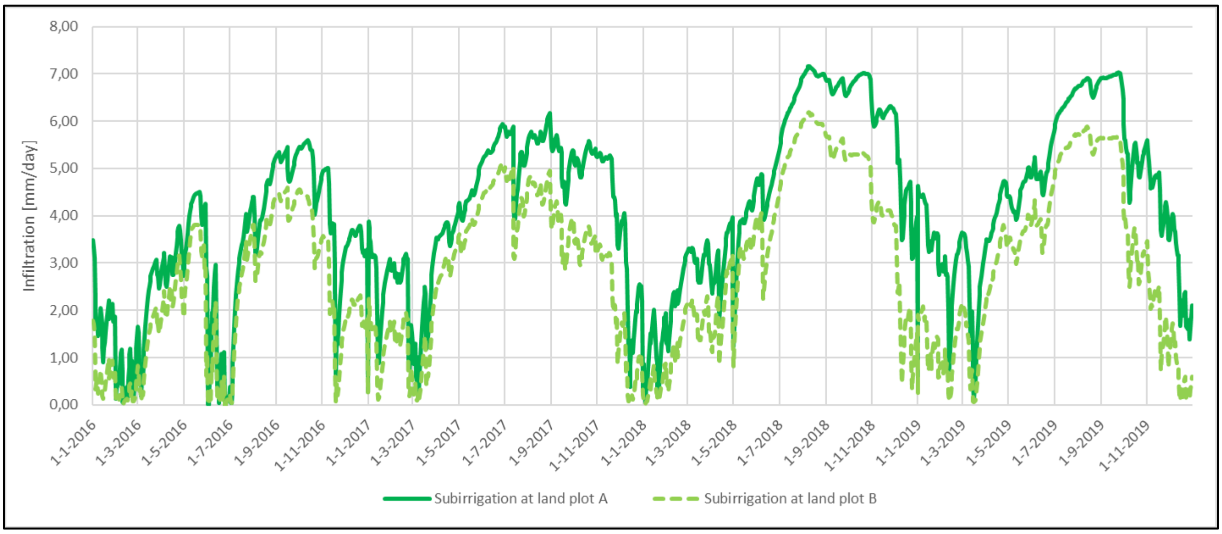


Figure 7, Infiltration rates in mm/day for land plot A (solid) and B (striped); Data is shown for unrestricted infiltration (scenario 14, Appendix B)

Figure 7 shows the infiltration rates over the years at land plot A and B. It shows that the infiltration rate builds up from the start of the growing season (April) until late summer (September) when maximum infiltration rates are reached. The amount of subirrigation water applied was highest for the years 2018 and 2019 when infiltration rates were 7.1 and 6.1 mm/day at maximum for land plot A and B respectively. Overall, infiltration was at its lowest in 2016 due to the extensive rainfall in June and a relatively wet summer, which reduced the water demands.

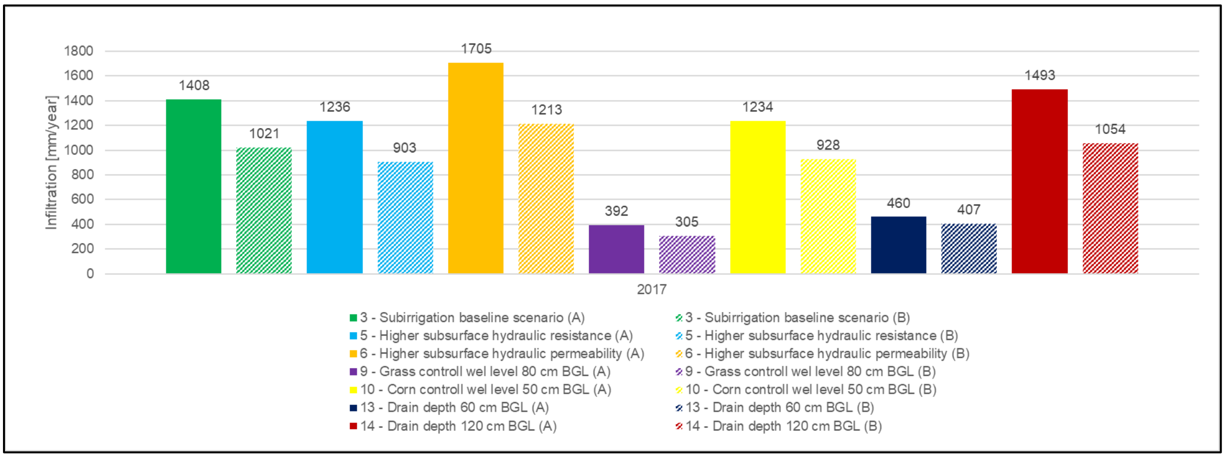


Figure 8, Total amount of subirrigation applied in mm/year under different scenarios for land plot A (solid) and B (striped) for the year 2017; Data for the other years (2016, 2018 and 2019) are included in Appendix D.

Figure 8 shows the yearly amount of subirrigation water applied under different scenarios over the year 2017. The most subirrigation water was applied under scenario 6, simulating a higher subsurface hydraulic permeability, whilst the least amount of subirrigation was applied under scenario 9, simulating grass grown with control well level 80 cm BGL.

When a higher hydraulic resistance in the subsurface beneath the supply pipes is simulated (scenario 5), the amount of infiltration slightly decreased (Figure 8). With more hydraulic resistance in the subsurface, percolation of infiltrated water to the groundwater is reduced. The opposite is recognised for scenario 6, as a higher subsurface horizontal permeability increases the amount of infiltrated water. Water then is more easily lost to the surroundings, which can be streams or neighbouring land plots. In perspective of the waterboard this is not necessarily a loss of water, as percolation replenishes the groundwater budget.

Furthermore, the applied amount of subirrigation water was lower when corn was cultivated instead of grass, as the total amount of subirrigation under scenario 10 (corn, 50 cm BGL) was lower than under baseline scenario 3 (grass, 50 cm BGL) (Figure 8). The reason for this is the deeper rooting depth of corn (max 35 cm against 25 cm for grass), which makes corn more vulnerable to oxygen stress when groundwater levels are too high. To prevent oxygen stress, the model decreases the amount of infiltration early in the growing season when groundwater levels are still high. On average 11% less subirrigation water was applied during the growing season (April – September) when corn is cultivated.

When a lower maximum control well level was simulated, the applied subirrigation water was also lower (scenario 3 versus 9, Figure 8). This is because with a lower control well level, the head difference towards the subsurface pipe system is lower and therefore the infiltration capacity is smaller. So, a difference in maximum control well level, from 50 cm to 80 cm BGL, significantly reduces the infiltration capacity of the system.

4.2.2 Hydraulic heads

As shown in the water balances, most of the subirrigation water ends up in the subsurface which raises the local groundwater levels. It was found that subirrigation (under scenario 14) was fairly adequate in achieving and maintaining desired groundwater levels of 60 – 90 cm BGL (Figure 9). Under scenario 3, where infiltration is limited (Appendix B), groundwater levels dropped below 1.0 m BGL during the summers of 2018 and 2019. Furthermore, in contrast to the current situation, subirrigation nullifies the consecutive effects of dry summers on winter groundwater levels, as groundwater restored to desired levels after the summer of 2018 and 2019. Consecutive drought effects can be compensated by infiltrating water after dry summers. Finally, it is confirmed that groundwater abstraction for sprinkling irrigation has a negative impact on groundwater levels at both land plots during summer, as groundwater levels for scenario 1 drop earlier and faster in comparison with scenario 2 (Figure 9).

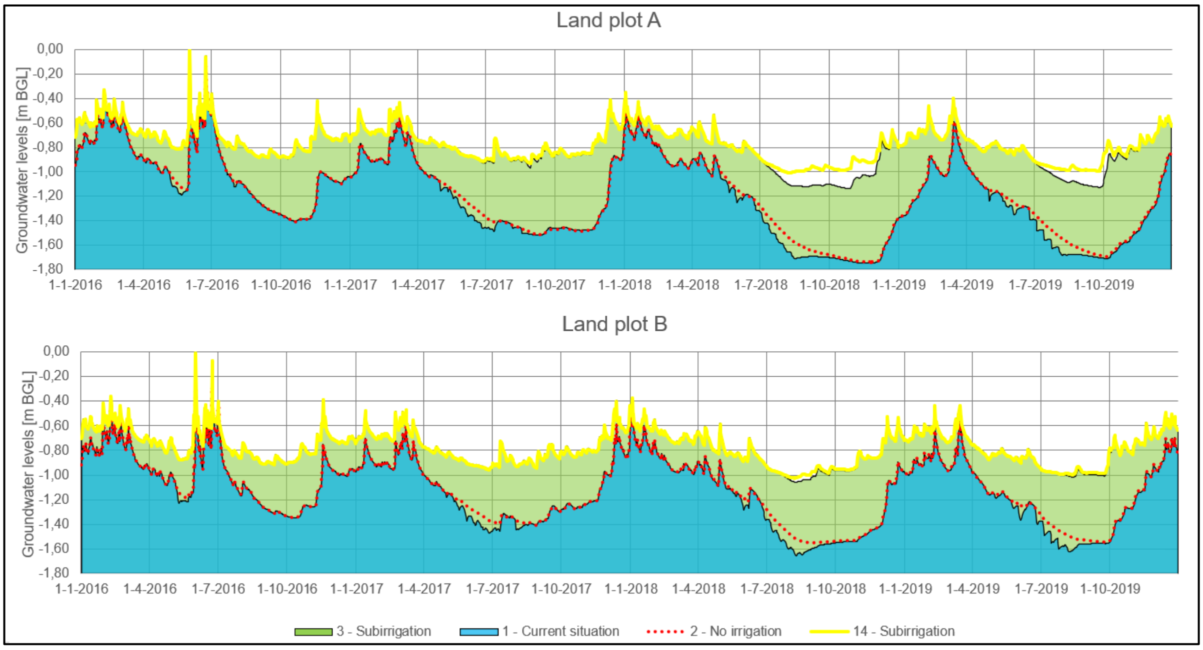


Figure 9, The effect of subirrigation on groundwater levels at both land plots; the drain depth under scenarios 3 and 14 were 90 cm BGL and 120 cm BGL respectively

When more hydraulic resistance is present in the subsurface (scenario 5), groundwater levels are even higher and better maintained in comparison with the baseline scenario, as less water is percolating downwards (Appendix E). A higher subsurface permeability (scenario 6) leads to lower and more fluctuation of groundwater levels in comparison with scenario 3. Both the vertical resistance and the hydraulic permeability of the subsurface are found to be important for retaining the infiltrated water at location.

When subirrigation starts after being absent during winter (scenario 7), groundwater levels at both land plots restore fast (7-10 days) to desired levels in early spring (Appendix E). This indicates that the system is fast responding and it implies that temporary lowering of groundwater levels has no sustaining negative effects. Results show that with restrictions, such as a supply stop, a lower control well water level or a water supply limit (scenarios 8, 9 and 12) groundwater levels cannot be maintained at desired levels and are therefore unfavourable for functioning of the subirrigation system (Appendix E).

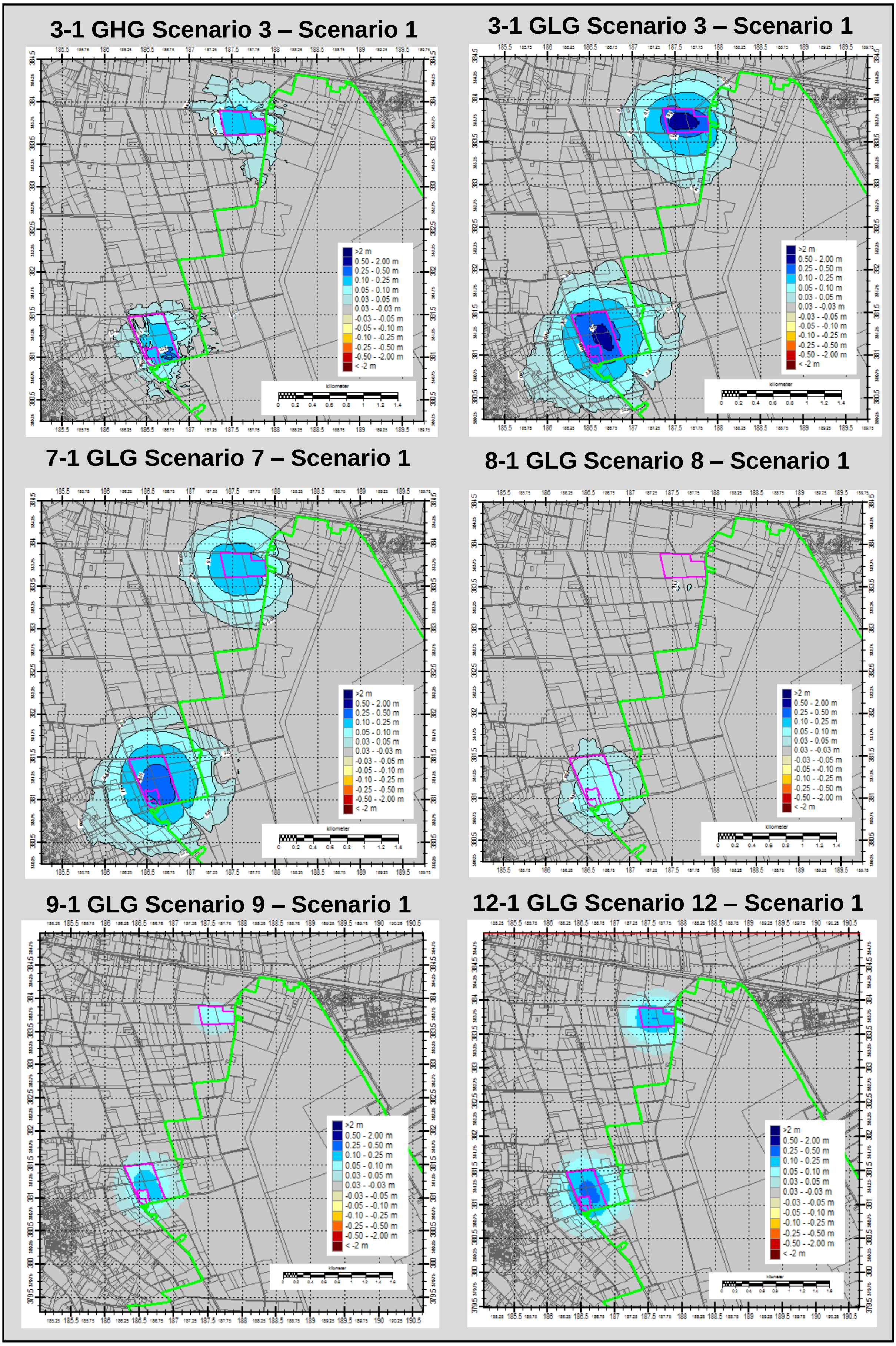


Figure 10, Anomaly maps between the GLG or GHG of different scenarios; Positive values indicate an increase in the GLG or GHG when subirrigation is applied under the specific scenario; In purple: Pilot land plots; In green: N2000 Deurnsche Peel protection zone

Subirrigation also affects groundwater levels at surrounding land plots. Figure 10 illustrates the deviation in GHG or GLG over the years 2016-2019 for certain scenarios, relative to the current situation (scenario 1). Firstly, the comparison of the GHG between scenario 3 and 1 shows that the highest groundwater levels still have some room to rise, which indicates the storage capacity of both land plots that can be filled by using controlled drainage with subirrigation. Besides the increase of high groundwater levels up to 25 centimetres at both land plots, the GHG increases up to 5 cm in the direct vicinity of the land plots. This increase is unlikely to cause structural damage to fields and or crops surrounding the pilot land plots.

More importantly, the low groundwater levels are also positively affected by implementing subirrigation. First of all, anomaly map 3-1 shows that subirrigation increases the GLG at both land plots up to 0.6 meters (Figure 10), which is significant given the fact that groundwater levels usually drop to 1.4 up to 1.8 meters BGL during summer. Groundwater levels beyond the borders of both land plots also increase, which means that neighbouring farmers can benefit from subirrigation at both pilot land plots. Lower elevated land plots however, can experience flooding, especially during winter, because of the elevated groundwater levels by subirrigation. Neighbouring nature area of the N2000 Deurnsche Peel benefits from subirrigation as groundwater levels can increase up to 10 cm near the border of the nature area (Figure 10).

Anomaly map 7-1 (Figure 10) shows that low groundwater levels after the subirrigation system being inactive during winter (scenario 7) are still significantly higher in comparison with current situation groundwater levels (scenario 1) (Figure 10). This suggests that groundwater levels restore fast enough when subirrigation is turned on. Anomaly maps 8-1, 9-1 and 12-1 (Figure 10) all show that a summer supply stop (scenario 8), a lower control well water level (scenario 9) and a limited infiltration capacity (scenario 12) are unfavourable for achieving the desired groundwater effects in the HPZ (Figure 10), as groundwater levels under these scenarios deviate less with the current situation (scenario 1).

4.2.3 Crop development

Overall, crop yields for grass are slightly higher when subirrigation is applied (scenario 14) in comparison with sprinkling irrigation (Table 2). Crop yields for grass over the years 2016-2019 are between 15.000 and 19.000 kg/ha dry matter, which indicates that circumstances are favourable for growing grass in the study area. Moreover, crop yields under scenario 1 show little variation over the years at both land plots, which implies that sprinkling is an effective irrigation technique in this area.

Table 2, Yearly crop yields for grass in kg/ha for land plot A and B; Crop yields for scenarios 2 up to 14 are given relative to ***scenario 1*** *(current situation)*

Scenario	2016		2017		2018		2019	
	A	B	A	B	A	B	A	B
1	**16855**	**16824**	**17285**	**16991**	**16731**	**17023**	**17269**	**17178**
2	-208	-188	-727	-722	-2534	-1340	-1666	-1044
3	+518	+398	+593	+279	+282	+661	+831	+769
4	+518	+399	+681	+338	+992	+1176	+1502	+1008
5	+508	+386	+622	+291	+562	+832	+1106	+831
6	+174	+401	-468	-2	-1405	+44	-1174	+15
7	+522	+413	+592	+281	+253	+660	+813	+781
8	+16	+19	+526	+261	-1106	-663	-111	-268
9	+60	+164	-195	-383	-1675	-819	-849	-563
12	+202	+348	+64	-123	-1131	-375	-429	-255
13	+98	+265	-168	-333	-1616	-750	-801	-517
14	+521	+397	+607	+269	+552	+698	+1117	+816

Crop yields are generally higher when subirrigation is applied in comparison with sprinkling irrigation (Table 2). Applying additional sprinkling irrigation when already applying subirrigation (scenario 4) results in the highest crop yields, especially in dry years (2018 and 2019). Furthermore, a higher hydraulic resistance in the subsurface (scenario 5) positively affects crop yields. Interestingly, winter inactivity of the subirrigation system (scenario 7), does not diminish crop yields in comparison with the baseline scenario (3). This suggests that storing water during winter does not result in additional gains regarding crop yields. But more importantly, this also suggests that temporal lowering of the groundwater level before the growing season, does not negatively impact yearly crop yields.

Crop yields are lower in comparison with the current situation for scenarios 2, 6, 8, 9, 12 and 13, especially during dry years 2018 and 2019. First of all, a higher hydraulic permeability in the subsurface (scenario 6) negatively influences crop yields, as groundwater levels cannot be maintained due to increased groundwater flow to the surroundings. Secondly, subirrigation restrictions such as a summer supply stop (scenario 8), limited water supply (scenario 12) or a lower control well water level (scenario 9), all result in lower crop yields in comparison with the subirrigation baseline scenario (3). It must be noted however, that crop yields under these unfavourable scenarios (scenarios 6, 8, 9 and 12) are still higher than when no irrigation is applied at all (scenario 2). This shows that subirrigation, when compared with no irrigation, is always beneficial for crop growth.

Against expectations, sprinkling irrigation water demands remained relatively high when additional sprinkling irrigation was simulated under scenario 4 (Figure 11). Yearly additional sprinkling water demands were on average 45% of the amount of sprinkling irrigation needed for the current situation (scenario 1). This is however, more a result of how and when sprinkling irrigation is applied in the model and does not mean that there is additional sprinkling required, since crop yields are already equal or higher with subirrigation compared to sprinkling. Furthermore, it can be recognised that, similar to the subirrigation water demands, sprinkling water demands are higher at land plot A, which is the result of lower groundwater levels at land plot A.

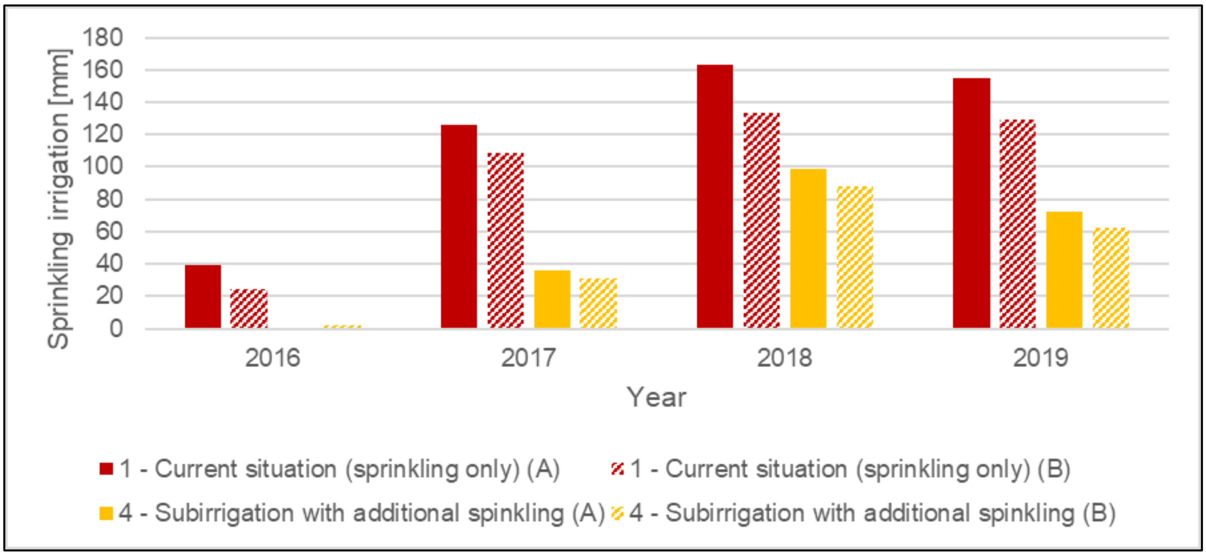


Figure 11, Sprinkling irrigation water demands under different scenarios for land plot A (solid) and B (striped)

In Figure 12 below, crop yields are shown for scenarios varying in crop type (grass or corn) and control well water level (50 or 80 cm BGL). A higher maximum control well level results in higher crop yields for both crop types. Furthermore, it can be recognised that corn is more vulnerable to drought and flood damage in comparison with grass, as end of the season yields are lower for the years 2016 (wet), 2018 (dry) and 2019 (dry) in comparison with 2017 (normal).

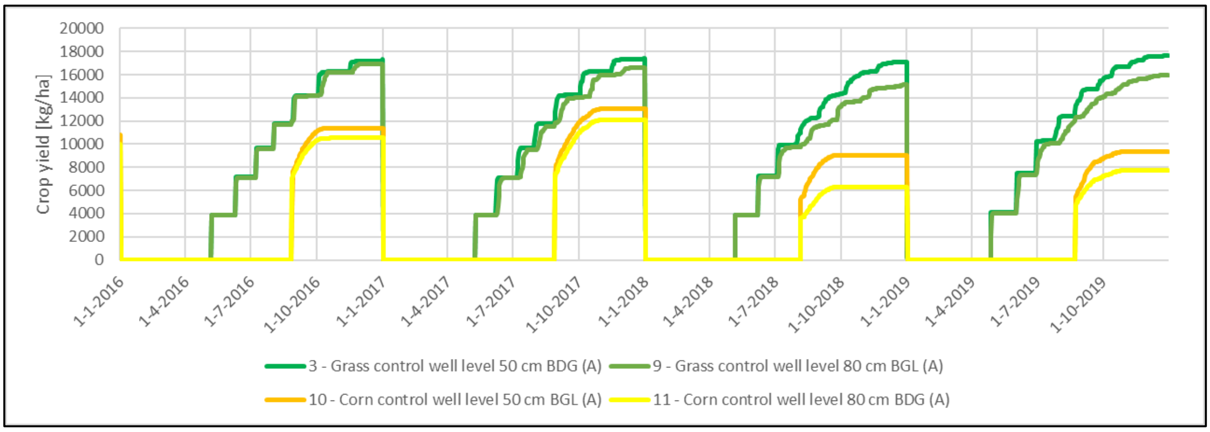


Figure 12, Crop yields over the years 2016-2019 for different scenarios at land plot A

4.3 Large scale subirrigation

4.3.1 Water balance

The total water demand for subirrigation (scenario 15) in the HPZ, over the months April up to and including September was 523 mm on average whilst the water demand for sprinkling irrigation under scenario 17 was 72 mm. By implementing subirrigation on 43% of the area of the HPZ, the water abstraction for sprinkling irrigation over the whole HPZ was reduced with 51%.

The regional water balance shows that besides the applied sprinkling irrigation water, mainly the discharge, the groundwater in- and outflow and the change in storage, are affected when subirrigation is applied in the HPZ (Table 3).

Table 3, Water balance for the current situation (Curr.) and large scale implementation of subirrigation (Sub.); The water balance is calculated for the HPZ with an additional buffer zone of 1 km downstream of the HPZ (Appendix F). Values are given in mm over the months April up and including September

Water balance term	2016		2017		2018		2019	
	Curr.	Sub.	Curr.	Sub.	Curr.	Sub.	Curr.	Sub.
Precipitation	426	426	303	303	191	191	240	240
Evapotranspiration	-378	-380	-366	-371	-353	-361	-345	-354
Sprinkling irrigation on surface	16	13	40	31	54	45	54	44
Sprinkling irrigation abstraction	-16	-13	-40	-31	-54	-45	-54	-44
Subirrigation		42		65		70		71
Infiltration from streams	15	15	33	28	36	36	39	34
Discharge	-130	-148	-29	-43	-26	-36	-23	-34
Increased discharge		18		14		10		11
Groundwater inflow	94	91	92	85	93	86	90	83
Groundwater outflow	-116	-125	-108	-124	-115	-131	-114	-131
Change in storage	87	77	75	56	173	148	112	89

When analysing the year 2017 it can be recognised that in total 65 mm of water is used for subirrigation over the months April-September (Table 3). At least 15% of the infiltrated water replenishes back into local watercourses. In 2017 this is 14 mm, so in total 51 mm of water is being abstracted from local water courses. This translates to 94 l/s, whilst there is 330 l/s of water available in the HPZ during normal hydrological years. On average the water demand for subirrigation consumes 30% of the total water available in the area during normal years. The 51 mm of infiltrated water causes an increase of the groundwater outflow (+16 mm) and the evapotranspiration (+5 mm). The remaining 30 mm is counterbalanced by less infiltration form streams (-5 mm), less groundwater inflow (-7 mm) and a smaller change in storage (-18 mm). This smaller change in storage is a result of higher and more stable groundwater levels when subirrigation is applied, in comparison with the current situation.

In drier years (2018 and 2019), the subirrigation water demand is higher and roughly 70 mm is subtracted for subirrigation water needs, whilst the discharge increases with 10 mm (Table 3). Therefore, 60 mm of water is needed for subirrigation which translates into 112 l/s over the months April-September. During dry years the water supply to the HPZ is increased to 520 l/s. So, 22% of the total water available is used for subirrigation purposes during dry years.

Furthermore, the groundwater outflow increases which means that more groundwater is available in the surrounding areas such as the Deurnsche Peel or agricultural lands downstream of the HPZ (Table 3). This effect is larger in drier years (2018 and 2019) as more water is being infiltrated via subirrigation. As a result, the regional groundwater budget is supplemented when applying subirrigation in the HPZ.

To analyse the water demand versus availability in more detail for specific areas in the HPZ, the potential subirrigation land plots (total area of 353.000 ha) were divided into four clusters based on their common water supplying stream, which are the Vlier, Oude Aa, Soeloop and the Zinkskeloop (Figure 13). Water demands were calculated and compared with known water inlet distributions under normal years and dry years.

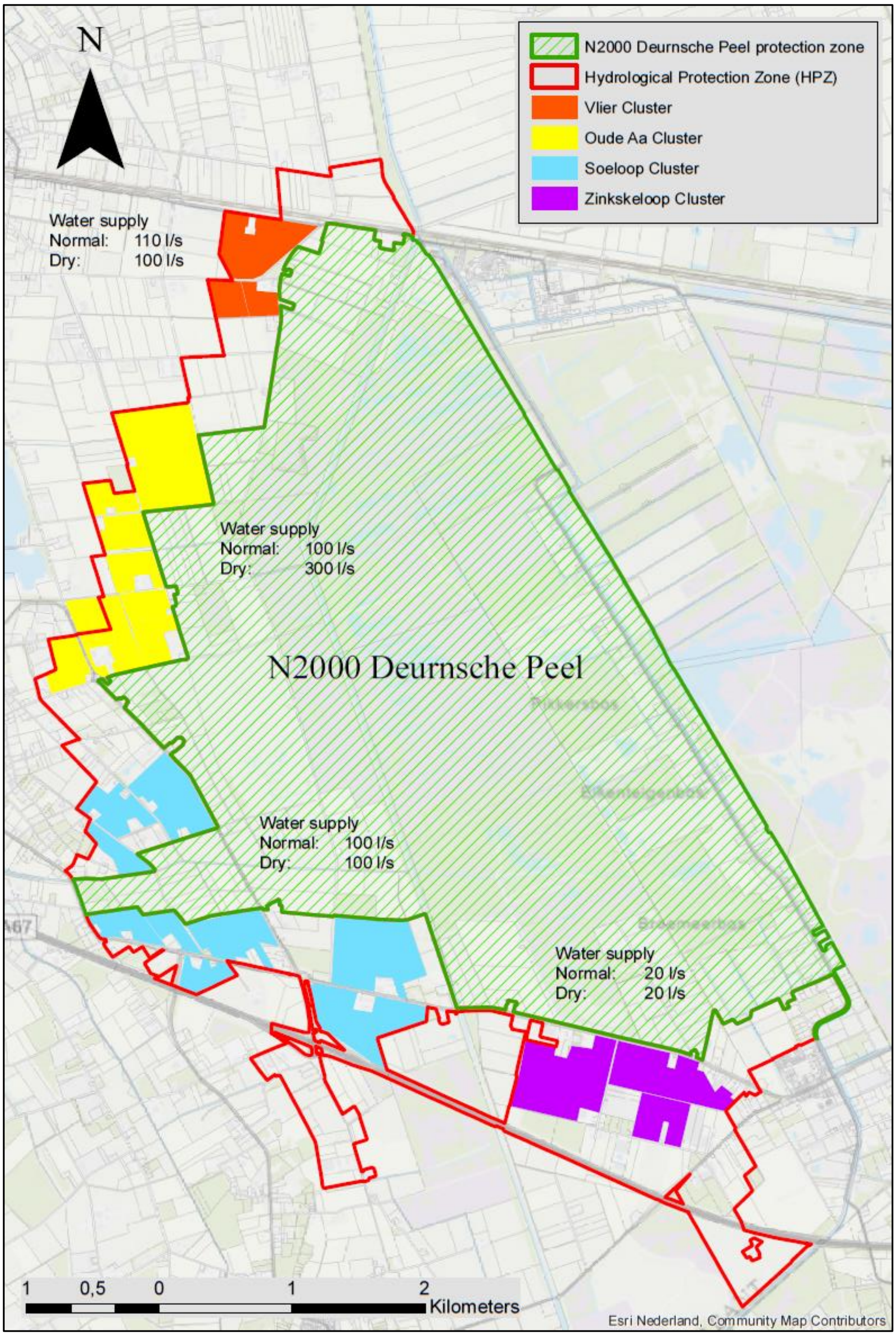


Figure 13, Overview map of the subirrigation land plot clusters in the HPZ with known water inlet distribution; Water inlets are based on a report from Folmer et al. (2020)

By analysing water demand versus availability for all clusters, it can be recognised that subirrigation requires a significant share of the total water inlet, especially during summer (Figure 14). For the Vlier cluster, the water demand covers 10% to 20% of the total water inlet to the Vlier. Land plots connected to the Oude Aa require in total up to 20% and 30% of the water inlet. With the current water distribution, there will be less water available downstream of the HPZ in both the Vlier and the Oude Aa and water shortages are more likely to occur, when subirrigation is applied.

The water inlet into the Oude Aa increases from 100 to 300 l/s during dry years which theoretically increases the water availability for subirrigation. It must be noted however, that the reason behind this relatively large supply through the Oude Aa is necessary for maintaining aquatic life and supplying water to capital intensive cultivation, especially during dry summers. So the Oude Aa has high priority in terms of water allocation which complicates the intake of water for subirrigation.

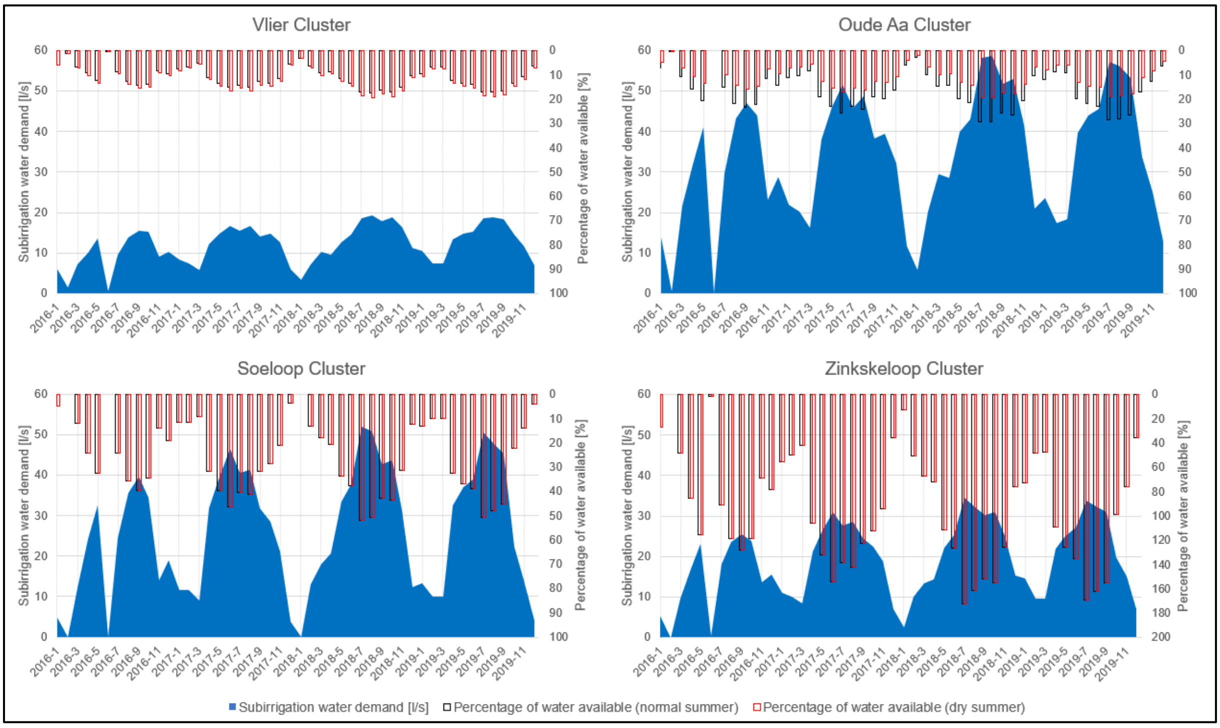


Figure 14, Water demand versus water availability for the Vlier, Oude Aa, Soeloop and Zinkskeloop clusters; Note that the right side scale is different for the Zinkskeloop diagram.

The water supply to the Soeloop cluster is moderate and is not increased during dry summers (Figure 13). Subirrigation water demands on the contrary, are relatively high because of the larger area of subirrigation land plots. As a result, water demands can take up to 50% of the total water available in the Soeloop during summer (Figure 14). It is expected that under the current water distribution, water cannot be supplied to all land plots in the Soeloop cluster without causing water shortages downstream. Therefore, an increase of the water inlet into the Soeloop is necessary to implement large scale subirrigation in this part of the HPZ.

Finally, the Zinkskeloop water demand versus supply diagram shows that implementing subirrigation as it is proposed is not feasible, since summer water demands exceed the total availability of water during all years (Figure 14). This is because only 20 l/s of water is available whilst water demands are between 25 and 40 l/s during summer for the Zinkskeloop cluster. An upgrade of the water supply to the Zinkskeloop is necessary in order to realise subirrigation is this part of the study area.

4.3.2 Hydraulic heads

When subirrigation is implemented on a larger scale (scenario 15), i.e. on multiple land plots in the HPZ, groundwater levels are even slightly higher in comparison with the small scale implementation (Figure 15). Interestingly, on average the yearly amount of infiltrated water is reduced by 16% and 26% for land plot A and B respectively. This is because the subirrigation land plots are positioned as clusters, which leads to lower hydraulic gradients between land plots and therefore groundwater levels can be increased by applying less subirrigation water. Despite this reduction in infiltrated water, the groundwater levels are still increased and maintained, similar as with the small scale implementation of subirrigation.

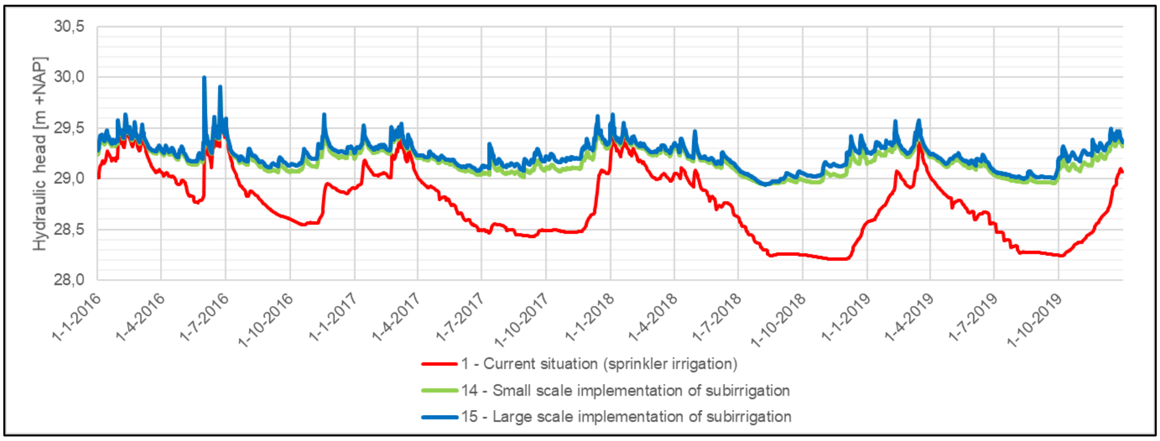


Figure 15, Groundwater levels under different scales of implementation at land plot A

Scenario 18 was simulated to determine the effect of groundwater abstractions for sprinkling irrigation. Short lowerences (peaks) of the hydraulic head in layer 4 at land plot A are visible in Figure 16, which are caused by daily groundwater abstractions for sprinkling irrigation. The effects of groundwater abstractions on the GLG were found to be negligible, both in the HPZ (centimetres) and in the nature area (milimetres).

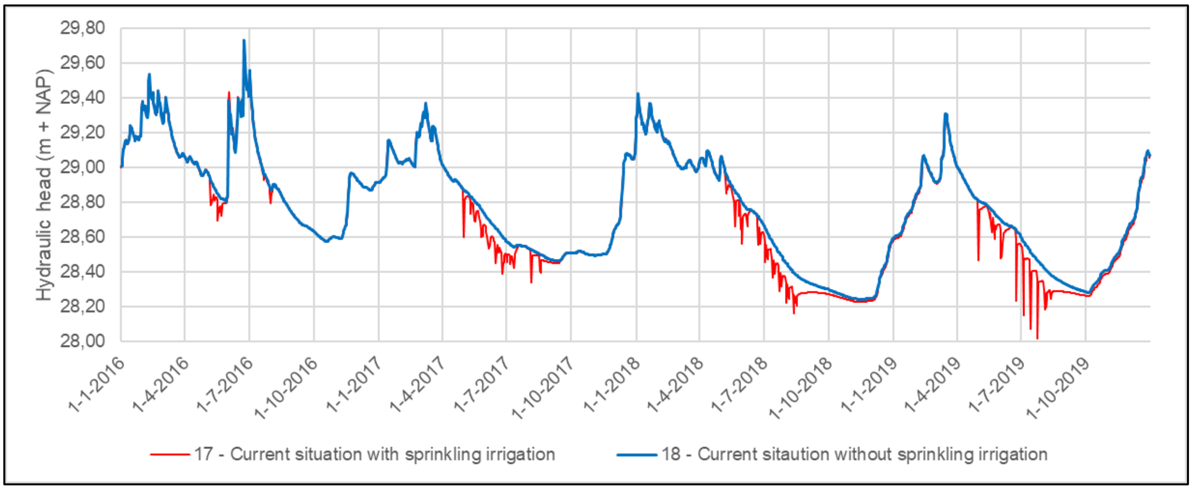


Figure 16, The effect of water abstraction for sprinkling irrigation on the hydraulic head in layer 4 at land plot A

High groundwater levels are increased on and surrounding the subirrigation land plots as illustrated on the GHG difference map in Figure 17 . Dark blue spots on the map show locations where high groundwater levels are significantly increased, up to 1.2 meters occasionally. These locations are prone to flood damage due to ponding in winter/early spring when hydraulic heads in the first layer exceed the surface level. Therefore, it is important to identify these locations beforehand and reduce infiltration or increase drainage to prevent flooding and wet damage because of subirrigation. The effects on high groundwater levels in nearby villages such as Liessel, Griendtsveen and Helenaveen are limited to a maximum of 5 centimetres.

The GHG is also increased in the Deurnsche Peel protection zone when subirrigation is implemented, especially near the borders close to the subirrigation land plots. Additionally, an increase of the GHG of 5 to 10 centimetres can be recognised in the centre of the nature area. This is assuring as it indicates that more water is being stored in the nature area when subirrigation is applied on a large scale.

Some locations show a decrease of the GHG up to 50 centimetres, indicated by the reddish colours in Figure 17. These locations correspond with land plots where prior to applying subirrigation, no drainage system was present and the GHG was already relatively high. Then when subirrigation is implemented, a drainage network is installed. Although this drainage network is controlled in order to store and retain water during winter and spring, such a intervention can have a drying effect on locations with naturally high groundwater levels.

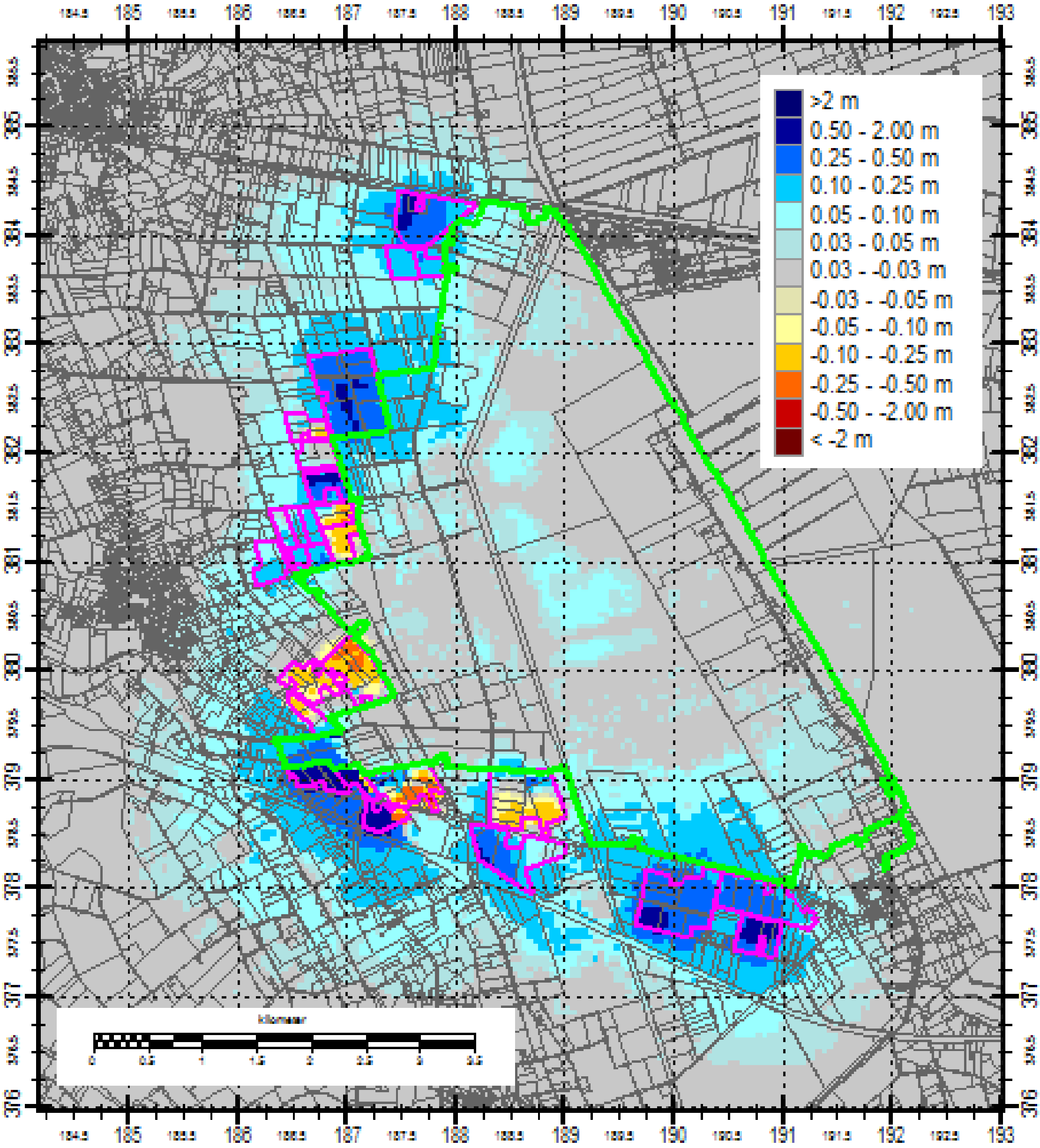


Figure 17, Effect of subirrigation on the average of the highest groundwater levels over 2016-2019 (GHG) when subirrigation is applied on a larger scale; In green: the Deurnsche Peel protection zone; In purple: the specific land plots where subirrigation was applied on

Besides high groundwater levels during winter or spring, also low groundwater levels are affected by the large scale implementation of subirrigation. Figure 18 shows that the GLG increases up to 1.2 meters in the subirrigation land plots. Moreover, the effects of larger scale implementation of subirrigation are more widespread in comparison with the smaller scale aplication, which is clearly visible by the extent to which the Deurnsche Peel protection zone is affected. Especially near the western and southern border of the protection zone, groundwater levels have increased. Moreover, spots in the middle of the nature area show an increase in GLG up to 15 centimeters because of subirrigation.

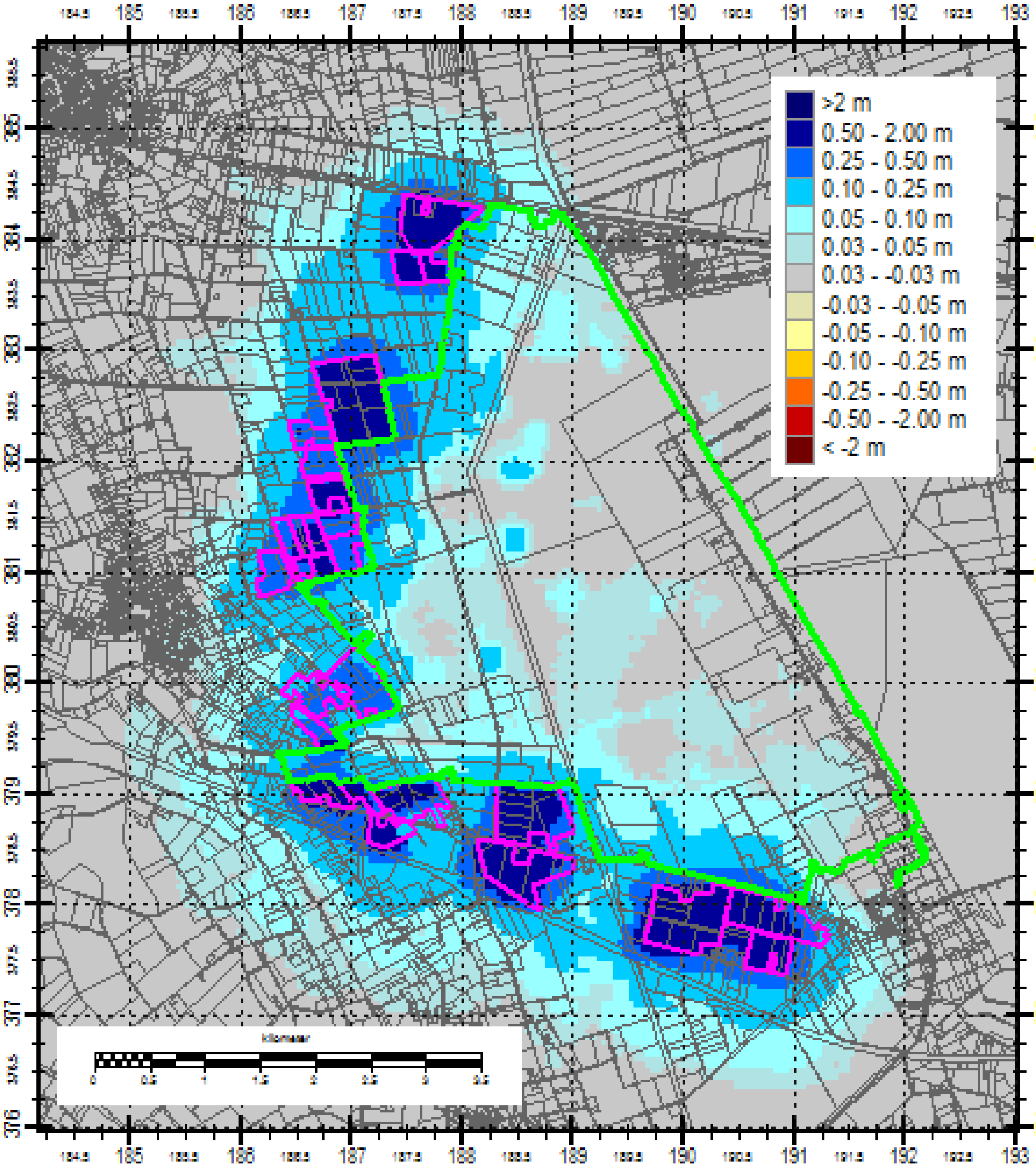


Figure 18, Effect of subirrigation on the average of the lowest groundwater levels over 2016-2019 (GLG) when subirrigation is applied on a larger scale; In green: the Deurnsche Peel protection zone; In purple: the specific land plots where subirrigation was applied on

When subirrigation is applied on a larger scale with a maximum control well water level of 80 cm BGL (scenario 16) instead of 50 cm BGL (scenario 15), effects on groundwater levels are far less both in quantity and in space. For high groundwater levels this means that a lower control well water level is beneficial for preventing water damages and ponding. Yet during summer, subirrigation is less effective in achieving the desired effect on groundwater levels, when a lower controll well level is simulated.

4.3.3 Percolation in the Deurnsche Peel

In Figure 19 the groundwater flux difference over layer 1 is given between subirrigation (scenario 15) and the current situation (scenario 17), for the summer of 2017 (months June up to and including September). First of all, the subirrigation land plots are clearly visible by the reddish colours which represents an increase in downward flux when subirrigation is applied. The green colours indicate a negative flux difference, which is caused under two circumstances. First, when subirrigation decreases the downward flux, which represents a decrease in percolation. Secondly, when subirrigation increases upward flux, which represents seepage of groundwater. Overall seepage or a decrease in percolation can be recognised in the Deurnsche Peel protection zone, confirming that the infiltrating water in the land plots, causes a counter pressure which reduces water losses via percolation from the nature area.

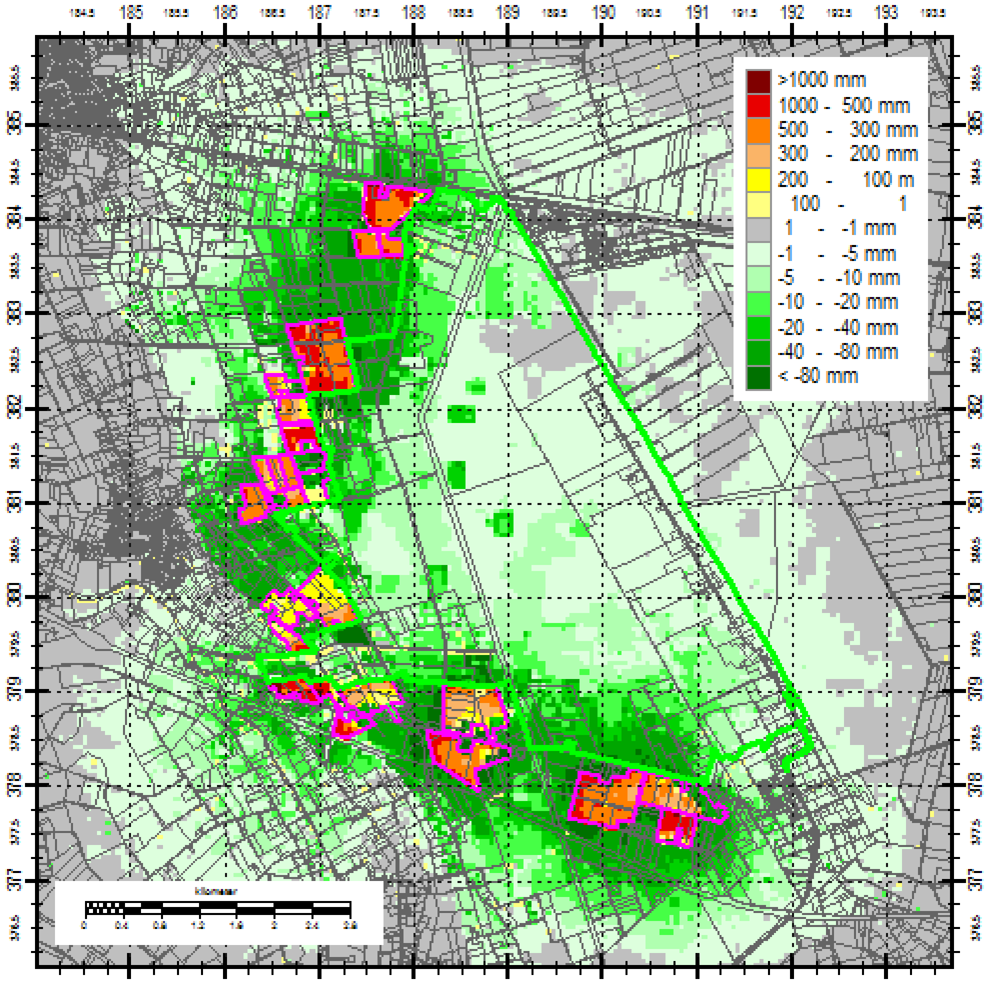


Figure 19, Groundwater flux difference for the lower face of layer 1 between subirrigation (scenario 15) and the current situation (scenario 17) over the months June-September in year 2017; Positive values represent an increase in downward flux or a decrease in upward flux; Negative values represent a decrease in downward flux or an increase in upward flux

The same is true for groundwater flux differences over layer 4 (Figure 20). Again positive values surrounding the subirrigation land plots indicate an increase of downward flux because of infiltration. The darker green spots mostly represent locations where because of subirrigation seepage from layer 4 has increased. This is beneficial for the Deurnsche Peel as it increases the amount of water available for vulnerable nature.

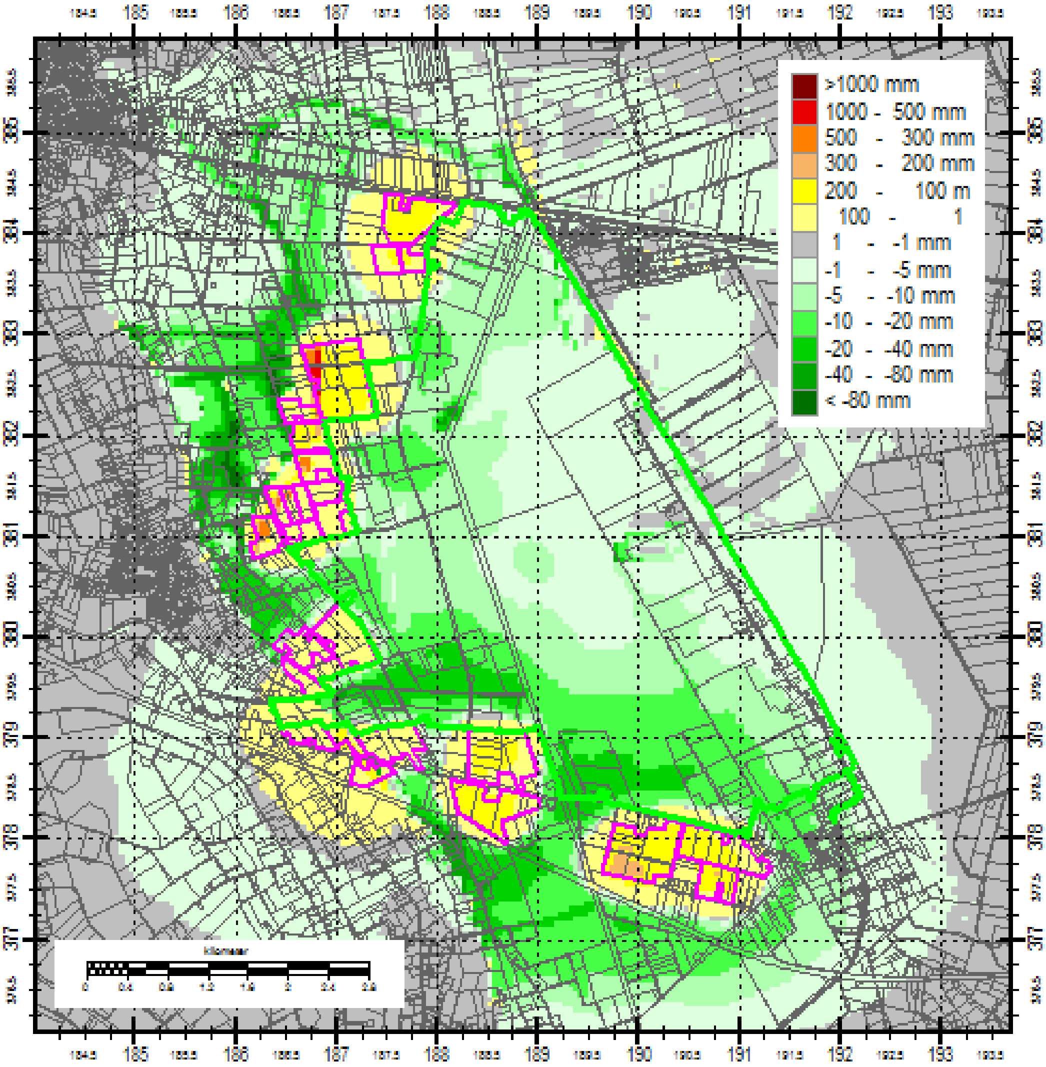


Figure 20, Groundwater flux difference for the lower face of layer 4 between subirrigation (scenario 15) and the current situation (scenario 17) over the months June-September in year 2017; Positive values represent an increase in downward flux or a decrease in upward flux; Negative values represent a decrease in downward flux or an increase in upward flux

4.4 Subirrigation policy recommendations

In this section recommendations for the future waterboard policy regarding subirrigation are given based on the sub-questions under research question 3.

4.4.1 Subirrigation, where to prevent or to stimulate?

The waterboard considers subirrigation as a potential measure to increase groundwater levels and realise more sustainable water management in agriculture for the coming years. The success of subirrigation is however dependent on multiple variables such as the location and purpose of implementing subirrigation. Therefore it is important for the waterboard to have a clear understanding where subirrigation is desired and where not.

Table 4 provides an overview of success criteria for implementing subirrigation. It could be interesting to examine potential locations in the service area of the waterboard, where subirrigation has a potential for success. This can be done by constructing a subirrigation opportunity map as is done by van den Eertwegh et al. (2016). The success criteria in Table 4 can serve as a basis for this map. Data will be needed such as the subsurface composition/layering, groundwater depths and land use in the service area of the waterboard.

Table 4, Overview of subirrigation success criteria for constructing an opportunity map

Success criteria	**Explanation**
Hydrological permeability and resistance of soil layers	- Hydraulicly resistant soil layers beneath the drains are required to conserve the infiltrated water and realise desired groundwater levels - Resistant soil layers between the drains and rootzone are undesired for subirrigation water supply to the rootzone - High permeable soil layers directly below the drains are unfavourable as desired groundwater levels cannot be achieved because of excessive percolation
Water availability	- Without water supply, subirrigation can have a drying effect because the increased drainage
Groundwater levels	- Shallow groundwater levels are unfavourable as this provides less room for conserving/storing water via subirrigation - Groundwater levels deeper than 2 m BGL are unfavourable (for agriculture) as subirrigation is not able to adequately elevate these groundwater levels for water supply to the root zone
Location	- Subirrigation around nature areas can support highly water dependent nature (“natte natuurparels” in Dutch)

Whilst in the study by van de Eertwegh et al. (2016) the physical suitability of the subsurface is solely based on the permeability and resistance of the subsurface between the drains and rootzone, the future subirrigation opportunity map should also include the permeability and resistance beneath the supply drains. Results (section 4.2.3) showed that a high horizontal hydraulic permeability and/or a low vertical resistance beneath the drains is negative for achieving desired groundwater levels when implementing subirrigation.

In the hydrological protection zone (HPZ)

First of all, results show that subirrigation in the HPZ can have a positive effect on the neighbouring nature area, as subirrigation creates a hydrological counter pressure which reduces percolation of groundwater in the nature area. Furthermore, large scale implementation of subirrigation in the HPZ increases the GLG (+10 cm on average) at the border regions of the nature area (section 4.3.2). Especially around nature areas which are strongly dependent on sufficient and stable groundwater levels, subirrigation can therefore be used as an adequate drought adaptation measure. However, the positive effects can only be achieved with a sufficient and constant water supply for subirrigation. Otherwise, the subirrigation system solely functions as controlled drainage. Installing controlled drainage systems in areas with previously no drainage, can have a drying effect on nature instead (Kuijper et al., 2012).

Current waterboards policy is reserved regarding the implementation of drainage systems in HPZ's around nature areas. Permits for installing drainage are required and the stand-still principle holds in the HPZ, which implies that any intervention in the HPZ may not lead to negative hydrological effects on the border of the protected area. The reserved attitude towards drainage is appropriate as controlled drainage with subirrigation can have a drying effect on nearby nature when there is no water supply. For subirrigation installation requests it is therefore important to consider the effects of subirrigation during times of limited or no water supply.

Subirrigation for agriculture

Subirrigation can replace conventional irrigation to reduce groundwater abstractions for irrigation purposes. Furthermore, results show that crop yields can be equal or even higher when subirrigation is applied instead of sprinkling (section 4.2.3). To achieve sufficient crop yields it is however essential that groundwater levels at the land plot can be elevated and maintained when applying subirrigation. With a lack of sufficient hydraulic resistance in the subsurface, there is more percolation of groundwater and sprinkling irrigation can be a more efficient irrigation technique (Bartholomeus et al., 2019). Subirrigation as a replacement for sprinkling irrigation is therefore only applicable for areas with adequate hydraulic resistance in the subsurface beneath the supply drains. Subirrigation on land plots where the subsurface mainly consists of coarse sand, should therefore be prevented or at least discouraged. The same applies for areas where the groundwater levels in the growing season are deeper than 2.0 m BGL, as in these circumstances subirrigation is not adequate in realising the necessary groundwater levels for proper crop development (Bartholomeus et al., 2019). An accurate soil and subsurface analysation is recommended before permission is granted for installing a subirrigation system.

Because of the large spatial influence of subirrigation on groundwater levels, also neighbouring lands are affected by subirrigation. The radiance effect of large scale subirrigation in the HPZ is roughly 500 meter from the land plots where subirrigation takes place. Land plots within these 500 meters can experience an increase of the GLG of roughly 10 cm. So even farmers outside of the HPZ can benefit from subirrigation, as groundwater levels in their fields drop less during summer when subirrigation is applied. However, neighbouring farmers can also experience problems as the GHG increases as well, which can induce flood damages at lower lysing areas. Effect modelling is therefore recommended to predict and prevent any flood damage, especially when subirrigation is applied on a larger scale.

Conserving of water

From a waterboard perspective, where the aim is to conserve as much water as possible, areas with low groundwater levels (>50 cm BGL) during winter and spring are desired as this provides much room for infiltration via subirrigation. Furthermore, sufficient hydraulic resistance in the subsurface for adequate capillary rise, is not a prerequisite when the goal of subirrigation is solely supplementing the groundwater budget. On the horst areas of the Peelrand fault zone for example, groundwater levels are relatively deep which provides room for conserving and storing of water. Subirrigation can make these areas more drought proof because of the added groundwater. On top of that, infiltrating water on the horst potentially increases seepage and therefore water availability on the flanks and in the graben. This supports the existence of the seepage dependent “Wijstgronden”, which are rare and vulnerable nature areas in the service area of waterboard Aa en Maas. The question however remains, whether subirrigation on the horst areas is feasible in practice, given the limited water available via surface waters and possibility for other (less expensive) measures to supplement groundwater on the horst areas.

In the lower lying areas and polders, subirrigation is expected to have no added value, since drought problems are less prominent here and the relatively high groundwater levels provides less room for infiltration. Subirrigation in combination with high groundwater levels can even induce flood damages and is therefore undesired in lower lying areas and polders in the service area of Aa en Maas. Controlled drainage only (without subirrigation) on the other hand, can be beneficial for reducing discharges from agricultural lands during winter.

Results show that when a crop is grown with a deeper rooting depth than grass, less water is needed for subirrigation (section 4.2.1). The reason for this is that groundwater levels need to be maintained at a lower level to prevent oxygen stress to the deeper rooting crops. Growing corn instead of grass can therefore be beneficial in areas with a limited water supply. On the contrary, in areas with abundant water supply and where the goal is maximum replenishment of groundwater, grass is a better crop for agriculture. The choice of crop type is therefore dependent on both the goal and water availability for subirrigation.

4.4.2 Regulations, bans and instructions

Surface water abstractions for subirrigation

Model results show that large scale implementation of subirrigation in the HPZ has a significant impact on the water demand in the area. On average 20% to 25% of the total water currently available in the area, is required for subirrigation in the summer months (May-September). Water abstractions for subirrigation can therefore have a significant impact on water availability in local streams downstream of the HPZ. As a result, streams downstream of the HPZ can run dry earlier during summer which is harmful for stream ecology and water quality downstream. To minimise the impact of subirrigation, a redistribution of water is needed to increase water available for the HPZ. The planned upgrade of the Noordervaart, which supplies the area with water from the Meuse river, can potentially make this redistribution possible. Furthermore, regulations are needed to minimise the impact of subirrigation on downstream areas. For example, a water abstraction limit can be imposed during times of water scarcity. This way only a maximum amount of water can be abstracted for subirrigation from a certain watercourse. Moreover, a complete surface water abstraction ban can be imposed to temporarily stop water abstraction for subirrigation. However, such a complete stop during summer does nullify the desired effects on groundwater levels for example in neighbouring nature areas (section 4.2.2).

Currently, subirrigation is excluded from surface water abstraction bans, which leaves farmers able to abstract water for subirrigation even during periods of water scarcity. On the other hand, farmers abstracting water for sprinkling irrigation are subject to water abstraction bans, which seems to be unfair. However, there is an important difference between water abstraction for subirrigation or sprinkling irrigation. Besides subirrigation being a more efficient irrigation technique, the goal of subirrigation is also to replenish and maintain local groundwater levels and in some cases create a hydrological counter pressure to minimise water losses from a nearby nature area. The interest to ensure water availability is larger for subirrigation in comparison with conventional sprinkling irrigation. However, subirrigation should not be completely excluded from any water abstraction bans, as water scarcity downstream can certainly be exaggerated by subirrigation. It is therefore still recommended to impose water abstraction bans for subirrigation during times of water scarcity, however only as a last option to maintain the positive effects of subirrigation as long as possible.

Abstracting surface water for subirrigation currently only requires a permit when the abstraction rate exceeds 100 m^3/hour. Assuming a maximum subirrigation water demand of 7 mm/day, in practice the permit requirement is only applicable to land plots larger than 34 ha. With a more strict permit requirement, subirrigation can be better mapped and water abstractions from surface water are more apparent in the service area of the waterboard.

Besides water scarcity there are also concerns regarding potential flooding downstream when subirrigation is applied. The discharge over the winter months (October-March) downstream of the HPZ appears to increase with a maximum of 10% when implementing subirrigation on a large scale. This is the result of the elevated groundwater levels which partly replenishes local streams. However, this increase is not likely to directly cause flooding as this is an increase of the baseflow. On the contrary, peak flows, occurring when fields are drained simultaneously to create a buffer right before a threatening thunderstorm, can induce flooding downstream. To prevent this it is recommended to impose a ban on the usage of mechanical pumps to drain fields.

User instructions and regulations

The effectiveness of subirrigation on groundwater levels and crop yields is strongly dependent on how the system is used. Although the farmer is only concerned in higher groundwater levels during summer, in a water conserving perspective it is important to maintain high groundwater levels in the winter as well. Especially when there is a water surplus during winter, the groundwater budget can be supplemented. Therefore it is important that the waterboard takes an active role in instructing and providing knowledge to the farmers using the subirrigation system. This can be done by instructing farmers to execute a certain groundwater level in their field during winter.

Furthermore, the functioning of subirrigation in the service area of Aa en Maas should not be based on good faith between the farmer and the waterboard. User instructions and regulations are recommended to steer the functioning of subirrigation. Besides, user instructions and regulations make using a subirrigation system enforceable. When a farmer uses the system in an undesired manner, the waterboard is able to point this out based on the known instructions. The exact instructions are debatable yet it is recommended that by all means it should be clear for the farmer which drainage depth level he or she should apply, in order to realise maximum replenishment of the groundwater budget.

Subirrigation water allocation

In the Netherlands a priority ranking is in place, called the “verdringingsreeks”, for water allocation during times of water scarcity. Water supply to prevent irreversible damage to nature and flood defences and to prevent peat soil compaction, is prioritised over other water users such as agriculture, shipping and industry. The position of subirrigation in the verdringingsreeks is a complex issue since subirrigation is used for irrigation whilst it also can serve as support for nearby nature areas. Results from this study can provide a first indication of where subirrigation can potentially be ranked within the Dutch verdringingsreeks.

Currently, agriculture is one of the first sectors for which water supply becomes limited during times of water scarcity. This is necessary to ensure water availability for drinking water and energy supply and to prevent irreversible damages to nature and flood defences. When subirrigation is implemented with the underlying intention to support nearby nature, the question arises whether water supply towards these land plots must be prioritised over other agriculture lands, where conventional sprinkling irrigation is used. It is difficult to determine whether subirrigation prevents irreversible damage to nature and therefore should have priority regarding water allocation. Subirrigation in the HPZ around the N2000 Deurnsche Peel appears to have a positive impact on water availability in the nature area. However, by limiting the water supply towards the HPZ, the positive effects of subirrigation can no longer be achieved. Furthermore, with a lack of water supply, a subirrigation system can have a drying effect on nearby nature instead, which can cause irreversible damage. Therefore, subirrigation should have priority over other irrigation purposes when it prevents or minimizes damages to nearby nature areas.

5. Discussion

5.1 Subirrigation application

This study shows that subirrigation can be an appropriate replacement for conventional sprinkling irrigation, as it increases local groundwater levels, supplements the regional groundwater budget and can decrease percolation in nearby nature areas. Results showed that subirrigation created a hydrological counter pressure which reduced water losses from the Deurnsche Peel nature area. This is promising, as subirrigation proves to be a potential drought adaptation measure for supporting N2000 nature areas in the Netherlands. Furthermore, subirrigation can contribute in achieving the waterboards goal to practise more sustainable and climate proof water management in the future, as the regional groundwater budget is supplemented which creates a buffer capacity for dry periods. With subirrigation, the higher elevated sandy soils in the Netherlands can better cope with future drought events, which is one of the goals in the 2021 Delta program posed by the Dutch government (Rijksoverheid, 2020).

Subirrigation also proved to be a suitable replacement for sprinkling irrigation in terms of crop development. This is in line with expectations and another modelling study where subirrigation also led to equal or higher crop yields in comparison with sprinkling irrigation (Brakkee et al., 2021). Furthermore, a field experiment with a subirrigation system in America (Netherlands), showed that grass developed better with subirrigation, as the Normalised Difference Vegetation Index (NDVI) was higher when subirrigation was applied instead of sprinkling irrigation (Bartholomeus et al., 2018).

However, this study also illustrated that equal or better crop yields in comparison with sprinkling are not guaranteed when applying subirrigation. Sufficient water supply for subirrigation and the appropriate hydraulic properties in the subsurface were found to be crucial for achieving sufficient crop yields when applying subirrigation. Groundwater levels could not be maintained properly as a result of simulating a higher horizontal hydraulic permeability, which is therefore unfavourable for achieving sufficient crop yields. On the contrary, a higher vertical hydraulic resistance below the drains resulted in more constant groundwater levels and was therefore found to be beneficial for crop growth. These findings are in line with a study by Bartholomeus et al. (2019), which showed that achieving sufficient groundwater levels for capillary rise, is essential for the effectiveness of subirrigation on crop growth. When extensive amounts of subirrigation water are lost to the surroundings, because of a lack of sufficient hydraulic subsurface resistance, conventional sprinkling irrigation can be a more effective technique for crop development.

With subirrigation, groundwater levels increased in a relative short period of time. Against expectations, creating a buffer in advance of the growing season (during winter) did not result in added benefits for crop yield and groundwater levels in the study area. It can even be argued that applying no subirrigation during winter is preferred to spare pumping costs and minimise the risk of flood damage. This is confirmed in a guiding report by Evans & Skaggs (1996) as saving water preseason can induce wet stress and therefore discourage root development. However in a water conserving perspective, applying subirrigation preseason is still preferred to supplement the regional groundwater budget.

It is important to realise that subirrigation will not be universally applicable, as it requires substantial amounts of water and subsurface properties must be appropriate for the subirrigation system to function. Besides, water abstractions for subirrigation will reduce water availability for downstream areas which can endanger stream ecology downstream. It can be argued that (large scale) subirrigation then only shifts the drought problem to other regions downstream. Subirrigation is therefore expected to be a more location and situation specific measure. Recent studies on alternative water sources such as treated wastewater for subirrigation, are promising for realising subirrigation in the Netherlands (Brakkee et al., 2021; Narain-Ford et al., 2020). A study by Narain-Ford et al. (2021) even showed that treated wastewater can potentially cover 17% of the total agricultural water demand, during a dry year in the Netherlands. Using alternative water resources for subirrigation can aid in realising more sustainable and climate proof water management in the Netherlands for the coming years.

5.2 Model performance

The modelling scale and uncommon combination of using a groundwater model (iMOD), an unsaturated zone model (MetaSWAP) and a crop development model (WOFOST), proved to be effective in analysing the effects of subirrigation. In general, modelled groundwater levels showed good resemblance with measured data, which indicates that the model used is representative for the hydrology in the area. Modelled hydraulic heads however, slightly diverged from measured heads during the wetting phase (when heads increased). This is potentially the result of the model layers being homogeneous in terms of hydraulic conductivity. In practice structural irregularities and variability in subsurface hydraulic properties can cause preferential flow, which results in faster responding hydraulic heads in comparison with groundwater models (Hendrickx & Flury, 2001). So the lack of heterogeneity of the model layers caused the difference in response time between modelled and measured hydraulic heads.

The subirrigation module used in this study produced plausible results and was effective in simulating controlled drainage with subirrigation. Calculated amounts of subirrigation (April-September) are in line with measured amounts of infiltration in field experiments, as they lie within the range of 750-900 mm (Brakkee et al., 2021). However, the module was found to be sensitive to variations in drainage depth position. When a shallower drainage depth was simulated and groundwater levels dropped below this drainage depth position during summer, infiltration was limited abruptly (Appendix B). This possibly led to an underestimation of the amount of infiltration and therefore the effects of subirrigation on groundwater levels and percolation, on a few land plots under the large scale modelling of subirrigation.

5.3 Further research

Subirrigation in the HPZ around the Deurnsche Peel is one of multiple measures to minimise future drought effects in the Deurnsche Peel nature area. Other measures such as raising surface water levels in the area are not included in this modelling study. Therefore it would be useful to incorporate the complete set of drought adaptation measures in this model, to determine the overall effects of the waterboards drought adaptation strategy on the Deurnsche Peel nature area. Secondly, it would be interesting to perform a similar study solely on controlled drainage, to determine its impact on agriculture, nature and the water system.

Finally, results of this study can be compared with future measurements from monitoring of both pilot projects starting in April 2021. This way results from this study can be validated and the subirrigation module can be improved based on measurements. Secondly, after this study it would be useful for the waterboard to construct a subirrigation suitability map, based on the success criteria found in this study. This way the waterboard will have a clearer view of where subirrigation can be implemented in the coming years.

6. Conclusion

The answers on the research questions are presented in this section.

6.1 Part 1: Subirrigation modelling

1a Is only subirrigation itself sufficient during droughts or is additional sprinkling irrigation needed?

When subirrigation was applied, crop yields were found to be equal or higher in comparison with sprinkling irrigation. Additional sprinkling irrigation was therefore unnecessary for achieving sufficient crop yields. However, when water supply for subirrigation is limited, groundwater levels cannot be maintained properly and additional sprinkling irrigation may be needed to prevent drought damages.

1b How does a higher hydraulic resistance in the subsurface affect the local groundwater levels and subirrigation water demand?

The hydraulic resistance in the subsurface below the drains was found to be crucial in achieving desired groundwater levels. Desired groundwater levels were not maintained with a higher horizontal permeability. Secondly, a higher vertical resistance below the drains was beneficial for achieving and maintaining desired groundwater levels whilst it decreased the subirrigation water demand.

1c What is the effect of inactivity during winter and an earlier stop of subirrigation water supply on crop development and nature?

Applying subirrigation preseason did not result in higher crop yields for both pilot land plots. When subirrigation was started later in spring, groundwater levels responded fast enough to ensure sufficient water supply to the rootzone during the growth season. This shows that by using subirrigation, a temporal lowering of the groundwater level in this study area, for example for sowing practices, does not have any negative effects on both nature and crop development.

A summer water supply stop however, was found to be detrimental for yearly crop yields. With a water supply stop at the end of June, water levels dropped back to previous levels (as under the current situation), which caused drought damages to crops. Despite the induced drought damages when a supply stop is posed, applying subirrigation during spring was still beneficial for crop yields when compared with a scenario where no irrigation was applied at all. Additional sprinkling irrigation may be desired in these situations. Furthermore, applying a water supply stop for subirrigation was found to be unfavourable for achieving the desired groundwater increase in the nearby nature area.

1d What is the effect of the maximum water level in the subirrigation control well on crop development of grass and corn and how does the control well water level affect nature and the water system?

The control well water level in the subirrigation system affected the infiltration capacity of the system and was therefore crucial for achieving the desired groundwater levels and sufficient crop growth. With a lower control well water level (80 cm BGL instead of 50 cm BGL) the system was not able to maintain desired groundwater levels and as a result, crop yields were lower in comparison with applying sprinkling irrigation. Furthermore, a lower control well water level decreases the spatial effect of subirrigation on water levels, which limits the impact on groundwater levels in nearby nature areas.

Corn has a deeper rooting depth in comparison with grass, which results in overall less water infiltration because of the increased risk of oxygen stress. When the goal of subirrigation is merely maximum conservation/infiltration of water, subirrigation can best be practiced in combination with grass.

1e *What is the effect of a subirrigation water supply limit on crop development?*

Limiting the maximum supply of water for subirrigation negatively affects the crop development. Similar to a lower control well water level, limiting the water supply decreases the amount of infiltration through the subirrigation system and desired water levels cannot be maintained. When the water supply for subirrigation is limited, sprinkling irrigation is therefore a more effective irrigation technique regarding crop development.

1f *What is the effect of the drain depth in the subirrigation system on agriculture and nature?*

The module used in this study to simulate subirrigation, was found to be sensitive for variations in the drain depth. When a shallower drain depth was simulated, the amount of infiltration that could take place was limited. This led an underestimation of the effects of subirrigation and therefore no conclusions can be drawn regarding the effect of the drain depth on agriculture and nature.

2a *How are groundwater levels and hydraulic heads in the Hydrological Protection Zone and N2000 Deurnsche Peel influenced by larger scale subirrigation?*

Larger scale implementation of subirrigation intensified the effects on groundwater levels in the HPZ and the N2000 Deurnsche Peel nature area. First of all, winter groundwater levels increased when subirrigation was applied during winter, which increased the risk for flooding on lower elevated land plots in the HPZ. During summer, groundwater levels dropped less in the vicinity (500 meter) of the HPZ, when subirrigation is applied on a large scale. Overall, subirrigation proved to be beneficial for the Deurnsche Peel nature area, as groundwater levels increased which is positive for water availability in the nature area.

Large scale application of subirrigation in the HPZ also decreased the amount of percolation of groundwater in the nature area. This is caused by the reduction of water abstractions for sprinkling irrigation and the infiltration of water in the HPZ by subirrigation. Subirrigation in the HPZ was able to create a hydrological counter pressure, which reduced water losses via percolation from the Deurnsche Peel nature area. Overall, subirrigation and the subsequent reduction of water abstraction in the HPZ, can be an effective measure to reduce drought damages in the Deurnsche Peel nature area.

2b *How much water is needed for subirrigation in the Hydrological Protection Zone and could the system meet this water demand?*

Since a large amount of the subirrigation water is “lost” via percolation to the groundwater budget, a relative large amount of water is needed to maintain groundwater levels. On average 100 l/s is required for large scale subirrigation in the HPZ, which is 30% and 20% of the total water available during normal and dry years respectively. Although subirrigation can have a positive effect on nearby nature areas, water abstractions can lead to water scarcity in downstream regions, which can be harmful for downstream stream ecology.

With the current water allocation and supply system, the subirrigation water demand cannot be met throughout the entire HPZ and a reallocation of water is needed for realising large scale application of subirrigation in the HPZ. The planned upgrade of the Noordervaart can aid in achieving this.

6.2 Part 2: Subirrigation policy recommendations

This research provides a first indication on how future policy regarding subirrigation for the waterboard can be formed. First of all, it is clear that subirrigation cannot be applied universally and can even be undesirable at certain locations/situations. For instance, subirrigation can increase the risk of flooding in areas where groundwater levels are already shallow. In general, subirrigation can be an effective drought adaptation measure around nature areas or to supplement the groundwater budget and make areas more drought proof. Regions where groundwater levels are relatively deep, are suitable for supplementing the regional groundwater budget via subirrigation.

Regulations, bans and instructions are needed to ensure proper functioning of subirrigation in the service area of the waterboard. First of all, water abstraction bans can be implemented to minimise the occurrence of water scarcity, caused by upstream water abstractions for subirrigation. However, it is advised to pose such a ban as late as possible to maintain the desired effects of subirrigation on groundwater levels and percolation in nearby nature (when applicable) as long as possible. Besides water scarcity, there are also concerns regarding flooding, as sudden and simultaneous drainage on subirrigation land plots can potentially cause peak flows. Therefore, it is advised to ban the usage of pumps to mechanically drain subirrigation systems.

Finally, it is expected that the subirrigation system functioning and achieving the desired effects on groundwater levels is strongly dependent on how the system is used. Therefore, education and spreading of knowledge from the waterboard to the farmer is essential. It is advised to compose clear instructions and regulations regarding subirrigation, to ensure proper functioning of subirrigation systems in the future. These instructions should at least include guidelines on which drainage level should be maintained in advance of the growth season.

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Appendix A: Model layer structure and properties

Table A1, Overview of model layer structure and hydraulic properties at land plot A and B

Pilot land plot A				
	Top [m + NAP]	*Bottom [m+ NAP]*	*KD [m^2/day]*	*Hydraulic resistance (C) [days]*
Layer 1	30.10	30.00	0.57	5.48
Layer 2	30.00	29.05	2.50	5.45
Layer 3	29.05	28.48	1.29*	8.57
Layer 4	28.48	14.39	161.93**	75.00
Layer 5	14.39	14.29	0.19	2.87
Layer 6	14.29	14.19	0.13	2.67
Layer 7	14.19	14.09	0.17	0.78
Layer 8	14.09	13.99	0.28	441.30
Layer 9	13.99	13.69	0.46	440.10
Layer 10	13.69	13.79	0.01	0.005
Layer 11	13.79	13.69	0.00	0.017
Layer 12	13.69	13.59	0.34	0.005
Layer 13	13.59	13.49	0.02	0.012
Layer 14	13.49	13.39	0.82	0.012
Layer 15	13.39	13.29	0.84	0.012
Layer 16	13.29	13.19	0.86	0.012
Layer 17	13.19	13.09	0.84	0.012
Layer 18	13.09	12.99	0.84	10.95
Layer 19	12.99	-	1549.00	-
Pilot land plot B				
	Top [m + NAP]	*Bottom [m+ NAP]*	*KD [m^2/day]*	*Hydraulic resistance (C) [days]*
Layer 1	29.18	29.08	0.67	4.16
Layer 2	29.08	28.04	3.56	4.32
Layer 3	28.04	27.09	2.2***	9.48
Layer 4	27.09	16.30	200.8****	33.19
Layer 5	16.30	16.20	0.09	5.19
Layer 6	16.20	16.10	0.07	4.78
Layer 7	16.10	16.00	0.08	1.53
Layer 8	16.00	15.90	2.41	835.3
Layer 9	15.90	15.80	1.61	897.64
Layer 10	15.80	15.70	0.008	127.27
Layer 11	15.70	15.60	0.001	64.12
Layer 12	15.60	15.50	0.64	0.069
Layer 13	15.50	15.40	0.015	102.7
Layer 14	15.40	15.30	0.48	102.7
Layer 15	15.30	15.20	0.51	0.019
Layer 16	15.20	15.10	0.53	0.019
Layer 17	15.10	15.00	0.51	0.02
Layer 18	15.00	14.90	0.51	17.5
Layer 19	14.90	-	913.3	

* KD layer 3 for scenario 6 = 7,1 m^2/day

** KD layer 4 for scenario 6 = 966 m^2/day

*** KD layer 3 for scenario 6 = 7,5 m^2/day

***** KD layer 4 for scenario 6 = 587 m^2/day

Appendix B: Subirrigation module

The amount of subirrigation in the model is calculated in a similar way as infiltration from a water body is calculated in MODFLOW. Subirrigation is applied based on the gradient between the control well water level and the hydraulic head in the drain. Two situations can be distinguished:

A. Groundwater levels in the field are higher than the depth position of the drain (Figure B1). The amount of infiltration is calculated by the gradient between the control well water level and the groundwater level in the field.
B. The groundwater level in the field is equal or lower than the depth position of the drain (Figure B1). Infiltration in this situation is only dependent on the gradient between the control well water level and the depth position of the drain, which is fixed.

Infiltration under situation B is limited to prevent extreme and unrealistic infiltration rates when groundwater levels drop below the drain depth position. In fact this occurs also in practice as the infiltration resistance around the drain increases when the soil becomes unsaturated. With this subirrigation module, the limitation of the infiltration (situation B) occurs earlier with a shallower drain depth (60 cm BGL) in comparison with a deeper drain depth (120 cm BGL). Furthermore, the gradient between the control well water level and drain depth position is lower with a shallower drain depth, which leads to a lower infiltration maximum. Overall, less infiltration is calculated with a shallower drain depth position (60 cm BGL) in comparison with a deeper drain depth (120 cm BGL).

Chapter 6. Conceptualization and Implementation of Stress Packages 6–9

$$QRIV_n = CRIV_n\left(HRIV_n - h_{i,j,k}\right), \qquad h_{i,j,k} > RBOT_n \qquad (6\text{–}8A)$$

$$QRIV_n = CRIV_n\left(HRIV_n - RBOT_n\right), \qquad h_{i,j,k} \leq RBOT_n\,. \qquad (6\text{–}8B)$$

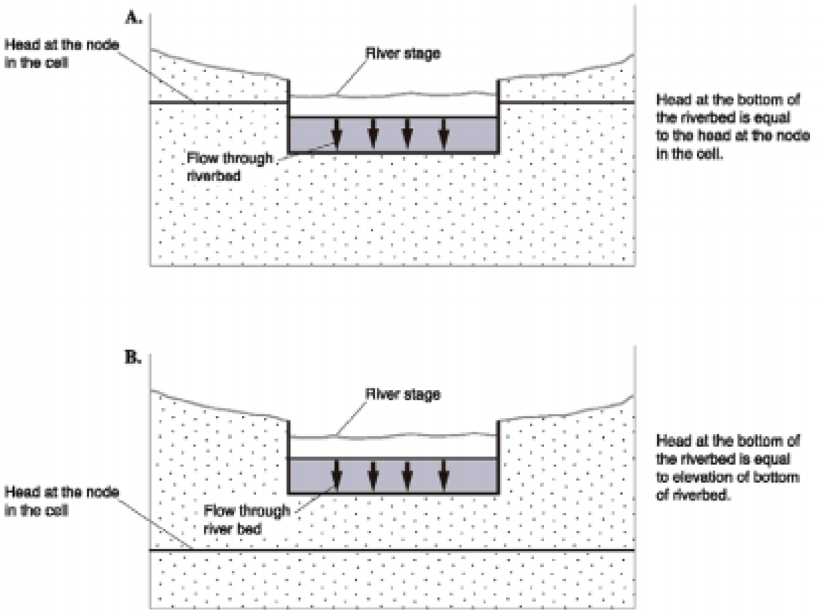
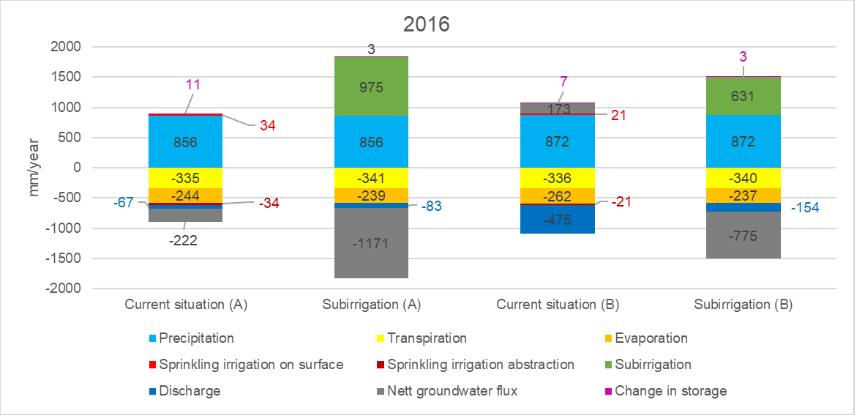
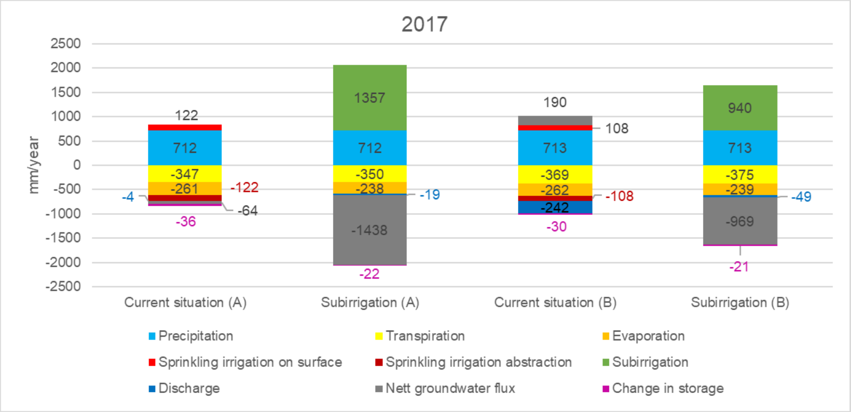
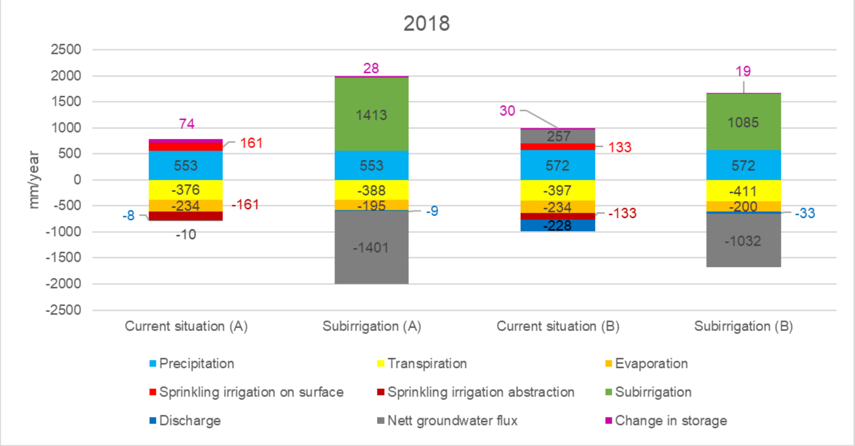


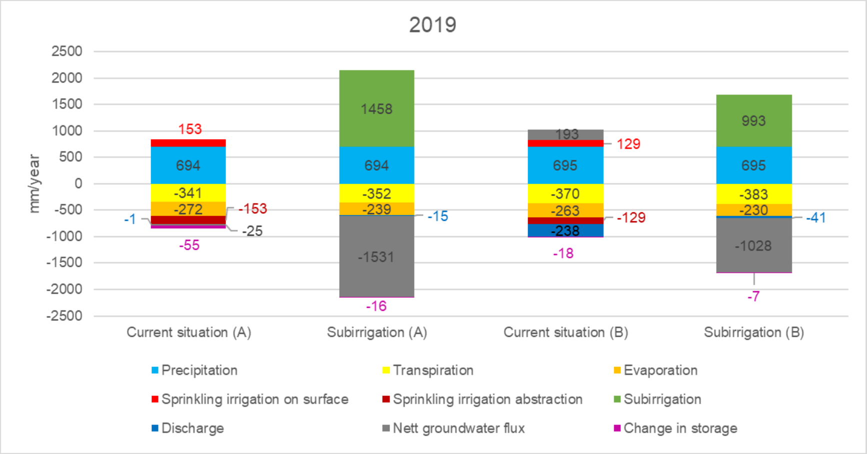
Figure B1, Situations (A and B) under which infiltration is calculated; from: Harbaugh (2005)

Appendix C: Small scale water balances

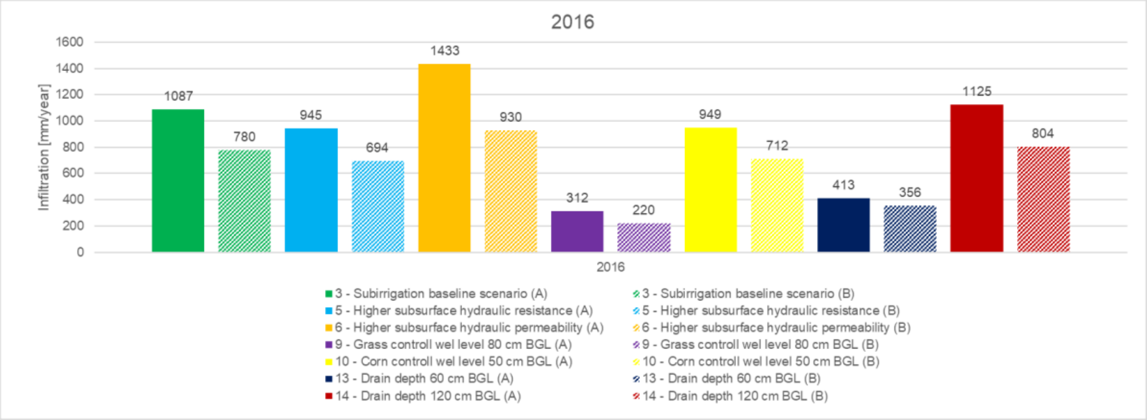


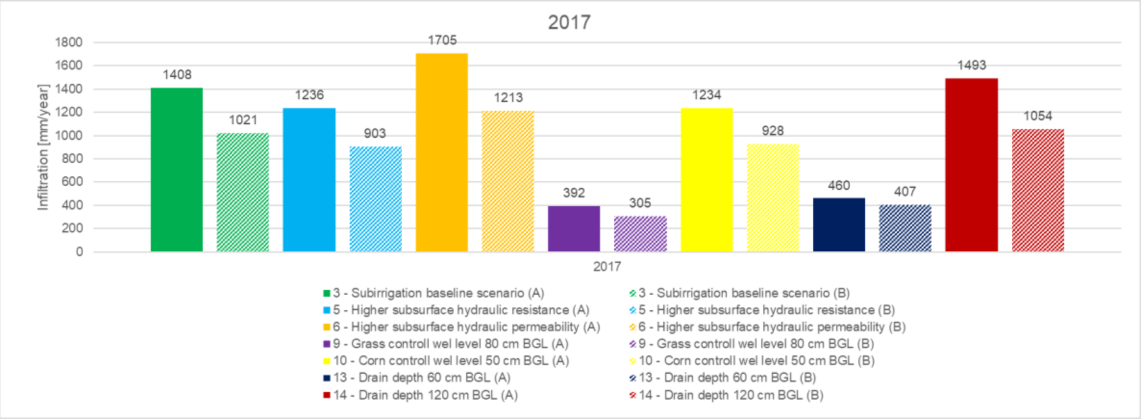


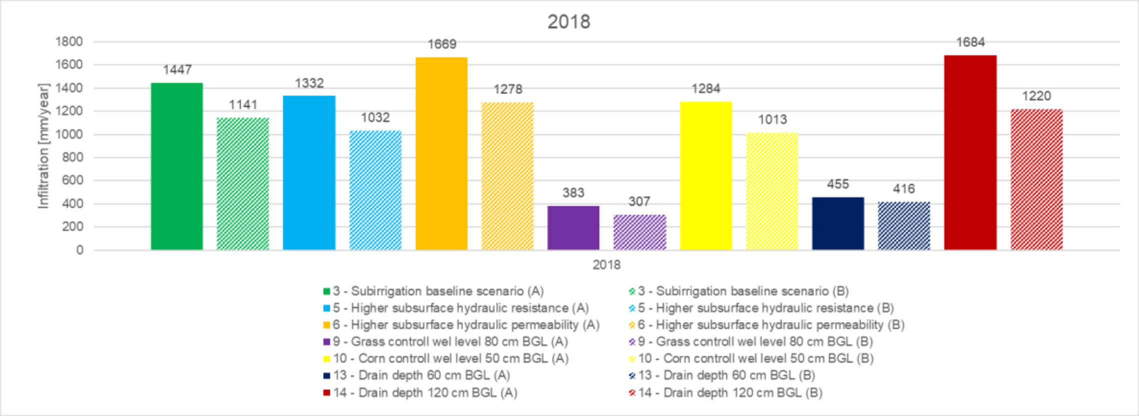


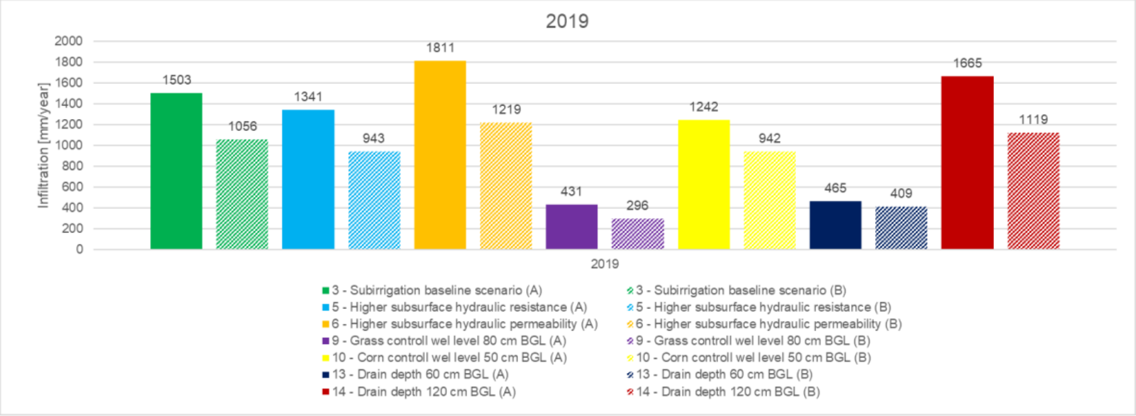


Appendix D: Applied subirrigation water per scenario

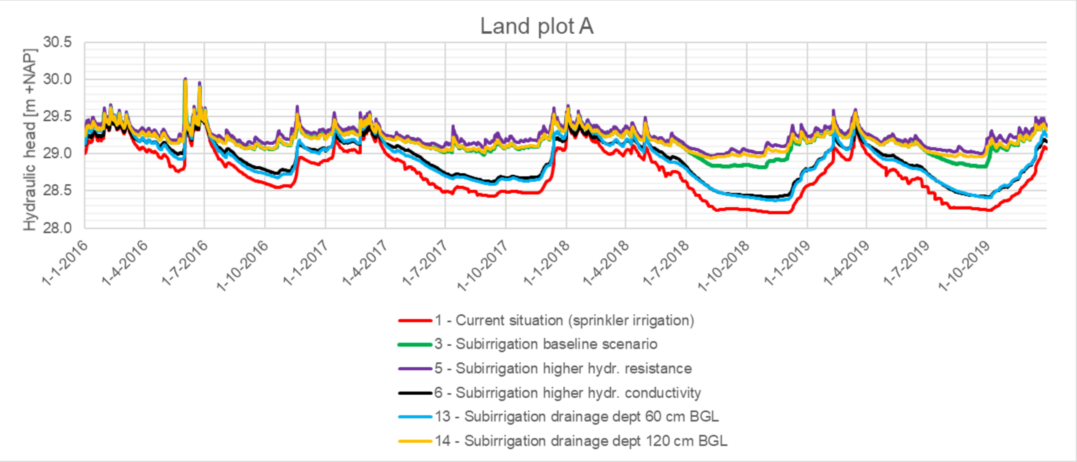


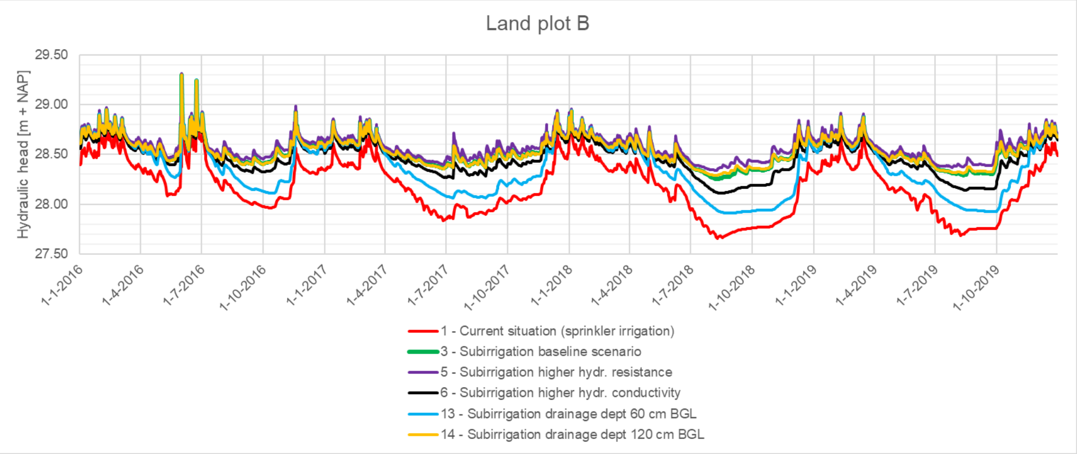


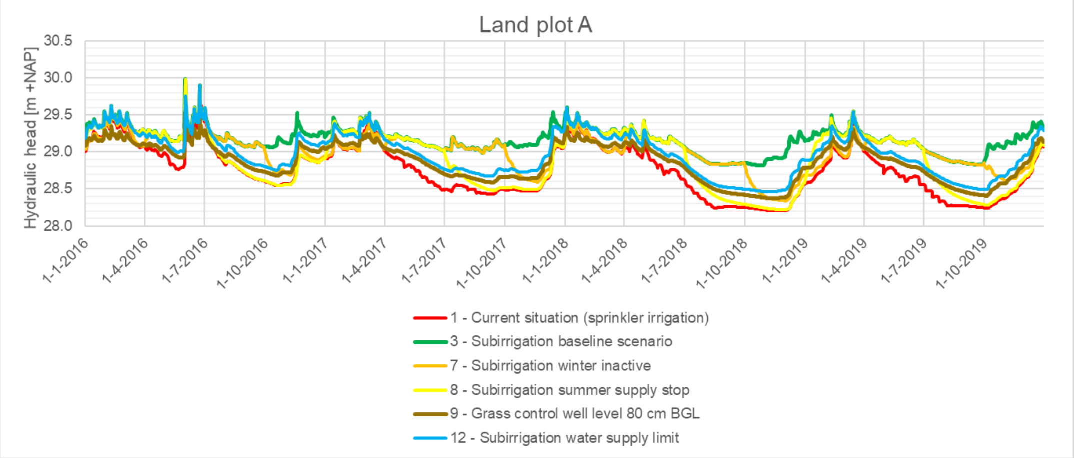


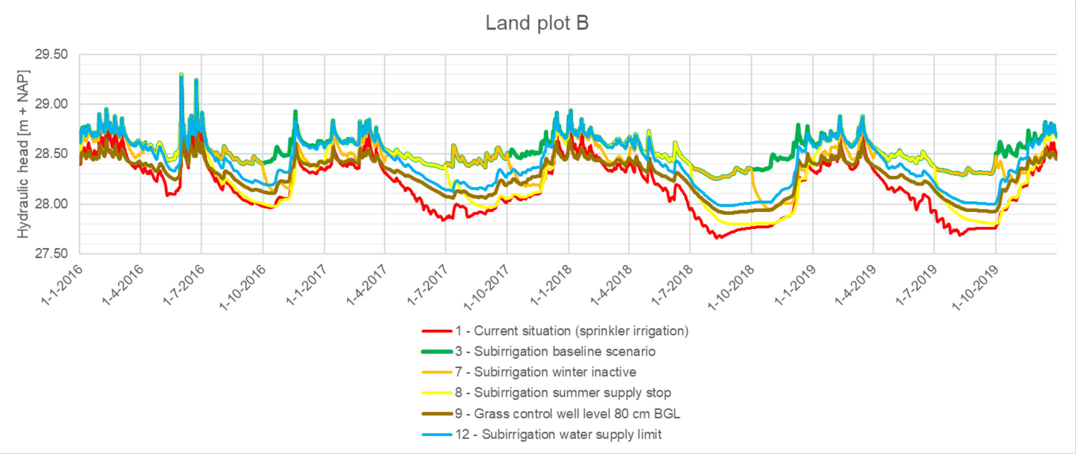


Appendix E: Groundwater levels per scenario









Appendix F: Water balance area for large scale modelling

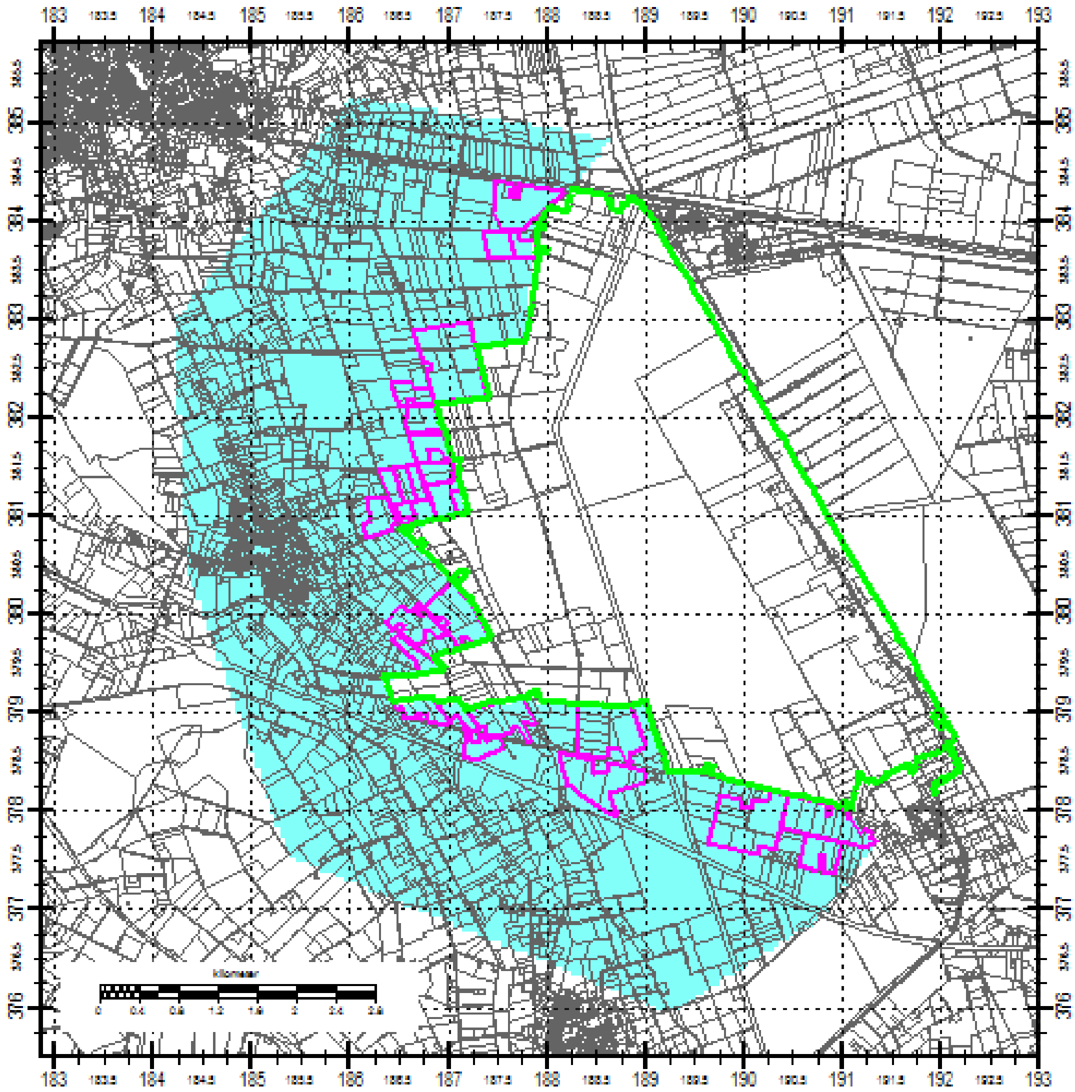


Figure E1, Overview of the area (in light blue) over which the water balance in section 4.3 is calculated; In purple: the subirrigation land plots; In green: the N2000 Deurnsche Peel